BSc Thesis

Battery Free Jogger Light - Energy Harvester

Jelle Klein - 4474384
Jhorie Slot - 4344472

Electrical Engineering
Delft University of Technology

Delft University of Technology

BSc Thesis

Battery Free Jogger Light - Energy Harvester

Delft University of Technology

Jelle Klein - 4474384
Jhorie Slot - 4344472

Supervisors:

Dr. Massimo Mastrangeli
Dr. Virgilio Valente

June 21, 2019

Thesis committee:

Dr. ir. Rob Remis
Dr. Virgilio Valente
Dr. ir. Arjan van Genderen

Faculty of Electrical Engineering (EE)
Delft University of Technology

Abstract

This thesis treats designing and building a linear generator which is used to power the Battery Free Jogger Light. This harvester needs to be able to generate power from the movement of a jogger. This Battery Free Jogger Light is meant to be used by people while jogging in dark environments to improve their visibility and thus safety.

The complete system consists of the energy harvester which is connected to a full-bridge rectifier. This full-bridge rectifier consists of two LEDs and two schottkydiodes. The bridge is connected to a voltage regulator which provides a constant voltage to a super-capacitor while the jogger is moving. After having the super-capacitor charged to a sufficient voltage level, the super-capacitor is able to power three other LEDs using a clocked-decade counter until the voltage level of the super-capacitor becomes to low.

A MATLAB model is created to be able to optimise the parameters of the model to comply with the needs of the rest of the system. To this point the model is able to calculate the voltages which are induced in the harvester. Using the model, a prototype was designed and built which was able to deliver plenty of power to the circuitry of the device.

A final prototype of the harvester is designed and built, the harvester is tested in combination with the rest of the system and the complete system is proven to be working.

Preface

This thesis is written in context of the Bachelor Graduation Project of the Bachelor Electrical Engineering at Delft University of Technology.

The goal of this project is to design a Battery Free Jogger Light which is able to keep on shining for a short period of time after a jogger stops moving. This thesis will address the energy harvesting part of the device. The goal is to determine the optimal dimensions and components for the harvester and ultimately a prototype needs to be delivered.

We would like to express our gratitude to our daily supervisors dr. Massimo Mastrangeli and dr. Virgilio Valente, for their guidance during the project. Furthermore we would like to thank dr. John Schmitz for proposing the project and also mr. M. Schumacher for providing us with all the components we needed to achieve our goals. Finally, we would like to thank our colleagues: Bart van Nobelen, Boyd Riemens, Jory Edelman and Koen Mesman for a productive and enjoyable collaboration.

Jhorie Slot & Jelle Klein
Delft June 21, 2019

Contents

1. Introduction

Back in the day people used to go jogging without any lights, and thus were poorly visible in the dark, which resulted in a high risk of accidents. Nowadays most people make use of small lights when they go jogging in the dark, but these lights are usually powered by batteries which will eventually run out of power. These batteries are in most cases not rechargeable and not replaceable, resulting in a useless device after some time, for example the 'Tunturi LED ARMLIGHT' [1]. However, one particular light exists which doesn't use batteries, the 'Million Mile Light' [2], which emits light based on the joggers movement in an angle of 180°. Ideally, the Battery Free Jogger Light should feature the emission of light after the movement has stopped with an angle covering 180° as well as increased visibility and decreased need for maintenance, due to optimisation.

It is important that joggers can run safely in the dark, as not everyone is able to go jogging during the day. So it is of importance that joggers are wearing an attention drawing, comfortable, and durable jogging light, while jogging in the dark. Road-users will benefit of the increase of visibility of joggers. This is why the product should be accessible for a wide-range of joggers around the world. There are currently two types of jogger lights on the market: battery based lights and lights which do not use a battery like the Million Mile Light. The battery based lights ensure that joggers are always visible while jogging or standing still until the battery dies. The Million Mile Light ensures that the jogger is also always visible while jogging, but not when the jogger is standing still at a traffic light for example. The goal of this research is to develop a product that combines the advantages of the two types of jogger lights that are currently on the market, thus improving upon the Million Mile Light by adding the operative function of temporarily maintaining light emission after the jogger's movement has stopped. The product is limited by the amount of power that can be generated per unit volume. This causes a limited amount of light emission when the movement stops, without compromising the comfort of the jogger. Additionally, the light configuration should fan out more than 180°. Lastly, the frequency of blinking should be independent of the frequency of the jogger's movement.

The environmental footprint of the product should be an improvement over the conventional jogger lights. Since no batteries will be used in the product, the production is more environmentally friendly and the durability is increased, which also improves its environmental footprint. However, the plastics which are used, are made from oil, which will always have a negative impact on the environment, but by using recycled and biodegradable materials the impact can be minimised. As it is a small light, the impact on light pollution will also be minimal.

So the goal of this research is to design a light that joggers can wear, that does not use a battery but is powered by energy harvested from the jogger's environment or movement, called the Battery Free Jogger Light. It should also emit light for awhile when the person stops jogging, for instance at a traffic light. Studies show that a flashing light ensures better visibility in the dark compared to a steady light [3]. That is why the Battery Free Jogger Light should be pulsating instead of continuously shining.

1-1 Task division

This project is divided into three subgroups; the energy harvesting group, the energy conversion & storage group and the lighting & casing group.

The conversion & storage group will convert the energy from the harvester to usable voltages and currents for the lighting group and store a part of the energy to be able to power the device while the jogger is not moving.

The lighting & casing group is responsible for the blinking lights and for building the casing.

This thesis addresses the energy harvesting part as mentioned earlier. The goal is to develop an energy harvester which could harvest energy from the environment, the human body or the movement of the human body. This must be done as efficiently as possible without impeding the joggers movement, because of the fact that it is a wearable device which brings limitations like weight and size to the jogger.

1-2 State-of-the-art solutions

There is already one battery free joggers light commercially available, the Million Mile Light, which consists of a few LEDs and one coil with one moving permanent magnet inside the coil[2]. This Million Mile Light only emits light when it undergoes a shaking motion, so it is assumed that it does not contain any short-term electrical power storage. In addition, it blinks at the frequency of the motion of the jogger, which supports the previous mentioned expectation. The LEDs in this device act like a full bridge rectifier where the LEDs function as diodes. This results in LEDs blinking while shaking the device. An important difference with the Million Mile Light is the fact that the Battery Free Jogger Light also needs to store some energy. Thus there will be more power needed for the Battery Free Jogger Light.

To develop the energy harvester for the Battery Free Jogger Light, some research is done at first in Section 3-1 about different sources of energy present while jogging outside in the dark and different methods to harvest the energy. There is looked into some already existing types of energy harvesters and those are compared according to size and amount of generated power in Section 3-1-1. Next, in Section 3-2 the theory about induced voltage by magnetic flux change is explained. Then Section 3-3 explains a MATLAB model which is built to determine which design parameters should be used for the harvester in the Battery Free Jogger Light. Thereafter, the delivered power to different loads are discussed in Section 3-4. Several prototypes were built and tested to compare to the MATLAB model to prove its working. When the model was proven to be accurate enough, a final harvester was built and tested as explained in Chapter 4. The harvester was tested in combination with the complete circuitry of the Battery Free Jogger Light to prove the functioning of the whole system. At the end the results from the prototypes are discussed and several improvements for the future are addressed in Chapters 5 and 6.

2. Program of requirements

These are the programme of requirements for the Battery Free Jogger Light. The goal of this chapter is to determine and specify the features of the Battery Free Jogger Light. The mandatory requirements are listed below. The trade-off requirements also listed below are criteria which are preferred to comply with as much as possible.

Mandatory requirements are:

- **Must not have a battery**
- Must have a flashing light
- The frequency of the flashing light must be independent of the jogger's movement
- **Must not obstruct the running movement**
- Must not be harmful for the jogger
- **Must functions in every moment of the day**
- Must be able to store energy for 30 seconds of lighting, when fully charged
- **Must be fully charged within 2 minutes of jogging**
- Must at least deliver 4 candela (*cd*) intensity
- The casing must be water-resistant (IP54)
- The degree of lighting must be at least 180 °
- Must have a life time of at least 3600 jogging hours (2 hours per day, for 5 years)
- **Must be wearable: Max. 250 *g* (incl. casing)**
- **Max. depth dimension must be 2.5 *cm***
- Max. material costs for the final prototype must be €50,-

Trade-off requirements are:

- **Maximise harvested power**
- Minimise charging time
- Maximise flashing duration when standing still
- Maximise light intensity (*cd*)
- Maximise angle of visibility
- Maximise durability
- **Minimise weight**
- **Minimise volume**
- Minimise production costs

The requirements that are put in bold are the requirements that are critical for the energy harvesting part of the project. Some other requirements are set for the Battery Free Jogger Light as a whole like durability, weight and production costs. These have to be taken into consideration as well, but these requirements are also dependent on the energy conversion & storage and lighting & casing parts of the research. These requirements will be taken into account during the research and will be discussed whether they have been achieved in Chapter 5.

3. Design process

3-1 Different ways of energy harvesting

Multiple sources of energy from which electrical energy could be harvested do exist. The most obvious forms which may be used as a source for the battery-free light, are kinetic energy, thermal energy, potential energy and electromagnetic energy. Solar energy is obviously also meeting those criteria, but solar energy could not be used by the battery-free light, because the light is worn mostly in dark environments.

Different ways of energy harvesting from these sources were analysed. Taking in consideration that the device is going to be used while jogging, the device should not impede the jogger's movements. Devices which harvest energy from the joints using some brace-like device, are not a feasible solution, because they will influence the free movement of the joints[4][5]. Devices which are embedded in the shoes are also not preferred because they will obligate the jogger to use a specific shoe instead of their own preferred shoes[6][7]. Harvesting energy from thermal energy, ambient vibration and ambient RF waves are not a feasible solution due to their low energy potential[8][9][10].

The remaining two solutions which are considered, are the linear and rotational generators, which both convert kinetic energy to electrical energy. These could be implemented in small devices and thus be worn on the body. Considering the complexity of the gears and small rotating components of a rotational generator, this would be too complex to build. This would also increase the production costs too much[11][12][13]. This concludes that a moving magnet linear generator is probably going to be the most feasible solution for the Battery Free Jogger Light.

3-1-1 Linear and rotational generator

A linear generator converts mechanical energy to electrical energy using the principles of electromagnetic induction. The difference between regular rotational generators which make use of rotary motion, and linear generators is that the linear generator makes use of the linear motion of a magnet inside a coil, meaning this magnet has a motion in a straight line. There are different ways to construct a linear generator. In another project a moving permanent magnet stator linear generator is used[14], due to the less complex mechanical design compared to a moving coil stator permanent magnetic linear generator. A well-known implementation of a linear generator is the renewable energy flashlight[15]. The optimisation of linear energy harvesters to harvest the energy from human movement, considering different types of magnets and their configurations, is discussed in another report[16] .

3-1-2 Linear generator on human body

In previous work a micro linear generator is used in a shoe to generate energy while walking. The consideration is made between harvesting energy from the upper and the lower limbs. Harvesting energy from the upper limbs is more difficult due to the more complex movement pattern and multiple degrees of movement freedom, in contrast to the lower limbs. These lower limbs are a better choice for energy scavenging, however it would not benefit the visibility of the jogger to mount the light low to the ground. The harvester needs to be optimised for low frequencies to adapt to the frequency of the human movement[17].

A study proposed an energy harvester which exploits the swing motion of the foot, using a permanent magnet suspended between two repelling permanent magnets inside a coil, see Figure 3-1. The voltage which is induced on the coil, is given by Equation 3-1 where N is the number of turns and Φ the magnetic flux. Several design considerations are made for example the number of turns of the coil and the remanence of the permanent magnet. The highest measured average power for this device was 0.84 mW at a motion speed of 6 km/h with a volume of 21 cm^3 and the average power density is 40 $\mu W/cm^3$[18]. A rather bigger version of this energy harvester which was also attached to the foot of a person, was able to produce an average power of 1 mW up to 2.14 mW with a walking speed of 4 km/h and 10 km/h respectively. With a total volume of 46.69 cm^3 (including housing) and an active volume of 33.28 cm^3, this results in a maximum power density of 45.8 $\mu W/cm^3$ and 64.3 $\mu W/cm^3$ respectively[19].

$$V = -N\frac{d\Phi}{dt} \tag{3-1}$$

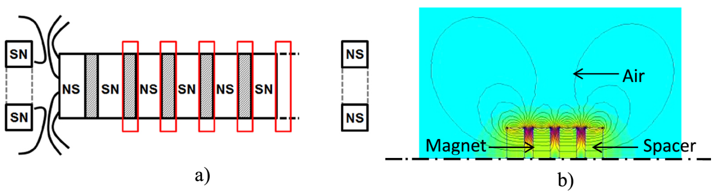


Figure 3-1: Linear energy harvester which could be attached to a shoe[18].

