KANTONSSCHULE AM BURGGRABEN

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Maturaarbeit

A Research on Piezoelectric Elements as a new sustainable energy resource with the emphasis on Roads, Railways and Pathways

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Contents

Chapter 1

Introduction

1.1 Overview

In recent years, mankind is facing a challenge never encountered before. Researchers have shown that the globally rising temperatures are a consequence of us, humans, emitting green-house gases. Research shows that once we exceed an globbaly increase of 1.5 degrees, we will enter a loop where the overall temperature will not decrease. This has devastating effects on our ecosystem such as raising the water level of the ocean, extreme weather conditions as well as droughts and huge forest fires. These effects are already visible in the present. However, as much as humans cause global warming humans are capable of preventing it. Over the past few years, countries around the world have sat together to negotiate goals to prevent climate change. Research was done to find alternatives to produce resources needed in our daily lives whithout emitting greenhouse gases. One of the biggest areas which is being researched now apart from sustainable transport is renewable energy. Aside from the commonly known solar panels and wind turbines, researchers are trying to find other ways to produce energy renewably and efficiently. Along with the ideas of bridges planted with carbon dioxide absorbing plants and roads made from solar panels, one idea caught our interest. The idea was to use piezoelectric elements in roads to harvest energy using the vibrations created by the vehicles. This idea could also be applied to railways and pedestrian walkways.
In this essay we are trying to answer the question, **“Are piezoelectric elements a new renewable energy resource applicable in roads, railways, and pathways?”**. The goal is to recreate a model of this concept and compare the measured output with the data provided from other sources. Furthermore, we are calculating the outcome of other studies and whether they are accurate. Lastly, we are deciding whether it is worth implementing this new energy resource and whether it has potential for the future.

1.1.1 Method

To create a model which is as realistic as possible, we are conducting the experiment as follows. There are four piezo electric elements under the corners of a wooden board.

To recreate the vibrations, a person will jump on the board. A voltmeter measured and graphed the voltage output of the experiment over a 470kO resistor. This allowed us to calculate the theoretical power created by the four piezoelectric elements. Moreover, we are calculating the theoretical output to have a comparison and a basis to verify the experiments from the other sources. Once all the data is compared, a conclusion can be made.

1.1.2 Expectations

Seeing that so many researchers praise this concept, the expectations of a high power outcome are very high. Nevertheless, we expect a low outcome since the piezoelectric element can produce a high voltage but only for a short time which will reduce the power. Furthermore, the concept is fairly new and not much research has been done regarding the power outcome. There have been tests but they were never finished. We also expect that the piezo is more suitable in other areas rather than in energy harvesting and if it is used, it can only power small sensors. However, the concept could work, once the technology is provided.

Chapter 2

Piezoelectric Elements

2.1 Overview

Piezoelectric elements are defined as materials, such as crystals and certain ceramics or biological matter e.g. bones, DNA and protein which produce an electrical charge through mechanical stress.

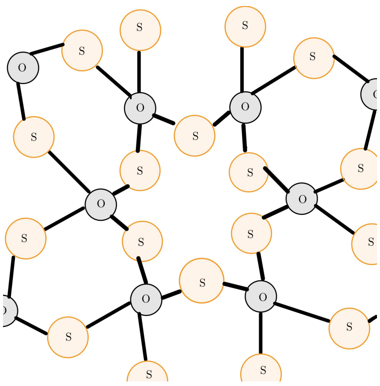

Figure 2.1: Structure of Quartz

To understand how a piezoelectric element works, one must have a look at the structure of a piezoelectric crystal. Most piezoelectric elements are made from quartz. Quartz is a material composed of silicon-dioxide whose structure can be seen in Figure 1. It is made of silicone and oxygen atoms arranged in a hexagonal shape. The silicone atoms are charged positively and the oxygen atoms negatively as the oxygen atom has a higher electronegativity.