Energy could also be harvested from motion of the upper limbs namely the wrists, without bothersome additional muscle work see Figure 3-2. A fly-wheel actuating an electromagnetic linear generator is used, resulting in an induced voltage. During activities like jogging or dancing a maximum output power of 2.2 mW and an average power output of 20 μW is generated[20].

Figure 3-2: Energy harvester worn on the wrist[20].

A linear harvester with the size of an AA battery, that can be implemented in a small backpack is able to generate a power from 300 μW up to 2.5 mW. This magnetic spring generator uses two permanent magnets, one on the top and one on the bottom of the generator to suspend the magnet inside a coil. Due to these two magnets which behave like a spring, this generator has a resonance frequency[21]. The generator delivers maximum power when operating at this resonance frequency. So this frequency should be tuned such that the generator operates at the frequency of the movement of the jogger.

3-2 Induced voltage

From Faraday's law it is known that an electric current can be generated in a closed loop by a changing magnetic field in time[22]. The permanent magnets produce a constant magnetic field B $[Wb/m^2]$ and Equation 3-2 gives the total flux $[Wb]$. When the magnet is moved through a coil (see Figure 3-3), the amount of flux linking the surface of the coil is changed and a voltage which is called the electromotive force V_{emf} is produced according to Equation 3-3. When the coil is connected to some load the V_{emf} produces a current in the coil and through the load. This current will produce its own magnetic field which opposes the change of flux that caused the current, resulting in the minus sign in Equation 3-3.

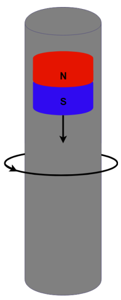


Figure 3-3: Schematic representation of a magnet moving through a coil.

$$\Phi = \int_S B \cdot ds \;\; [Wb] \tag{3-2}$$

$$V_{emf} = -N \cdot \frac{d\Phi}{dt} \;\; [V] \tag{3-3}$$

From Equation 3-3 it can be seen that the number of turns N and the change in magnetic flux determine the amount of voltage which is generated. The flux change depends on the speed of which the magnet moves through the coil and on the remanence of the magnet, because a permanent magnet is used. At last, the number of turns can be chosen such that a sufficient amount of voltage is generated.

The following design steps will thus be to investigate the properties and characteristics of different permanent magnet and coil configurations. At this point the most feasible option seems to be a magnetic spring generator which uses two fixed permanent magnets, one on the top and one on the bottom of the harvester. Both of these magnets repel the free moving magnet inside the tube. These three magnets all together operate like a damped mass spring system, which must be tuned to operate at resonance on the jogging frequency of the jogger.

3-3 MATLAB model

3-3-1 Model

A simple linear generator is modelled using MATLAB. This linear generator consists of a coil and a cylindrical permanent magnet. These are both aligned along and centred around the z-axis as can be seen in Figure 3-4. The centre of the coil is subject to a magnetic field due to the permanent moving magnet. The observation vector $\vec{p}$ points from the magnet towards the observation point p at the coil. While moving the magnet along the z-axis, a change of the total magnetic flux at the surface of the coil induces a voltage in the coil, according to Equation 3-3. This can be used to generate electrical power for a circuit.
This model simulates a single drop of the magnet from the top of the tube through the coil to the bottom of the tube. This will be used to compare the model to measurements on a prototype.

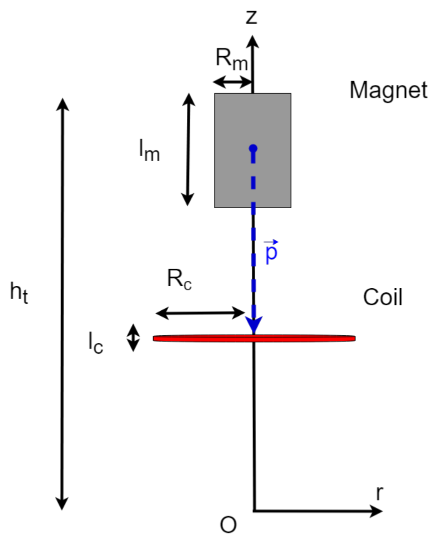


Figure 3-4: Schematic representation of the MATLAB model in cylindrical coordinates.

The induced voltage is calculated using Equation 3-4, where N is the number of turns in the coil and $\frac{d\Phi}{dt}$ is the change of the magnetic flux at the coil. This magnetic flux at the coil is the magnetic flux density B of the magnet multiplied by A, the area of the coil. Due to the fact that A is not varying in time, this area can be taken out of the differential factor.

$$V_{emf} = -N \cdot \frac{d\Phi}{dt} = -N \cdot \frac{d(A \cdot B)}{dt} = -N \cdot A \cdot \frac{dB}{dt} \;\; [V] \tag{3-4}$$

The assumption is made that the magnetic field inside the coil is homogeneous and that the length of the coil along the z-axis is approaching zero and thus all turns are located at the same plane. Thus $\vec{p}$ is the same for every turn in the coil. The magnetic field strength inside the coil due to the magnet can be calculated using Equation 3-5[23], where B_r is the remanence $[T]$ which is a property of a permanent magnet, p is the length of the observation vector $\vec{p}$, L_m is the height of the permanent magnet and R_m is the radius of the permanent magnet. The equation is originally used to calculate the magnetic field strength from the bottom of the magnet to the observation point p which is the terminal point of $\vec{p}$. This equation is shifted with half height of the magnet in the negative direction of the z-axis. This way the equation uses the centre of the magnet as the initial point of $\vec{p}$, as can be seen in Figure 3-4.

$$B = \frac{B_r}{2}\left(\frac{(p + 0.5 \cdot L_m)}{\sqrt{(p + 0.5 \cdot L_m)^2 + R_m^2}} - \frac{(p - 0.5 \cdot L_m)}{\sqrt{(p - 0.5 \cdot L_m)^2 + R_m^2}}\right) \;\; [T] \tag{3-5}$$

When an object is suspended at some height, that object has potential energy. This potential energy is converted to kinetic energy when it is dropped. This object will fall with a constant acceleration g, the gravity constant. The distance travelled by the mass as a function of time, is determined by Equation 3-6, with $g = 9.81\ m/s$ the gravity constant, t time and s the distance travelled. Losses like air resistance and magnetic damping are disregarded in this model. This magnetic damping is caused by the opposing induced magnetic field which is caused by the induced current flowing through the coil, this will be further elaborated in Section 3-13.

$$s = \frac{1}{2}gt^2 \;\; [m] \tag{3-6}$$

Rewriting Equation 3-4 to Equation 3-7 introduces a difference between two points in time. This way the equation can be implemented in MATLAB and V_{emf} can be calculated using Equation 3-7 and Equation 3-8.

$$V_{emf} = -N \cdot A \cdot \frac{dB}{dt} = -N \cdot A \cdot \frac{\Delta B}{\Delta t} \;\; [V] \tag{3-7}$$

$$\Delta B = \frac{B_r}{2}\left(\frac{(\Delta p + 0.5 \cdot L)}{\sqrt{(\Delta p + 0.5 \cdot L)^2 + R^2}} - \frac{(\Delta p - 0.5 \cdot L)}{\sqrt{(\Delta p - 0.5 \cdot L)^2 + R^2}}\right) \;\; [T] \tag{3-8}$$

3-3-2 Prototype

When the MATLAB model was finished, the prototype could be designed and built using the parameters as shown in Table 3-1. This way the measurements on the prototype can be compared to the results of the model. The Lighting/Casing group designed a 3D model of the tube and ordered the 3D printed tube. The 2550-turns coil is wound around the tube using a battery powered drill and using a specially designed drill-bit which could be attached to the tube, see Figure 3-5. Afterwards the precise length of wire used for the coil was determined by measuring the resistance of the coil and using the known resistance per meter of wire. The number of turns on the coil could than be determined, knowing the average circumference of the coil and the resistance per meter[24].

Parameter	**Value**
height of tube	8 cm
remanence of magnet	1.35 T
height of magnet	1.5 cm
radius of magnet	5 mm
weight of magnet	7.8 g
length of coil	14.6 mm
diameter of wire	0.15 mm
outer diameter of coil	13.8 mm
turns	2550
resistance	136.7 Ω
inductance	67.2 mH

Table 3-1: Parameters of prototype.

Figure 3-5: Picture of the prototype.

A neodymium magnet with a height of 1.5 cm and a diameter of 1 cm with an approximate remanence of 1.35 T is dropped from a height of 8 cm with the coil positioned at the centre of the tube. To measure the open terminal voltage of the prototype an oscilloscope is connected to the coil. This measured voltage is the V_{emf} on the coil. Using MATLAB a rms voltage of 2.83 V was determined from the measurement. The calculated V_{emf} from the model gives a rms voltage of 11.06 V. The measurements are shown in Figure 3-6.

Comparing the measured rms voltage and the rms voltage from the model a similarity is obtained of only 25.6 %. The shapes of both graphs in Figure 3-6 look the same, both have a positive peak at first. Right after the first peak, a second peak, but negative, arises. For both graphs it applies that the second peak is higher in amplitude than the first peak. This occurs because of the fact that when the magnet falls through the coil, it is accelerating. From which follows that the speed of the magnet is higher while leaving the coil compared to when entering the coil. Which in turn results in a higher magnetic flux change per time when leaving the coil and thus a higher voltage. After the two peaks there is an abrupt jump in the graph of the model, this is caused by the magnet which abruptly stops when it hits the bottom. For the measurement there is even a little spike visible which is caused by the magnet which bounces up a little when bumping into the bottom of the tube.

Because the model gives a result with the right shape, the assumption is made that the model is approaching reality, only it predicts a much higher voltage than measured on the prototype.

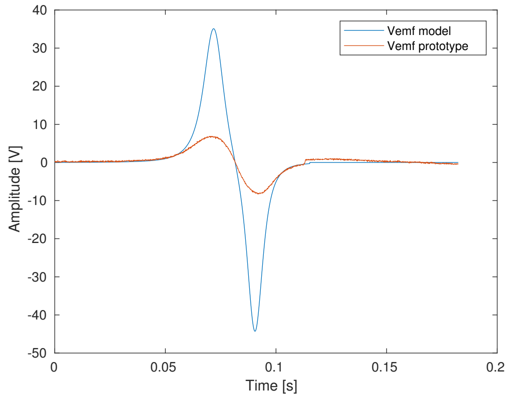


Figure 3-6: Induced voltage from dropping the magnet from 8 cm height.

After carefully going through the calculations and the MATLAB code from Appendix A-2-1, the conclusion was drawn that some assumptions made in the model do not comply with reality:

- There is some space between the magnet and the coil resulting in part of the magnetic field lines not going around the turns of the coil.
- The magnetic field at the coil is in reality not homogeneous.
- The coil has in reality not an infinitesimal height, and the magnetic field strength is thus different for different turns.
- Air resistance of the magnet is not taken into account, which would result in a lower speed of the magnet in reality.
- There is some friction between the tube and the magnet, resulting in frictional loss and a lower speed of the magnet.

These differences between the model and the prototype should be taken in consideration, to get a more accurate model. Firstly, the probably most significant difference is the fact that some of the magnetic field lines are not going around the coil, so these field lines are opposing others inside the coil, this will be addressed in Section 3-3-3. Secondly, the magnetic field due to the magnet is not homogeneous throughout the coil, since the turns in the coil have different distances to the magnet. So the assumption that the coil is exposed to a homogeneous magnetic field is inaccurate, this will be discussed in Section 3-3-4 and Section 3-3-5. Air resistance and frictional resistance are assumed to be not of a great influence and are considered as losses, and not included in the model.

3-3-3 Improving model using area of magnet

As mentioned earlier in Section 3-3-2, the fact that the magnet does not fill up the entire cross-sectional area inside the coil, gives rise to a difference between results of the model and the measurements of the prototype. Using the program "Finite Element Method Magnetics" [25] a model for a permanent magnet is made which is shown in Figure 3-7. In this figure the centred square is a permanent magnet of 1 cm by 1 cm with a remanence of 1.37 T. The outer blue rectangle represent the inner dimensions of the coil which are clearly bigger than the dimensions of the permanent magnet. Recall from Equation 3-4 that the total V_{emf} is induced by the change of the magnetic flux in the coil. This magnetic flux is calculated by integrating the magnetic field B over the area inside the coil. The white-marked area shows a part of the magnetic field which has a negative contribution to this integral, because the magnetic field is in opposite direction of the magnetic field in the cross-sectional area of the magnet. In the previous model this negative contribution occurred as a positive contribution. So by only integrating over the area of the magnet a better approximation of the change of magnetic flux is achieved. Thus in Equation 3-4 the area of the Coil A is replaced by the area of the magnet A_m as shown in Equation 3-9.

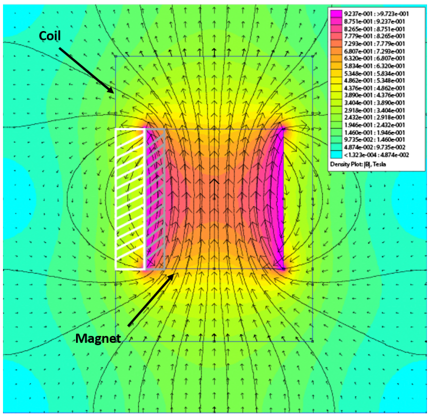


Figure 3-7: FEM model of a magnetic field inside a coil.

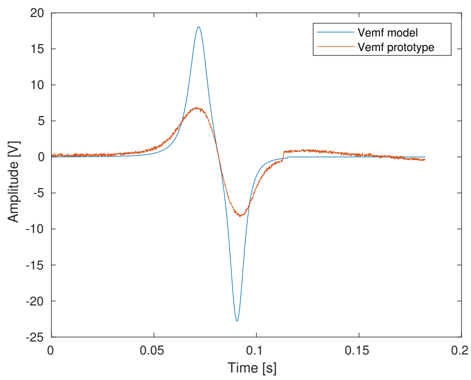


Figure 3-8: Induced voltage from dropping the magnet from 8 cm height using A_m.

$$V_{emf} = -N \cdot A \cdot \frac{dB}{dt} = -N \cdot A_m \frac{dB}{dt} = -N \cdot A_m \cdot \frac{\Delta B}{dt} \quad [V] \tag{3-9}$$

In further models and simulations the area of the coil A in Equation 3-7 is replaced with the area of the magnet A_m. This change in the model gives new results for the calculated induced voltage using the same parameters as in Table 3-1. These results are shown in 3-8. The rms voltage of the model is now 5.59 V. The measured rms voltage from the prototype in Section 3-3-2 is compared to the improved modelled rms voltage, which now shows a similarity of 51 %. This is a significant improvement.

3-3-4 Improving model using layers

From Section 3-3-2 it was concluded that another improvement of the model would be to consider the coil not having an infinitesimal height, but a coil which has turns at different distances from the magnet as can bee seen in Figure 3-9. The model will need to calculate the magnetic field strength per layer instead of using the same magnetic field strength for all layers. This means that every layer has its own magnetic field strength and thus its own induced voltage. By summing those different induced voltages for each time step, the total induced voltage per time step is obtained. This way the rms voltage of the model should decrease.

It is also considered that the length of the coil should be limited. When there are more turns than layers, this will result in multiple turns per layer. In Equation 3-10 the calculation of this total induced voltage is shown, where TPL is the turns per layer, which in the case of the prototype is 26, because not all turns can be wound next to each other. There are a total of 98 layers which can lay next to each other with the current dimensions. So in Equation 3-10 the $layers$ equals 98, which is the maximum number of layers for this coil length and wire diameter.

$$V_{emf} = \sum_{l=1}^{layers} -TPL \cdot A_m \cdot \frac{dB_l}{dt} \ [V] \tag{3-10}$$

To check whether the model does now more comply with the actual prototype, again the same parameters from Table 3-1 are used in the model and compared to the measurements. The results of the improved model are shown in Figure 3-10. The rms voltage of the model is now 4.10 V. The measured prototype's rms voltage from Section 3-3-2 compared to the modelled rms voltage, now has a similarity of 69 %.

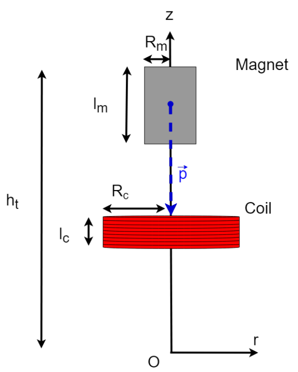


Figure 3-9: Schematic representation of the MATLAB model using layers in cylindrical coordinates.

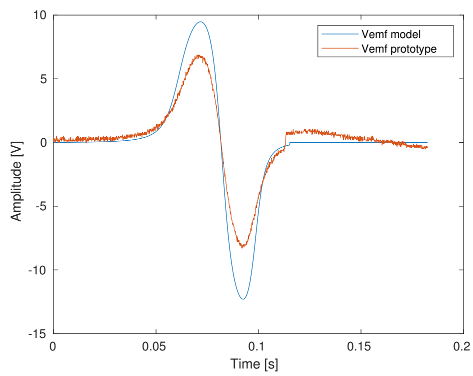


Figure 3-10: Induced voltage from dropping the magnet from 8 cm height using A_m and layers.

3-3-5 Improving model using rings

In previous models the assumption is made that for a layer the magnetic field strength is exactly the same over the surface of that layer. This assumption is rather inaccurate, because $\vec{p}$ is longer for the outer regions than the centre of a turn, as can be seen in Figure 3-11. This results in a magnetic field density at the boundary which is too high, compared to reality. The inaccuracy can be solved by dividing the surface of a turn in several rings. This way every ring has its own $\vec{p}$ and thus its own magnetic field strength. The length of the vector can be calculated using the Pythagorean theorem. The area of a ring is the area of the inner circle subtracted from that of the outer circle and $\vec{p}$ points towards the centre of the ring as can be seen Equation 3-11.

$$V_{emf} = \sum_{l=1}^{layers} -TPL \sum_{r=1}^{rings} (A_r \cdot \frac{dB_{lr}}{dt}) \ [V] \tag{3-11}$$

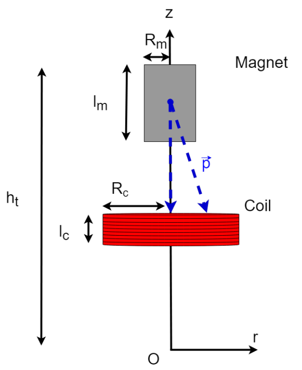


Figure 3-11: Schematic representation of the MATLAB model using layers and rings in cylindrical coordinates.

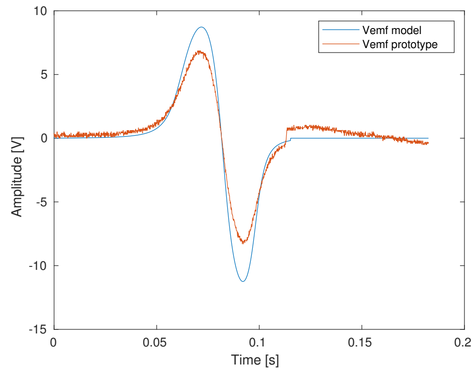


Figure 3-12: Induced voltage from dropping the magnet from 8 cm height using A_m, layers and rings.

Now that the possible improvements which were mentioned in Section 3-3-2 are implemented in the model, the resulting V_{rms} of the model is 3.68 V. The results of the model and the measurements from the prototype from Section 3-3-2 have a similarity of 77 %. The voltages are shown in Figure 3-12. The differences between the results from the model and prototype which are still present, are considered to be caused by frictional losses and measurement errors. Also the remanence of the magnet is not exactly known. The final MATLAB code can be seen in Appendix A-2-2.

3-4 Power delivered to a Load

In the previous part only the open terminal voltage (V_{emf}) has been considered. To determine the power delivered by the harvester, a load needs to be connected to the harvester. Figure 3-13 shows a schematic representation of the harvester connected to a load Z_L. R_c is the resistance of the coil where L_c is the inductance of the coil. To calculate the power delivered to the load the rms voltage at the load, $V_{L,rms}$ needs to be determined according to Equation 3-12, where $\omega = 2\pi f$ with f being the frequency of the generated signal from the harvester which is equal to the frequency of the jogger being around 3 Hz [26]. The delivered power can be determined using Equation 3-13. When the impedance from the harvester and the load are equal, the maximum power will be delivered to the load. Since the frequency of the signal is only around 3 Hz, L_c could be neglected and for further calculations and measurements only the real part of the impedance from the harvester is taken into account to simplify calculations.

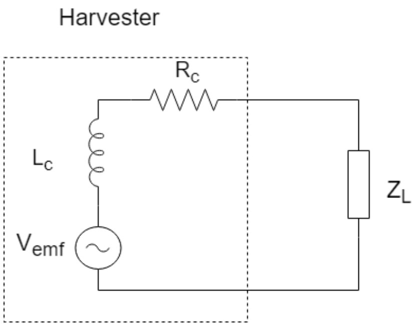


Figure 3-13: Circuit representation of the harvester connected to a load.

$$V_{L,rms} = \frac{V_{emf,rms} \cdot Z_L}{Z_L + (R_c + j\omega L_c)} \ [V] \quad (3\text{-}12)$$

$$P_L = \frac{V_{L,rms}^2}{R_L} \ [W] \quad (3\text{-}13)$$

When the harvester is connected to a load, a current can flow through the coil. From Ampère's law it is known that this current will produce a magnetic field at the coil according to Equation 3-14. The direction of this magnetic field will be in the opposite direction of the magnetic field due to the permanent magnet. Due to this opposing magnetic field the acceleration of the magnet will become negative when approaching the middle of the coil, and thus the falling speed will decrease. When the magnet is located in the middle of the coil, the falling speed of the magnet is lower, and thus it induces a smaller current, which will lead to a smaller opposing magnetic field. This will allow the magnet to accelerate again. This opposing magnetic force is not taken into account in the model due to time-constraints and it would too much complicate the model at this stage. This results in a bigger difference in the calculated V_L by the model and reality when the current is relatively high due to a relatively small load resistance.

$$B = \mu \frac{N}{L} I \ [T] \quad (3\text{-}14)$$

Figure 3-14 and 3-15 show the calculated and measured V_L respectively for different load resistances while dropping the magnet from 8 cm with the parameters from Table 3-1, having the coil positioned half-way the tube at 4 cm. From the measurements it can clearly be seen that for smaller load resistances the measured voltage peaks are longer in time and lower in amplitude. This time difference is due to the fact that the magnet falls with a lower average speed.

The model only calculates the V_{emf} and determines the load voltages via Equation 3-12. It does not take the opposing magnetic force from the coil into account for the falling speed. Thus the load voltage from the model and measurements show a difference in amplitude and time, which is shown in Figures 3-14 and 3-15. The differences are bigger for smaller load resistances due to the fact that for smaller resistances the current through the coil is higher, resulting in a stronger opposing magnetic field according to Equation 3-14. This repelling magnetic force results also in a lower delivered power measured from the prototype than was determined by the model as can be seen in Figure 3-16. This difference between the model and the measurements increases when the load becomes smaller as can be seen from Figure 3-17. It can be seen from Figure 3-16 that for a single drop of a magnet the maximum power of 7.1 mW is delivered to a load impedance of 136.7 Ω which is equal to the resistance of the coil (Table 3-1).

For the final design the resistance of the coil in the harvester and the load connected to it, should be matched to get the maximum power delivered to the load. It is concluded that the model can be used to optimise the energy harvester although the amplitude of the power which is delivered by the harvester will be lower than the model predicts.

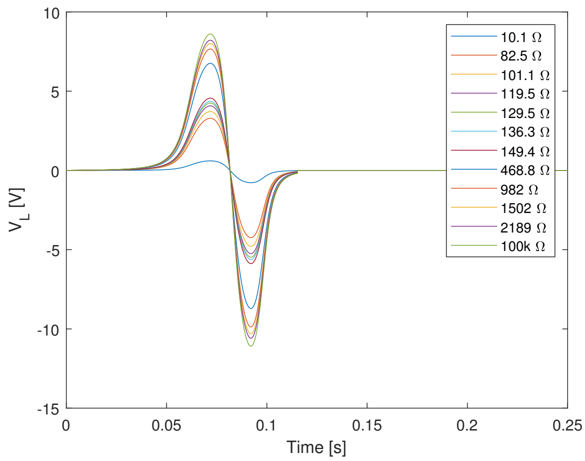


Figure 3-14: Modelled results using MATLAB.