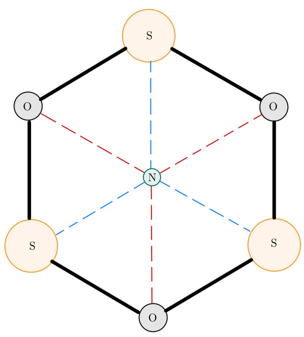

Figure 2.2: Quartzcell without any influence

In the beginning the average position of the charges overlap with each other. This means that no electromagnetic field is formed and thus no electric charge flows. However, when mechanical stress is applied onto the crystal the structure is changed.

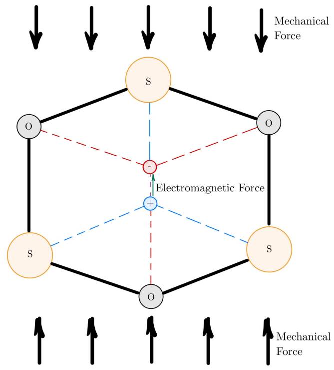

Figure 2.3: Quartzcell compressed

Mechanical stress can be either in the form of compression or expansion. In case of compression, the average position of the negative charge is moved upwards and the average position of the positive charge is moved downwards and vice versa when expanded.

In either way, a current can now flow as a positive face and a negative face is created. If a load such as a lightbulb is connected to the faces, the lightbulb would glow. It is important to note is that the load must be connected correctly. The anode and cathode differ depending on the type of mechanical stress.

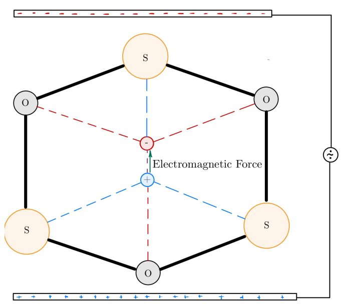

Figure 2.4: Quartzcell charged with a voltage

Besides the mechanical stress, a voltage can be applied onto the crystal. This is refered to as the reciprocal piezoelectric effect. When the cathode and anode are positioned like in Figure 2.4 the crystal will be compressed since the anode repels the negatively charged oxygen and the cathode repels the positively charged silicone and vice versa.

2.1.1 Formula

To calculate the power output of the piezoelectric element, the voltage output has to be calculated. With the resistor attached to the piezoelectric element, the power output can be calculated. The formula for the voltage output of a piezoelectric element can be calculated by simplifying the voltage output of a capacitor since the piezoelectric element is a capacitor.
Before going through the process of simplifying the formula, two piezoelectric constants must be defined. There are many, however, only the electromechanical coupling factor and the piezoelectric voltage constant will be defined as only these constants will be used. The electromechanical coupling factor d is defined as the effectiveness with which a piezoelectric element converts mechanical energy into electrical energy and vice versa. The piezoelectric voltage constant g is defined as the electric field generated by a piezoelectric element per unit stress applied. The constants differ depending on the direction of me-

chanical stress or the electrical field.

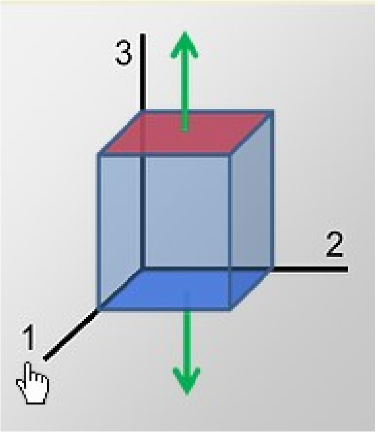

Figure 2.5: Expansion Mode of the Piezoelectric Element

The constants are marked with numbers. These numbers correspond to the direction of mechanical stress and the polarization which is depicted in Table 2.1 and Figure 2.5. In our case g_{33} and d_{33} will be used since the force acting on the crystal is from direction 3 and the polarization occurs in direction 3.