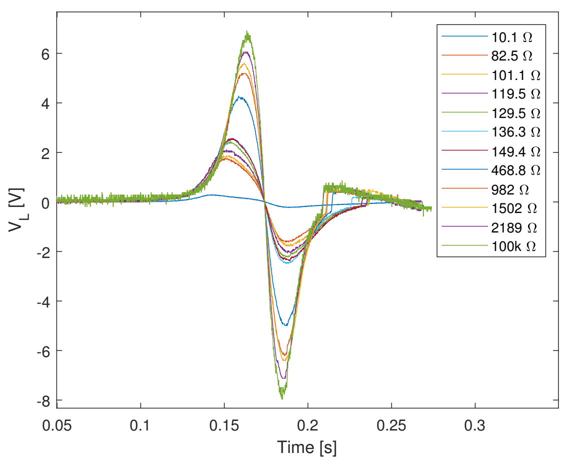


Figure 3-15: Measurements on prototype.

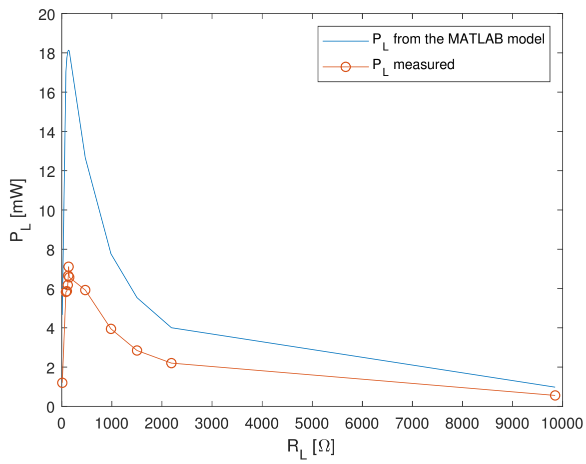


Figure 3-16: P_L for different R_L

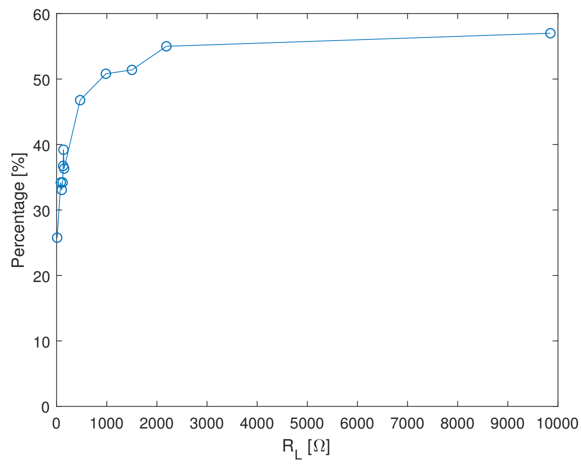


Figure 3-17: Difference in P_L between model and measurements for different R_L.

4. Final prototype implementation and validation results

4-1 Dimensions

Now that the MATLAB model gives accurate results compared to the prototype, the model can be used to determine the dimensions and parameters for the final prototype. The harvester is designed to harvest the maximum amount of power while still complying to the requirements as stated in Chapter 2. The maximum thickness of the complete Battery Free Jogger Light should not be more than 2.5 *cm*. Because the diameter of the coil determines the outer diameter of the harvester, this coil should not be more than 2.5 *cm* in diameter. For the moving magnet there is chosen to use the strongest magnets which were available from Conrad [27]. These were only available in 1 *cm* diameter, but different heights were available. The magnet needs to be able to slide through the tube so the inner diameter of the tube is chosen to be 1.01 *cm*.

For a maximal flux change the magnets should be able to be completely outside the coil on both ends. The coil will be positioned at the middle of the tube. The tube should thus have a height of at least 2 times the height of the magnet plus the height of the coil. The height of the tube for the final design is chosen to be maximal 8 *cm*, because the device should not impede the jogger's movements.

The conversion & storage group requires a high peak-peak voltage, because of a voltage drop caused by the full-bridge rectifier which includes both LEDs and diodes. This is achieved by using as many turns as possible on the harvester. This maximum number of turns is limited by the 2.5 *cm* outer-diameter of the coil, but it is also limited by the diameter of the wire and the number of turns. The length of the coil is designed to be around 1.5 *cm*. There were only a few different types of wire available at our supplier which all have a different length and diameter. The available wires at Conrad [27] have a smaller diameter for longer lengths. A consideration needs to be made between number of turns and total resistance of the coil. To get the maximum number of turns, the wire diameter is chosen to be 0.10 *mm*. What follows, is that the wire is 450 *m* long and will have a resistance of around 1000 Ω. Using this wire, a coil could be made which contains around 7600 turns.

After determining the dimensions for the tube and the coil, the tube is 3D printed. The coil is wound around the tube using a battery powered drill. The final product is shown in Figure 4-1. The resistance of the coil is measured using the known resistance per meter of wire. The actual number of turns is calculated to be approximately 7600 turns. All dimensions and other parameters are measured after the prototype was built and are shown in Table 4-1.

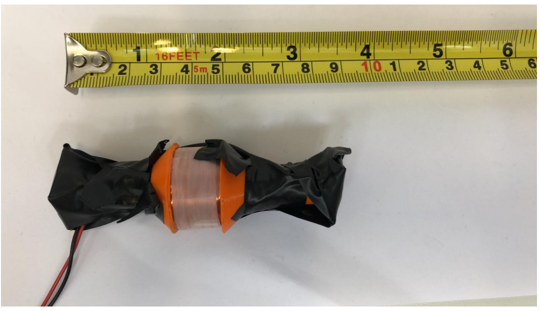


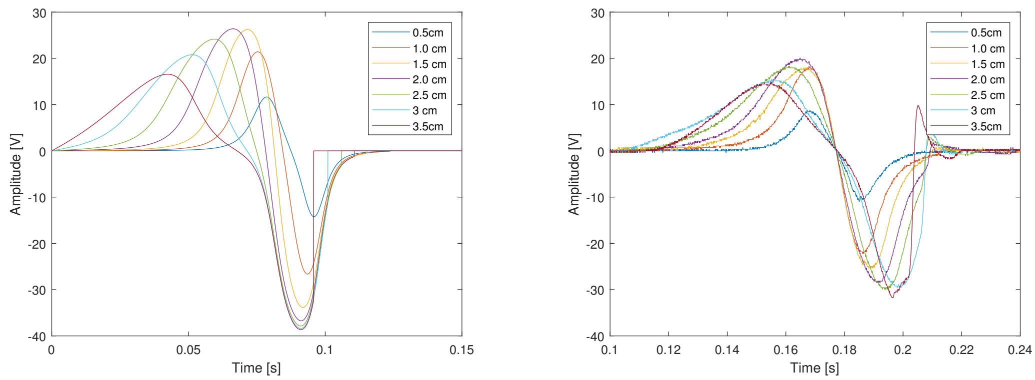
Figure 4-1: Picture of the final prototype.

Parameter	Value
height of tube	8 cm
remanence of magnet	1.35 T
height of magnet	2 cm
radius of magnet	5 mm
weight of magnet	9.9 gram
length of coil	14.6 mm
diameter of wire	0.10 mm
outer diameter of coil	26.0 mm
turns	7600
resistance	1035 Ω
inductance	620 mH
height of top/bottom magnet	0.2 mm
radius of top/bottom magnet	0.2 mm
remanence of top/bottom magnet	1.20 T

Table 4-1: Parameters of the final prototype.

4-2 Moving magnet

The next step is to determine the optimal dimensions and remanence of the moving permanent magnet. As discussed above, the diameter of the magnets is 1 cm. The moving magnet is selected to have the highest remanence, because this will result in the highest magnetic field strength. These N45 neodymium magnets have a remanence between 1.33 T and 1.37 T. The MATLAB model is used to determine the peak-peak voltages for different magnet heights. The results are shown in Figure 4-2a. It can be seen that the 2 cm magnet gives the highest peak-peak voltage. Figure 4-2b gives the measured open terminal voltages of the prototype for different magnet heights. These measurements also show that the 2 cm magnet gives the highest peak-peak voltage. For the final harvester a magnet with a height of 2 cm and a diameter of 1 cm is going to be used due to the highest peak-peak voltage.



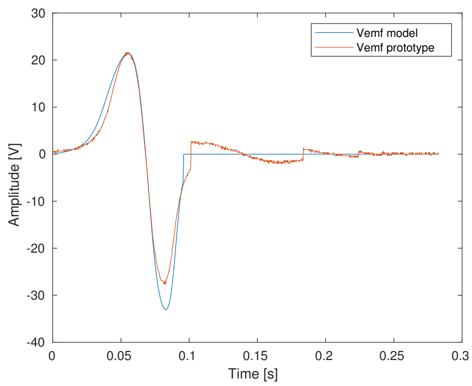
(a) Modelled results using MATLAB.

(b) Measurements on prototype.

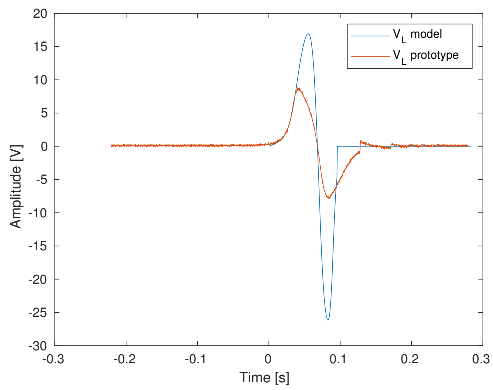
Figure 4-2: V_{emf} for different magnet heights.

4-3 Results of dropping magnet in final prototype and model

After having selected the height of the moving magnet inside the tube and thus having all parameters defined as in Table 4-1, voltage measurements for a single drop of the magnet are done on the final prototype as can be seen in Figure 4-3.
In Figure 4-3a the open terminal voltage is shown. The modelled and the prototype's measured rms voltages have a similarity of 88 %.
The measured rms load voltage of the prototype and the modelled are shown in Figure 4-3b. The connected load resistance is 1035 Ω, which is equal to the resistance of the coil. The model and the prototype's measurement have a similarity of 44 % for V_{load}, which is a significant difference comparing it to the open terminal similarity, this difference is explained in Section 3-4. In addition, the results for the power which is delivered to the 1035 Ω load has a similarity 19 %, ($0.44^2 = 0.19$) between the model and the measurement. The MATLAB code of the model using the final prototype's parameters can be seen in Appendix A-2-3.



(a) Open terminal voltage, V_{emf}.



(b) Voltage over load, V_L.

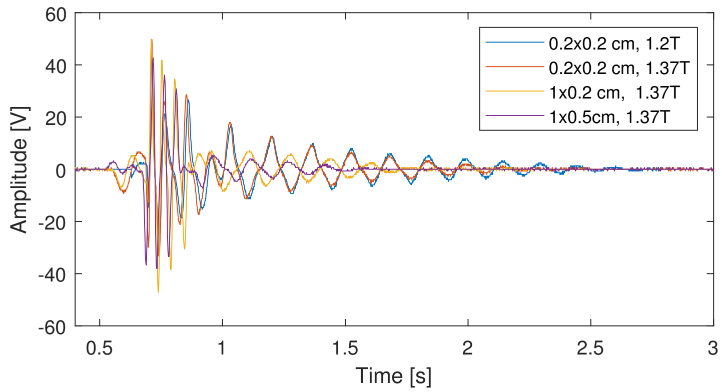
Figure 4-3: Measurements on final prototype.

4-4 Spring implementation

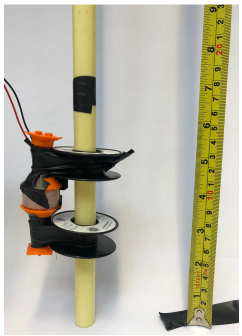
While shaking the harvester, the magnet is bumping into the top and bottom of the tube. This results in a loss of energy in the collision and results in an annoying clicking sound. To overcome these issues, two magnets could be mounted one at the top and one at the bottom of the tube. The moving magnet would together with the magnets on the top and bottom act like a damped mass spring system. The moving magnet oscillates with an amplitude and a frequency which both can be tuned by choosing top and bottom magnets with certain dimensions and a particular remanence.

It is considered that to harvest the maximum amount of energy and get the highest peak-peak voltage, the magnet should oscillate with a maximum amplitude without bumping into the top and bottom of the tube. To get this maximum amplitude, the natural frequency of the damped mass spring system should match with the jogger's jogging frequency. However this maximum amplitude should not lead to bumping at one of the ends of the tube as mentioned before. Thus the maximum amplitude should be tuned to be as close to the maximum displacement of the magnet inside the tube. Conclusively a magnet configuration with the least damping force but enough force to keep the moving magnet from bumping in to the top or bottom needs to be used.

Different magnets are mounted on the top and bottom of the harvester. The harvester is dropped along a tube from a height of 15 cm to represent the movement of the jogger and to use the same potential energy as input for every measurement as shown in Figure 4-4b. Figure 4-4a shows the results from the open terminal voltage measurement with an oscilloscope. From these measurements it can be concluded that the 1 cm by 0.5 cm and 1 cm by 0.2 cm magnets both with a remanence of approximately 1.35 T are damping the oscillation too quickly. Both the magnets with 0.2 cm by 0.2 cm, but with a different remanence of 1.2 T and 1.35 T give almost identical results, and are strong enough to stop the magnet from bumping into the top and bottom. For the final design there is chosen to use two magnets of 0.2 cm by 0.2 cm with a remanence of 1.2 T, because this one has the least damping and highest amplitude.



(a) Measured V_{emf} for different top and bottom magnets.



(b) Harvester, sliding along tube, ruler for dimensions.

Figure 4-4

As mentioned in Section 3-4, when a load is connected to the harvester the coil will produce its own opposing magnetic field. This field causes the magnet to move with a lower speed, and thus also influences the damping of the damped mass spring system. Figure 4-5 shows the voltage delivered to a load of 1035 Ω over time. It can clearly be seen that the damping is much stronger for all of the four top and bottom magnet configurations, compared to the open terminal measurement in Figure 4-4a. However for the final prototype the magnets of 0.2 cm by 0.2 cm with a remanence of 1.2 T represent still the most suitable configuration due to the lowest damping as can be seen in Figure 4-5.

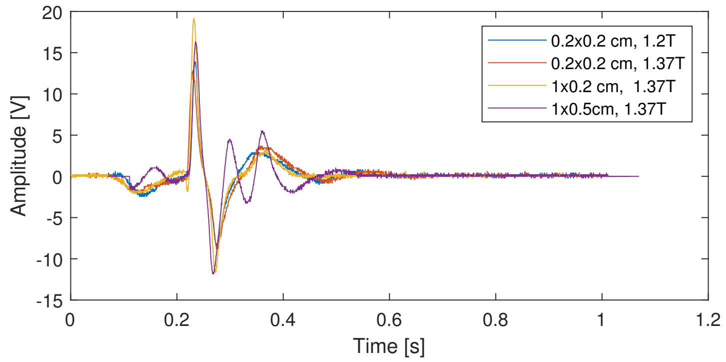
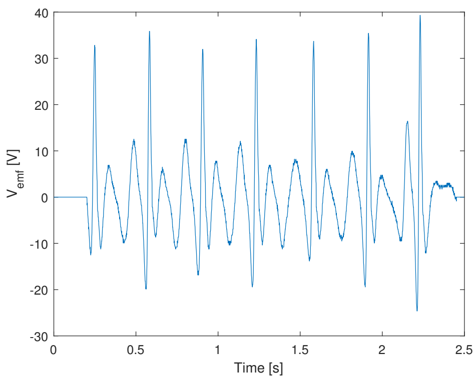


Figure 4-5: Measured V_L for different top and bottom magnets, R_L= 1037 Ω.

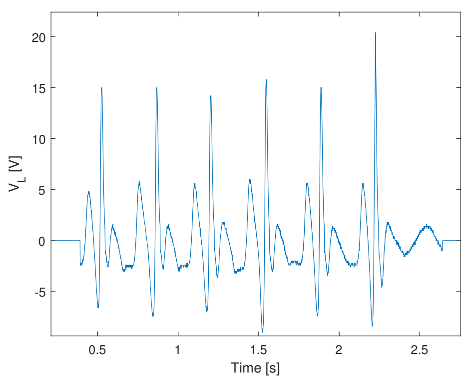
4-5 Generated power

Now that the final prototype is built, there needs to be looked into how much power the harvester is actually able to deliver to a load. At first the harvester is connected to an oscilloscope to measure the open terminal voltage (V_{emf}). The harvester is shaken by hand resulting in Figure 4-6a. Using an open terminal voltage, there is no current flowing and thus it is not possible to determine the power which could be delivered to a load.

Figure 4-6b shows the V_L when the harvester is connected to a load of 1035 Ω, which is equal to the resistance of the coil and thus the maximum power will be delivered to this load. Comparing Figures 4-6a and 4-6b, it can be seen that the damping is stronger when connected to the load which corresponds to the results shown in Section 4-4. MATLAB has been used to determine $V_{L,rms}$ from the measurement in Figure 4-6b, which turned out to be 3.67 V. Using Equation 3-13 the power delivered to the load is determined to be 13 mW. It should be noted that the harvester is shaken by hand for this measurement and thus this is not an accurate representation of the power which will be harvested during jogging, due to the difference in frequency and force of the shaking movement. However the measurements in Figure 4-6 show the wave forms of the signals which are produced by the harvester.



(a) V_{emf} measured.



(b) V_{load} measured using R_L = 1035 Ω.

Figure 4-6: Measured voltages on the final 7600-turn prototype while shaking by hand.

4-5-1 Power measurements while jogging

It is not possible to carry an oscilloscope while jogging, thus the harvester is connected to the full-bridge rectifier of the conversion & storage group, which is used to charge the super-capacitor. The load impedance is dependent on how far the super-capacitor is charged and thus it varies between 250 Ω and 7000 Ω. A voltmeter is used to measure the DC voltage over the capacitor. This setup is shown in Figure 4-7c. The harvester is tested while wearing it on the upper arm and on the waist of two different test persons, see Figures 4-7a and 4-7b.

(a) Harvester mounted on the upper arm. **(b)** Harvester mounted on the waist. **(c)** Measurement setup for determining delivered power.

Figure 4-7: Setup for power measurement while jogging.

For every measurement the capacitor is first fully discharged. After running 570 m the voltage and time are measured. Equations 4-1 and 4-2 can be written as Equation 4-3 which can be used to calculate the power delivered to the capacitor, using the measured time, voltage and a capacitance of 0.1 F. The efficiency of the full-bridge rectifier is 67 %. Using this efficiency, the power which is delivered by the harvester can be determined. The results are shown in Table 4-2. From these results it can be concluded that the harvester should be mounted on the waist of a jogger to harvest the maximum amount of power.

$$E = \frac{1}{2} C V_{DC}^2 \ \ [J] \tag{4-1}$$

$$P = E/t \ \ [W] \tag{4-2}$$

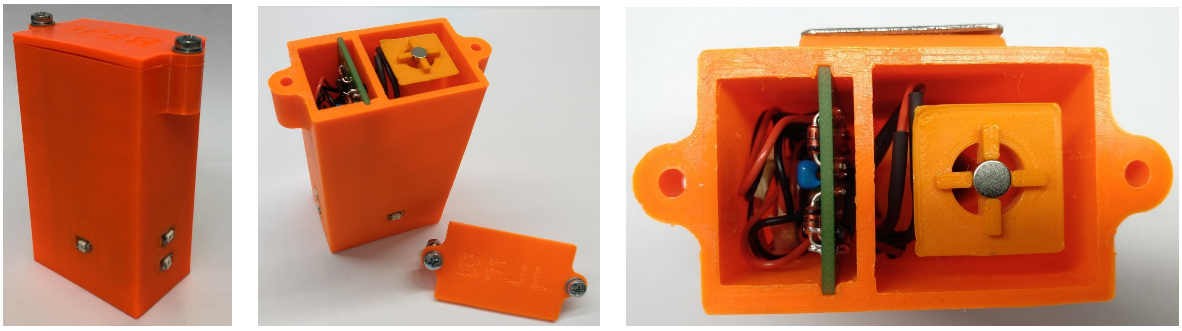
$$P = \frac{\frac{1}{2} C V^2}{t} = 0.05 \frac{V^2}{t} \ \ [W] \tag{4-3}$$

Position		Person 1		Person 2	
		Power $[mW]$	Speed $[km/h]$	Power $[mW]$	Speed $[km/h]$
Arm	Harvested	4.26	14.84	4.02	14.22
	Delivered	2.89		2.73	
Waist	Harvested	8.63	14.52	6.51	14.71
	Delivered	5.86		4.42	

Table 4-2: Power measurements final prototype.

4-6 Assembled Battery Free Jogger Light

At the end of the project when the three subgroups separately designed and tested their own circuits and designs. The harvester, circuitry and casing were all combined and mounted inside the casing as shown in Figure 4-8. The result is a device which functions correctly. After jogging for 5 minutes with a speed of approximately 12 km/h, the lights kept on flashing for 2 minutes.



(a) Front view **(b)** Top view **(c)** Top view

Figure 4-8: Pictures of the final device.

5. Discussion

The goal of this project was to design an energy harvester which will be used to power the Battery Free Jogger Light. After making a model for a linear harvester, a first prototype was built and tested. Multiple different measurements were made using multiple prototypes and they were compared to the results from the model. There turned out to be some substantial differences between the model and the measurement results. Multiple improvements were suggested and implemented in the model, resulting in a model which has a similarity of 77 % when comparing the V_{emf} of the model and the measured open terminal voltage on the harvester with the parameters from Table 3-1.

As discussed in Section 3-4, there is some difference between the model and the measurement results for calculating the V_L, and thus the P_L. These differences become bigger for smaller load resistances. This is occurring, because the induced current creates an opposing magnetic field which slows down the movement of the magnet, and this effect increases when the current running through the coil becomes higher, and thus when the load resistance gets smaller. The $V_{L,rms}$ of the final prototype differs with a factor 0.44 from the model when the load resistance is matched to the internal resistance of the coil at 1035 Ω. Because of the square in Equation 3-13 the measured power delivered to the load will differ by a factor $0.44^2 = 0.19$. Summarising, this difference in the delivered power between the model and the measurements is mainly caused by the magnetic damping. However the differences are mainly in the amplitude and thus the model may be used to optimise the energy harvester. Only the absolute results will slightly differ from the measured results.

For all measurements which were done on both the prototypes, the magnet was dropped or the harvester was shaken by hand. This results in quite a big difference in measurements due to the fact that this human input is not very constant.

Besides the prototypes which have 7600 and 2500 turns, two other prototypes were built. These prototypes have a length of 82 cm and 1.5 m with 10 and 38 turns respectively. These prototypes were meant to prove that the model, which didn't use layers and rings, would work correctly when the tube was much longer compared to the coil. However, the moving magnet had to be also much thinner to approach the idea that the V_{emf} could be calculated using only Equation 3-4, but this didn't work out.

The fixed top and bottom magnets were chosen based on the highest amplitude, the least damping and to overcome bumping of the moving magnet into the top or bottom of the tube. At the end the resonance frequency of the system was not determined, but the system is not damping too strong for the frequency of a jogger as can be seen in Figure 4-6.

Due to the fact that so many turns are needed to be wound around the coil using a battery powered drill, the precise number of turns is not known. The resistance of the coil is used to determine the number of turns as explained in Section 3-3-2. However, this has some error margin in the resistance measurement and thus this could result in a difference in the number of turns and thus in a difference between the results from the model and the measurements.

The load resistance of the connected device was unknown during the design process of the harvester. Due to this fact, it was not possible to use load matching during optimisation of the design.

The final prototype's depth did not meet the requirement of being maximal 2.5 cm. It turned out to be 3.4 cm.

At last measurements were done on the final prototype while jogging, from these measurements it can be concluded that the harvester delivers almost twice as much power when mounted on the waist compared tot the upper-arm. When mounting the harvester at the waist there could be harvested a average power of 7.57 mW while jogging with a speed of 14.63 km/h. The harvester has a volume of approximately 6.3 cm^3 which result in 1.2 mW/cm^3.

Conclusively, combining the works of the three subgroups, resulted in a functioning prototype. After jogging for 5 minutes, the device was able to keep on blinking for 2 more minutes.

6. Conclusion

There is looked into different sources of energy which are available while jogging, and different methods to harvest this energy. From these methods of energy harvesting, the linear generator is concluded to be the most feasible solution for The Battery Free Jogger Light. A MATLAB model of the linear generator is made and used to design the final prototype.

The final prototype is able to deliver a maximum of 8.89 mW when mounted on the waist of a jogger. This is a sufficient amount of power for the LEDs and also to charge the capacitor in 2.5 minutes. The light will keep on pulsating for a maximum of 2 minutes when the jogger does not move. This satisfies the requirement that the capacitor should be charged within two minutes, as mentioned in 2.

The complete Battery Free Jogger Light weighs 158.8 g, and has has an outer width of 54 mm, height of 88 mm and depth of 34 mm without the lid, the lid has a thickness of 3 mm. This corresponds broadly with the mandatory requirements, but the dept exceeds the requirements by 24 %. From tests conducted while running it is concluded that the device does not impede the movement of the jogger, although the device is quite bulky.

The weekly review and the collaboration with the subgroups are described in Appendix A-1.

6-1 Future work

Although the harvester is functioning properly in combination with the rest of the Battery Free Jogger Light, there are some improvements which could be made in future work.

- The magnetic damping due to the induced current in the coil should be implemented in the model, because the model mentioned in this thesis gives not quite accurate result for the load voltage and thus for the power which is delivered to the load.
- It is difficult to model permanent magnets and their fields using mathematical software like MATLAB. Using more suitable software to model the energy harvester, could help to get more accurate results.
- The final prototype which is mentioned in this thesis is designed to harvest the maximum amount of power while keeping the harvester inside the required dimensions mentioned in Section 2. Designing the harvester to deliver just enough power for the load instead of the maximum power could also be an improvement. This would probably result in a smaller and lighter harvester and thus a more compact Battery Free Jogger's Light, which would thus be more comfortable to wear wile jogging.

Bibliography

[1] "Tunturi," 04 2019. https://www.tunturi.com/product/tunturi-led-hardloop-armband.

[2] "Batteryfree.co.uk | million mile light," 04 2019. http://www.batteryfree.co.uk.

[3] A. Crawford, "The perception of light signals: The effect of the number of irrelevant lights," *Ergonomics*, vol. 5, no. 3, pp. 417–428, 1962.

[4] P. Niu, P. Chapman, R. Riemer, and X. Zhang, "Evaluation of motions and actuation methods for biomechanical energy harvesting," in *2004 IEEE 35th Annual Power Electronics Specialists Conference (IEEE Cat. No.04CH37551)*, vol. 3, pp. 2100–2106 Vol.3, June 2004.

[5] J. M. Donelan, Q. Li, V. Naing, J. A. Hoffer, D. J. Weber, and A. D. Kuo, "Biomechanical energy harvesting: Generating electricity during walking with minimal user effort," *Science*, vol. 319, no. 5864, pp. 807–810, 2008.

[6] H. Jeffrey Yukio, "Unobtrusive integration of magnetic generator systems into common footwear," 09 2007.

[7] J. Zhao and Z. You, "A shoe-embedded piezoelectric energy harvester for wearable sensors," *Sensors*, vol. 14, July 2014.

[8] Q. Brogan, T. O'Connor, and D. S. Ha, "Solar and thermal energy harvesting with a wearable jacket," in *2014 IEEE International Symposium on Circuits and Systems (ISCAS)*, pp. 1412–1415, June 2014.

[9] J. A. Paradiso and T. Starner, "Energy scavenging for mobile and wireless electronics," *IEEE Pervasive Computing*, vol. 4, pp. 18–27, jan 2005.

[10] X. Liu, J. Qiu, H. Chen, X. Xu, Y. Wen, and P. Li, "Design and optimization of an electromagnetic vibration energy harvester using dual halbach arrays," *IEEE Transactions on Magnetics*, vol. 51, pp. 1–15, Nov. 2015.

[11] J. Nakano, K. Komori, Y. Hattori, and Y. Suzuki, "Mems rotational electret energy harvester for human motion," in *Journal of Physics: Conference Series*, vol. 660, p. 012052, IOP Publishing, 2015.

[12] J. Wang, W. Wang, G. W. Jewell, and D. Howe, "Design of a miniature permanent-magnet generator and energy storage system," *Ieee transactions on industrial electronics*, vol. 52, pp. 1383–1390, Oct 2005.

[13] T. Xue, S. Kakkar, Q. Lin, and S. Roundy, "Characterization of micro-generators embedded in commercial-off-the-shelf watches for wearable energy harvesting," in *Industrial and Commercial Applications of Smart Structures Technologies 2016*, vol. 9801, p. 98010O, International Society for Optics and Photonics, 2016.

[14] I. Boldea and S. A. Nasar, "Linear electric actuators and generators," *IEEE Transactions on Energy Conversion*, vol. 14, pp. 712–717, Sep. 1999.

[15] S. R. Vetorino, J. V. Platt, and D. A. Springer, "Renewable energy flashlight," Nov. 2 1999. US Patent 5,975,714.

[16] C. Ma, W. Zhao, and L. Qu, "Design optimization of a linear generator with dual halbach array for human motion energy harvesting," in *2015 IEEE International Electric Machines Drives Conference (IEMDC)*, pp. 703–708, May 2015.

[17] P. Gui, F. Deng, Z. Liang, Y. Cai, and J. Chen, "Micro linear generator for harvesting mechanical energy from the human gait," *Elsevier, Energy*, vol. 154, pp. 365–373, July 2018.

[18] K. Ylli, D. Hoffmann, A. Willmann, P. Becker, B. Folkmer, and Y. Manoli, "Energy harvesting from human motion: Exploiting swing and shock excitations," *Smart Materials and Structures*, vol. 24, p. 025029, 02 2015.

[19] K. Ylli, D. Hoffmann, P. Becker, A. Willmann, B. Folkmer, and Y. Manoli, "Human motion energy harvesting for AAL applications," *Journal of Physics: Conference Series*, vol. 557, p. 012024, nov 2014.

[20] S. Brunner, M. Gerst, and C. Pylatiuk, "Design of a body energy harvesting system for the upper extremity," *De Gruyter*, vol. 3, pp. 331 – 334, September 2017.

[21] C. Saha, T. O'Donnell, N. Wang, and P. McCloskey, "Electromagnetic generator for harvesting energy from human motion," *Sensors and Actuators A: Physical*, vol. 147, no. 1, pp. 248 – 253, 2008.

[22] F. T. Ulaby and U. Ravaioli, *Fundamentals of Applied Electromanetics, Seventh Edition*. Pearson, 2010.

[23] J. M. Camacho and V. Sosa, "Alternative method to calculate the magnetic field of permanent magnets with azimuthal symmetry," *Revista mexicana de física E*, vol. 59, pp. 8–17, 06 2013.

[24] "Tru components, enameled copper wire," 04 2019. https://produktinfo.conrad.com/datenblaetter/1500000-1599999/001565202-da-01-en-KUPFERLACKDRAHT_9_M_AUSSEN_0_0_8_MM.pdf.

[25] "Finite element method magnetics," june 2019. http://www.femm.info/wiki/HomePage.

[26] A. V. Rowlands, M. R. Stone, and R. G. Eston, “Influence of speed and step frequency during walking and running on motion sensor output,” *Medicine & Science in Sports & Exercise*, vol. 39, no. 4, pp. 716–727, 2007.

[27] “Conrad,” june 2019. https://www.conrad.nl/.

A. Appendix

A-1 Collaboration

A-1-1 Weekly overview

Preparation
During the third quarter of the year from 11^{th} of February until the 21^{st} of April, we were assigned to the bap thesis project the Battery Free Jogger Light. After meeting for the first time with the group and our bap supervisors, we divided the project in three separate subjects; The energy harvesting, The conversion & storage and the light & casing. Thereafter, we determined some preliminary requirements and made agreements on which parts of the designs would be carried out by which subgroup. During the third quarter we already organised some brainstorm sessions to think and discuss together with the whole group some possible solutions and methods for our parts.

Week 1
From Monday the 22^{nd} of April to the 26^{th} of April, we worked on our literature study. During our literature study we looked into many different types of energy harvesting, and summarised our findings and conclusions in the literature report. Friday 3^{th} of May we finished the first draft of the literature study and submitted the report to receive the first feedback.

Week 2
The second week of the 4^{th} quarter from the 29^{th} of April to the 3^{th} of May, we started the design process of the energy harvester. From the literature study we already concluded that we would try to build a linear generator. To investigate the influence of the different design considerations we wrote a MATLAB model. Using this model we were able to determine how much power there could be harvested. The other two subgroups used this estimation of the potential generated power to start designing their parts. We used the MATLAB model to determine what type of permanent magnets and what type and diameter of wire we needed, and ordered these materials at the end of the week. Also the lectures and classes for Ethics and Business plan started this week.

Week 3
Monday the 6^{th} of May the ordered parts and the first 3D printed tube from the casing group arrived. So we were able to start building the first prototype. After comparing the measurements on the prototype to the MATLAB model we observed quite big differences in generated voltage and delivered power between the model and the measurements on the prototype. We have been busy for the rest of this week to find the reasons for this differences and thus we had built some additional prototypes, and overlooked our MATLAB codes. Also we attended the lectures and classes of the Ethics and Business plan courses.

Week 4
During the 4^{th} week, we have been busy with the business plan and the ethics course, also the green light assessment has been prepared this week. Due to this fact we only had 1 day to work on improving the MATLAB model.

Week 5
At Monday of week 5 the green light assessments were held, all three the subgroups received a positive result and were allowed to pursue with the project. We used the rest of the week to improve the MATLAB model and implemented the method of calculating the change of magnetic field for small parts of the coil and per layer. After some time we concluded that this resulted in a more accurate assumption to the actual prototype. Now the model could actual be used to make an assumption for the power which will be delivered.

Week 6
Due to the fact that there were two day's off this week we only had three days to work together in the Tellegen hall. At the beginning of this week during the weekly meeting there was concluded that the design for the conversion and the oscillating circuits would not work with the low voltage and power from the first prototype. Several changes were proposed for the different parts to get the complete system to work, for example the oscillating circuits should reduce the power needed and there should be looked into a more efficient way of charging the capacitor in the storage part. Also improving the harvester to generate a higher voltage and thus deliver more power was concluded to be a possible solution. So a new harvester is designed which should generate much higher voltages, parts were ordered and it was built during this week. This harvester has almost 3 times more turns as the first prototype so as expected there is generated much more power. After connecting all of the circuits and the harvester to each other the complete system does function properly, while some minor changers must be made to improve the stable working of the Battery Free Jogger Light.

Week 7
This week the other groups, have been busy by improving there circuits and choice of components using the harvester to determine the efficiency's and optimisation's of their circuit's. We used this week to do lots of measurements on the harvester to determine the optimal magnet configurations. Also some measurements are done on the delivered power by the harvester.

Week 8
This week is used to write the mayor part of the final bachelor thesis. We also conducted the measurements on how much power the harvester could generate on which part of the body. At the end of this week we submitted the first draft of this thesis to the supervisors.

Week 9
The last week we worked hard on finalising the thesis, and conducted the last measurements. Also the complete system of the Battery Free Jogger light is tested while jogging and some measurements are done on the delivered power for different places on the body.

A-1-2 Group work

It has proven to be challenging to work together on designing and testing different parts of the system divided over the three groups. Because all the different parts depend on each other. At the beginning of this project the requirements for the different subgroups were not entirely clear due to the fact that groups could not know in advance how much power they could generate or would need. However, due to much looking into each others projects and discussing different solutions for the difficulties we faced, we eventually managed to work very efficiently together and were able to solve all problems. Finally, we were able to deliver together the Battery Free Jogger Light.

A-2 Matlab

A-2-1 First model dropping magnet through coil

```
close all;
clear;

% First model dropping of magnet
tResolution = 0.0001; % [s]
turnsOfCoil = 2546; % turns
lengthOfCoil = 0.0146; % length of coil [m]
remanence = 1.35; % [T] average remanence
thicknessMagnet = 0.0099 * 1.5; % [m]
radiusMagnet = 0.0049; % [m]
diameterOfWire = 0.15 / 1000; % [m]
innerRadiusOfCoil = 0.0138/2; % radius of coil [m]
heightTube = 0.08 ; % [m]
halfHeightTube = heightTube / 2; % [m]
csvLoadFilename = "./meting/load/data-load.csv"; % data v load measurement ... [time; voltage]
csvVemfFilename = "./meting/open/data-open.csv"; % data v emf measurement ... [time; voltage]
leeds = 0.80 * 2; % [m]

%% constants
mu0 = 4*pi*1e-7; % [H/m]

%% Dimension calculations of coil
areaOfWire = pi * (diameterOfWire/2)^2; % [m^2]
circumferenceOfInnerRadiusOfCoil = 2 * pi * innerRadiusOfCoil; % [m]
lengthOfWire = turnsOfCoil * circumferenceOfInnerRadiusOfCoil + leeds; % [m]
areaOfCoil = pi * innerRadiusOfCoil ^2; % [m^2]


rho = 1.68E-8; % resistivity of copper [Ohm m]
resistanceOfCoil = rho * lengthOfWire / areaOfWire; % [Ohm]


g = 9.81; % [m/s^2] gravity constant

t = (0:tResolution:0.2)'; % [s]
% (time)
z(1:length(t)) = heightTube-0.5*thicknessMagnet; % [m]


L = thicknessMagnet;
R = radiusMagnet;
areaOfMagnet = pi * R^2;
M = remanence;

s = 0.5 * g * t.^2; % [m]
for i = 1:length(s)
    if z(i) - s(i) < 0.5 * thicknessMagnet % prevent z from going through ... the end of the coil
        s(i:size(s,1)) = s(i-1);
```

```
        break;
    end
end

z = z - s;

p(:) = halfHeightTube - z(:);

B(:) = M / 2 * (((p(:)+0.5*L)./ sqrt((p(:)+0.5*L).^2+R^2)) - ...
    ((p(:)+0.5*L)-L)./ sqrt( ((p(:)+0.5*L)-L).^2 + R^2) );

Vemf(1:length(t)) = 0;
for i = 2:length(t)
    Vemf(i) = turnsOfCoil * (areaOfCoil .* squeeze((B(i)-B(i-1)))') / ...
        (t(i)-t(i-1));
end


%% Inductance of coil
inductanceOfCoil = mu0 * turnsOfCoil^2 * areaOfCoil / lengthOfCoil; % ...
    inductance [H]


%% circuit options
f = 2; % [Hz]
Rload = 3.9e3; % [Ohm]

Zin = 1i*2*pi*f*inductanceOfCoil + resistanceOfCoil; % [Ohm]
Zload = Rload; % [Ohm]

Vload = Vemf * Zload / (Zload + Zin); % [V]
Iload = Vemf / (Zload + Zin); % [I]
VloadRms = rms(abs(Vload(1:(length(z)-1)))); % [V]
Pload = abs(VloadRms)^2 / real(Zload) % [W]

%% Measured Vemf
[dataVemf] = readtable(csvVemfFilename,'Format','%f%f');
[~,maxRealLoc] = max(dataVemf.voltage);
[~,minRealLoc] = min(dataVemf.voltage(maxRealLoc:length(dataVemf.voltage)));
minRealLoc = minRealLoc + maxRealLoc - 1;
[~,maxModelLoc] = max(Vemf);
[~,minModelLoc] = min(Vemf(maxModelLoc:length(Vemf)));
minModelLoc = minModelLoc + maxModelLoc - 1;

[ ~, ixReal ] = min( abs( dataVemf.voltage(maxRealLoc:minRealLoc) ) );
[ ~, ixModel ] = min( abs( Vemf(maxModelLoc:minModelLoc) ) );

dataVemf.time = dataVemf.time - (dataVemf.time(ixReal+maxRealLoc-1) - ...
    t(ixModel+maxModelLoc-1));

dataVemfTime = dataVemf.time;
dataVemfVoltage = dataVemf.voltage;

% The following lines of code make sure that the datasets model and
% prototype are having the same length, this way the the rms values are
% comparable
if dataVemfTime(1) > t(1)
```

```
    stepsToRemove = round(dataVemfTime(1) / (dataVemfTime(2) - ...
        dataVemfTime(1)));
    t = t((stepsToRemove+1):length(t));
    Vemf = Vemf((stepsToRemove+1):length(Vemf));
else
    stepsToRemove = round(abs(dataVemfTime(1) / (dataVemfTime(2) - ...
        dataVemfTime(1))));
    dataVemfTime = dataVemfTime((stepsToRemove+1):length(dataVemfTime));
    dataVemfVoltage = ...
        dataVemfVoltage((stepsToRemove+1):length(dataVemfVoltage));
end

tDifferenceBetweenModelAndPrototype = t(length(t)) - ...
    dataVemfTime(length(dataVemfTime));
if tDifferenceBetweenModelAndPrototype > 0
    stepsToRemove2 = (t(length(t)) - dataVemfTime(length(dataVemfTime))) / ...
        tResolution;
    t = t(1:(length(t)-stepsToRemove2));
    Vemf = Vemf(1:(length(Vemf)-stepsToRemove2));
else
    stepsToRemove2 = (dataVemfTime(length(dataVemfTime)) - t(length(t))) / ...
        (dataVemfTime(2) - dataVemfTime(1));
    dataVemfTime = dataVemfTime(1:(length(dataVemfTime) - stepsToRemove2));
    dataVemfVoltage = dataVemfVoltage(1:(length(dataVemfVoltage) - ...
        stepsToRemove2));
end


plot(t,Vemf);
hold on;
plot(dataVemfTime, dataVemfVoltage);
xlabel("Time [s]");
ylabel("Amplitude [V]");

legend('Vemf model', 'Vemf prototype');
VemfRMSPrototype = rms(dataVemfVoltage);
VemfRMSModel = rms(real(Vemf));
percentVemf = VemfRMSPrototype / VemfRMSModel

return;
```

A-2-2 Final model dropping magnet through coil

```
close all;
clear;

% Model using rings and compensating for space between magnet and coil for
% dropping magnet
tResolution = 0.0001; % [s]
turnsOfCoil = 2550; % turns
lengthOfCoil = 0.0146; % length of coil [m]
remanence = 1.35; % [T] average remanence
thicknessMagnet = 0.0099 * 1.5; % [m]
radiusMagnet = 0.0049; % [m]
diameterOfWire = 0.15 / 1000; % [m]
innerRadiusOfCoil = 0.0138/2; % radius of coil [m]
heightTube = 0.08 ; % [m]
halfHeightTube = heightTube / 2; % [m]
csvLoadFilename = "./meting/load/data-load.csv"; % data v load measurement ...
    [time; voltage]
csvVemfFilename = "./meting/open/data-open.csv"; % data v emf measurement ...
    [time; voltage]
leeds = 0.80 * 2; % [m]

%% constants
mu0 = 4*pi*1e-7; % [H/m]

%% Dimension calculations of coil
areaOfCoil = pi * innerRadiusOfCoil ^2; % [m^2]
layers = min([turnsOfCoil, ceil(lengthOfCoil / diameterOfWire)]); %
turnsPerLayer = turnsOfCoil / layers; %
averageRadiusOfCoil = turnsPerLayer/2*diameterOfWire + innerRadiusOfCoil; ...
    % [m]
outerRadiusOfCoil = innerRadiusOfCoil + turnsPerLayer*diameterOfWire; % [m]
innerAreaOfCoil = pi*innerRadiusOfCoil^2; % area [m^2]
outerAreaOfCoil = pi*outerRadiusOfCoil^2; % area [m^2]
medianAreaOfCoil = (outerAreaOfCoil + innerAreaOfCoil) / 2; % [m^2]
innerCircumference = 2 * pi * innerRadiusOfCoil; %  [m]
averageCircumference = 2 * pi * averageRadiusOfCoil; % [m]
lengthOfWire = turnsOfCoil * averageCircumference + leeds; % [m]
areaOfWire = pi * (diameterOfWire/2)^2; % [m^2]

middleLayer = round(layers/2); % []

rho = 1.68E-8; % resistivity of copper [Ohm m]
resistanceOfCoil = rho * lengthOfWire / areaOfWire; % [Ohm]

numberOfRings = 10; % []
coilAreaResolution = innerRadiusOfCoil / numberOfRings; % [m]

g = 9.81; % [m/s^2] gravity constant

t = (0:tResolution:1)'; % [s]
% z(time)
z(1:length(t)) = heightTube-0.5*thicknessMagnet; % [m]
z = z';

```

```matlab

%% Calculating radi of different rings
innerRadiusCircles(1:numberOfRings) = 0;
outerRadiusCircles = linspace(0,radiusMagnet,numberOfRings + 1);
for i = 1:numberOfRings
    innerRadiusCircles(i) = ...
        sqrt(0.5*outerRadiusCircles(i)^2+0.5*outerRadiusCircles(i+1)^2);
end
r = innerRadiusCircles;


L = thicknessMagnet;
R = radiusMagnet;
areaOfMagnet = pi * R^2;
M = remanence;

s = 0.5 * g * t.^2; % [m]
for i = 1:length(s)
    if z(i) - s(i) < 0.5 * thicknessMagnet % prevent z from going through ...
        the end of the coil
        s(i:size(s,1)) = s(i-1);
        break;
    end
end

z = z - s;

% p(time,layer,rings)
p(1:length(t),1:layers,1:numberOfRings) = 0;
for i = 1:layers
    for j = 1:numberOfRings
        p(:,i,j) = halfHeightTube - z + (ceil(layers/2 - i)) * diameterOfWire;
    end
end

areaOfRings(1:numberOfRings) = 0;
for i = 1:numberOfRings
    p(:,:,i) =  round(p(:,:,i)./abs(p(:,:,i))) .* (sqrt( p(:,:,i).^2 + ...
        innerRadiusCircles(i)^2 )); %
    areaOfRings(i) = pi*outerRadiusCircles(i + 1)^2 - ...
        pi*outerRadiusCircles(i)^2;
end

B(:,:,:) = M / 2 * (((p(:,:,:)+0.5*L)./ sqrt((p(:,:,:)+0.5*L).^2+R^2)) - ...
    ((p(:,:,:)+0.5*L)-L)./ sqrt( ((p(:,:,:)+0.5*L)-L).^2 + R^2) );

for i = 2:length(t)
    for j = 1:layers
        VemfPerLayer(i,j) = sum(turnsPerLayer * (areaOfRings .* ...
            squeeze((B(i,j,:)-B((i-1),j,:)))') / (t(i)-t(i-1)));
    end
    Vemf(i) = sum(VemfPerLayer(i,:));
end

%% Inductance of coil
inductanceOfCoil = mu0 * turnsOfCoil^2 * areaOfCoil / lengthOfCoil; % ...
    inductance [H]
```

```


%% circuit options
f = 2; % [Hz]
Rload = 3.9e3; % [Ohm]

Zin = 1i*2*pi*f*inductanceOfCoil + resistanceOfCoil; % [Ohm]
Zload = Rload; % [Ohm]

Vload = Vemf * Zload / (Zload + Zin); % [V]
Iload = Vemf / (Zload + Zin); % [I]
VloadRms = rms(abs(Vload(1:(length(z)-1)))); % [V]
Pload = abs(VloadRms)^2 / real(Zload) % [W]


%% Measured Vemf
[dataVemf] = readtable(csvVemfFilename,'Format','%f%f');
[¬,maxRealLoc] = max(dataVemf.voltage);
[¬,minRealLoc] = min(dataVemf.voltage(maxRealLoc:length(dataVemf.voltage)));
minRealLoc = minRealLoc + maxRealLoc - 1;
[¬,maxModelLoc] = max(Vemf);
[¬,minModelLoc] = min(Vemf(maxModelLoc:length(Vemf)));
minModelLoc = minModelLoc + maxModelLoc - 1;

[ ¬, ixReal ] = min( abs( dataVemf.voltage(maxRealLoc:minRealLoc) ) );
[ ¬, ixModel ] = min( abs( Vemf(maxModelLoc:minModelLoc) ) );

dataVemf.time = dataVemf.time - (dataVemf.time(ixReal+maxRealLoc-1) - ...
    t(ixModel+maxModelLoc-1));
dataVemfTime = dataVemf.time;
dataVemfVoltage = dataVemf.voltage;

% The following lines of code make sure that the datasets model and
% prototype are having the same length, this way the the rms values are
% comparable
if dataVemfTime(1) > t(1)
    stepsToRemove = round(dataVemfTime(1) / (dataVemfTime(2) - ...
        dataVemfTime(1)));
    t = t((stepsToRemove+1):length(t));
    Vemf = Vemf((stepsToRemove+1):length(Vemf));
else
    stepsToRemove = round(abs(dataVemfTime(1) / (dataVemfTime(2) - ...
        dataVemfTime(1))));
    dataVemfTime = dataVemfTime((stepsToRemove+1):length(dataVemfTime));
    dataVemfVoltage = ...
        dataVemfVoltage((stepsToRemove+1):length(dataVemfVoltage));
end

tDifferenceBetweenModelAndPrototype = t(length(t)) - ...
    dataVemfTime(length(dataVemfTime));
if tDifferenceBetweenModelAndPrototype > 0
    stepsToRemove2 = (t(length(t)) - dataVemfTime(length(dataVemfTime))) / ...
        tResolution;
    t = t(1:(length(t)-stepsToRemove2));
    Vemf = Vemf(1:(length(Vemf)-stepsToRemove2));
else
```

```
    stepsToRemove2 = (dataVemfTime(length(dataVemfTime)) - t(length(t))) / ...
        (dataVemfTime(2) - dataVemfTime(1));
    dataVemfTime = dataVemfTime(1:(length(dataVemfTime) - stepsToRemove2));
    dataVemfVoltage = dataVemfVoltage(1:(length(dataVemfVoltage) - ...
        stepsToRemove2));
end


plot(t,Vemf);
hold on;
plot(dataVemfTime, dataVemfVoltage);
xlabel("Time [s]");
ylabel("Amplitude [V]");

legend('Vemf model', 'Vemf prototype');
VemfRMSPrototype = rms(dataVemfVoltage);
VemfRMSModel = rms(real(Vemf));
percentVemf = VemfRMSPrototype / VemfRMSModel
return;
```

A-2-3 Final model dropping magnet through coil using final prototype parameters

```
close all;
clear;

% Model using rings and compensating for space between magnet and coil

tResolution = 0.0001; % [s]
turnsOfCoil = 7600; % turns
lengthOfCoil = 0.0146; % length of coil [m]
remanence = 1.35; % [T] average remanence
thicknessMagnet = 0.0099 * 2; % [m]
radiusMagnet = 0.0049; % [m]
diameterOfWire = 0.0967 / 1000; % [m] 0.12 mm wire million mile light
innerRadiusOfCoil = 0.0138/2; % radius of coil [m]
heightTube = 0.065 ; % [m]
halfHeightTube = heightTube / 2; % [m]
csvLoadFilename = "./meting/load/data-load.csv";
csvVemfFilename = "./meting/open/data-vemf.csv";
leeds = 2 * 2; % [m]

%% constants
mu0 = 4*pi*1e-7; % [H/m]

%% Dimension calculations of coil
layers = min([turnsOfCoil, ceil(lengthOfCoil / diameterOfWire)]); %
turnsPerLayer = turnsOfCoil / layers; %
averageRadiusOfCoil = turnsPerLayer/2*diameterOfWire + innerRadiusOfCoil; ...
    % [m]
outerRadiusOfCoil = innerRadiusOfCoil + turnsPerLayer*diameterOfWire; % [m]
innerAreaOfCoil = pi*innerRadiusOfCoil^2; % area [m^2]
outerAreaOfCoil = pi*outerRadiusOfCoil^2; % area [m^2]
medianAreaOfCoil = (outerAreaOfCoil + innerAreaOfCoil) / 2; % [m^2]
innerCircumference = 2 * pi * innerRadiusOfCoil; %  [m]
averageCircumference = 2 * pi * averageRadiusOfCoil; % [m]
lengthOfWire = turnsOfCoil * averageCircumference + leeds; % [m]
areaOfWire = pi * (diameterOfWire/2)^2; % [m^2]

middleLayer = round(layers/2);

rho = 1.68E-8; % resistivity of copper [Ohm m]
resistanceOfCoil = rho * lengthOfWire / areaOfWire; % [Ohm]

numberOfRings = 10;
coilAreaResolution = innerRadiusOfCoil / numberOfRings; % [m]

g = 9.81; % [m/s^2]

t = (0:tResolution:1)'; % [s]
% z(time)
z(1:length(t)) = heightTube-0.5*thicknessMagnet; % [m]
z = z';


innerRadiusCircles(1:numberOfRings) = 0;
```

```
outerRadiusCircles = linspace(0,radiusMagnet,numberOfRings + 1);
for i = 1:numberOfRings
    innerRadiusCircles(i) = ...
        sqrt(0.5*outerRadiusCircles(i)^2+0.5*outerRadiusCircles(i+1)^2);
end
r = innerRadiusCircles;


L = thicknessMagnet;
R = radiusMagnet;
areaOfMagnet = pi * R^2;
M = remanence;

s = 0.5 * g * t.^2; % [m]
for i = 1:length(s)
    if z(i) - s(i) < 0.5 * thicknessMagnet
        s(i:size(s,1)) = s(i-1);
        break;
    end
end

z = z - s;

% p(time,layer,rings)
p(1:length(t),1:layers,1:numberOfRings) = 0;
for i = 1:layers
    for j = 1:numberOfRings
        p(:,i,j) = halfHeightTube - z + (ceil(layers/2 - i)) * diameterOfWire;
    end
end

areaOfRings(1:numberOfRings) = 0;
for i = 1:numberOfRings
    p(:,:,i) =  round(p(:,:,i)./abs(p(:,:,i))) .* (sqrt( p(:,:,i).^2 + ...
        innerRadiusCircles(i)^2 )); %
    areaOfRings(i) = pi*outerRadiusCircles(i + 1)^2 - ...
        pi*outerRadiusCircles(i)^2;
end

B = M / 2 * (((p+0.5*L)./ sqrt((p+0.5*L).^2+R^2)) - ((p+0.5*L)-L)./ sqrt( ...
    ((p+0.5*L)-L).^2 + R^2) );

% alpha = asin(innerRadiusCircles(k)/p(i,j,k));
for i = 2:length(t)
    for j = 1:layers
        VemfPerLayer(i,j) = sum(turnsPerLayer * (areaOfRings .* ...
            squeeze((B(i,j,:)-B((i-1),j,:)))') / (t(i)-t(i-1)));
    end
    Vemf(i) = sum(VemfPerLayer(i,:));
end

%% Inductance of coil
%inductanceOfCoil = mu0 * turnsOfCoil^2 * innerAreaOfCoil / lengthOfCoil; ...
    % inductance [H]
midRadiusOfCoil = (outerRadiusOfCoil + ...
    innerRadiusOfCoil)/2*100*0.393700787; % inches
```

```
depthOfCoil = (outerRadiusOfCoil - innerRadiusOfCoil)*100*0.393700787; % ...
    inches
inductanceOfCoil = 0.8*midRadiusOfCoil^2 *turnsOfCoil^2 / ...
    (6*midRadiusOfCoil + 9*lengthOfCoil*0.393700787*100 + 10 * depthOfCoil) ...
    /1000000; % inductance inches


%% circuit options
f = 2; % [Hz]
Rload = 3.9e3; % [Ohm]
clear j;
Zin = j*2*pi*f*inductanceOfCoil + resistanceOfCoil; % [Ohm]
%Zload = -j*2*pi*f*L + Rload; % [Ohm]
Zload = Rload; % [Ohm]

Vload = Vemf * Zload / (Zload + Zin); % [V]
Iload = Vemf / (Zload + Zin); % [I]
VloadRms = rms(abs(Vload(1:(length(z)-1)))); % [V]
Pload = abs(VloadRms)^2 / real(Zload) % [W]



%% Measured Load
[data] = readtable(csvLoadFilename,'Format','%f%f');
[¬,maxRealLoc] = max(data.voltage);
[¬,minRealLoc] = min(data.voltage);
[¬,maxModelLoc] = max(real(Vload));
[¬,minModelLoc] = min(real(Vload));
[ ¬, ixReal ] = min( abs( data.voltage(maxRealLoc:minRealLoc) ) );
[ ¬, ixModel ] = min( abs( Vload(maxModelLoc:minModelLoc) ) );

data.time = data.time - (data.time(ixReal+maxRealLoc-1) - ...
    t(ixModel+maxModelLoc-1));
dataVload = data;


%% Measured Vemf
[dataVemf] = readtable(csvVemfFilename,'Format','%f%f');
[¬,maxRealLoc] = max(dataVemf.voltage);
[¬,minRealLoc] = min(dataVemf.voltage);
[¬,maxModelLoc] = max(Vemf);
[¬,minModelLoc] = min(Vemf);
[ ¬, ixReal ] = min( abs( dataVemf.voltage(maxRealLoc:minRealLoc) ) );
[ ¬, ixModel ] = min( abs( Vemf(maxModelLoc:minModelLoc) ) );

dataVemf.time = dataVemf.time - (dataVemf.time(ixReal+maxRealLoc-1) - ...
    t(ixModel+maxModelLoc-1));

tVemf = t;
dataVemfTime = dataVemf.time;
dataVemfVoltage = dataVemf.voltage;
tLoad = t;
dataVloadTime = data.time;
dataVloadVoltage = data.voltage;

% The following lines of code make sure that the datasets model and
% prototype are having the same length, this way the the rms values are
```

```
% comparable
if dataVemfTime(1) > t(1)
    stepsToRemove = round(dataVemfTime(1) / (dataVemfTime(2) - ...
        dataVemfTime(1)));
    t = t((stepsToRemove+1):length(t));
    Vemf = Vemf((stepsToRemove+1):length(Vemf));
else
    stepsToRemove = round(abs(dataVemfTime(1) / (dataVemfTime(2) - ...
        dataVemfTime(1))));
    dataVemfTime = dataVemfTime((stepsToRemove+1):length(dataVemfTime));
    dataVemfVoltage = ...
        dataVemfVoltage((stepsToRemove+1):length(dataVemfVoltage));
end

if dataVloadTime(1) > tLoad(1)
    stepsToRemove = round(dataVloadTime(1) / (dataVloadTime(2) - ...
        dataVloadTime(1)));
    tLoad = tLoad((stepsToRemove+1):length(tLoad));
    Vload = Vload((stepsToRemove+1):length(Vload));
else
    stepsToRemove = round(abs(dataVloadTime(1) / (dataVloadTime(2) - ...
        dataVloadTime(1))));
    dataVloadTime = dataVloadTime((stepsToRemove+1):length(dataVloadTime));
    dataVloadVoltage = ...
        dataVloadVoltage((stepsToRemove+1):length(dataVloadVoltage));
end

tDifferenceBetweenModelAndPrototype = t(length(t)) - ...
    dataVemfTime(length(dataVemfTime));
if tDifferenceBetweenModelAndPrototype > 0
    stepsToRemove2 = round((t(length(t)) - ...
        dataVemfTime(length(dataVemfTime))) / tResolution);
    t = t(1:(length(t)-stepsToRemove2));
    Vemf = Vemf(1:(length(Vemf)-stepsToRemove2));
else
    stepsToRemove2 = round((dataVemfTime(length(dataVemfTime)) - ...
        t(length(t))) / (dataVemfTime(2) - dataVemfTime(1)));
    dataVemfTime = dataVemfTime(1:(length(dataVemfTime) - stepsToRemove2));
    dataVemfVoltage = dataVemfVoltage(1:(length(dataVemfVoltage) - ...
        stepsToRemove2));
end

tDifferenceBetweenModelAndPrototype = tLoad(length(tLoad)) - ...
    dataVloadTime(length(dataVloadTime));
if tDifferenceBetweenModelAndPrototype > 0
    stepsToRemove2 = round((tLoad(length(tLoad)) - ...
        dataVloadTime(length(dataVloadTime))) / tResolution);
    tLoad = tLoad(1:(length(tLoad)-stepsToRemove2));
    Vload = Vload(1:(length(Vload)-stepsToRemove2));
else
    stepsToRemove2 = round((dataVloadTime(length(dataVloadTime)) - ...
        tLoad(length(tLoad))) / (dataVloadTime(2) - dataVloadTime(1)));
    dataVloadTime = dataVloadTime(1:(length(dataVloadTime) - stepsToRemove2));
    dataVloadVoltage = dataVloadVoltage(1:(length(dataVloadVoltage) - ...
        stepsToRemove2));
end

```

```
% plot(t,Vload);
% hold on;
% plot(dataVload.time, dataVload.voltage);
% hold on;
plot(t, Vemf);
hold on;
plot(dataVemfTime, dataVemfVoltage);
xlabel("Time [s]");
ylabel("Amplitude [V]");

% legend('Vload model', 'Vload prototype', 'Vemf model', 'Vemf prototype');
legend('Vemf model', 'Vemf prototype');

% Load
figure;
plot(tLoad, Vload);
hold on;
plot(dataVloadTime, dataVloadVoltage);
xlabel("Time [s]");
ylabel("Amplitude [V]");

% legend('Vload model', 'Vload prototype', 'Vemf model', 'Vemf prototype');
legend('V_L model', 'V_L prototype');

percentVload = rms(dataVloadVoltage) / rms(real(Vload))
percentVemf = rms(dataVemfVoltage) / rms(Vemf)

return;
```