	PZT-5H	PZT-5A	PZT-5J
d_{31}	-320	-190	-270
d_{33}	650	390	485
d_{15}	1000	460	850
g_{31}	-9.5	-11.3	-11.5
g_{33}	19.0	23.2	21.3
g_{15}	35.3	32.4	32.6

Table 2.1: Piezoelectric Constants

From Table 2.1, one can see that the constant also depends on the type of piezoelectric material. There are three types of piezoelectric materials which are commonly used. The piezoelectric material used in this experiment is of type PZT-5J since the material was made from ceramic and the cathode was made from silver. This ensures that the piezoelectric element performs well under the specific stress and voltage. Depending on the direction, the type of piezo is chosen to maximise the power outcome. However, most piezos are of type PZT-5J since they are considered to be an allrounder for any case of stress or voltage.

Since the piezoelectric element is a capacitor, the formula $U = \frac{Q}{C}$ can be used where U is the voltage, Q is the charge and C is the capacity. From there the formula $\epsilon \cdot \frac{A}{t}$ where ϵ is the permitivity, A is the surface area where the mechanical stress is applied on and t is the thickness of the piezoelectric element. Furthermore, the formula $d \cdot F$ can be inserted for Q where F is the force applied onto the piezoelectric element and d is the effeciveness with wwhich a piezoelectric element converts mechanical energy into electrical energy and vice versa. Once all equations are inserted, $U = \frac{d \cdot F \cdot t}{\epsilon \cdot A}$ where $\frac{d}{\epsilon}$ can be replaced with g. This results in the formula $U = g \cdot \frac{F \cdot t}{A}$ for the Voltage output of the piezoelectric element.

$$U = \frac{Q}{C} \quad || \quad C = \epsilon \cdot \frac{A}{t} \text{ and } Q = d \cdot F$$

$$U = \frac{d \cdot F \cdot t}{\epsilon \cdot A} \quad || \quad g = \frac{d}{\epsilon}$$

$$U = g \cdot \frac{F \cdot t}{A}$$

To calculate the power, the formula $P = R \cdot I^2$ can be used where P is the power, R is the resistance, and I is the current. Since the current is unknown, it must be eliminated thus, $R \cdot I$ will be substituted with V resulting in $P = V \cdot I$. Then I will be substituted with $\frac{V}{R}$ resulting in the final formula $P = \frac{V^2}{R}$. With this formula the power output of the four piezoelectric elements can be calculated.

$$P = R \cdot I^2 \quad || \quad V = R \cdot I$$

$$P = V \cdot I \quad || \quad I = \frac{V}{R}$$

$$P = \frac{V^2}{R}$$

Chapter 3

Experiment

3.1 Overview

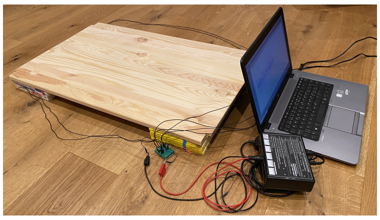

Figure 3.1: Experiment

For the experiment four piezoelectric elements were placed under the corners of a wooden board of dimensions $0.8 \times 0.4 \times 0.02$ m. These were then connected to a brad board parallel to a $470k\Omega$ resistor. A voltmeter was connected to the resistor and measured the voltage output while a person was jumping on the wooden board from a height of 20 cm ± 1 cm.

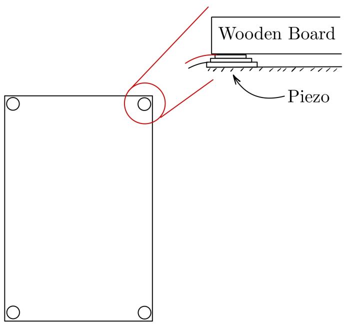

Figure 3.2: Wooden board with piezoelectric elements

To get an ideal result, the board must be elevated. This ensures an ideal result for the experiment since all the force will be applied onto the four piezo electric elements.

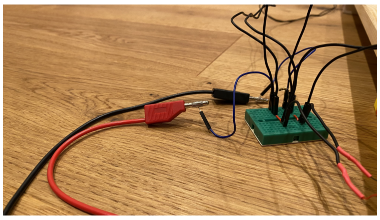

Figure 3.3: Piezoelectric Elements connected in parallel

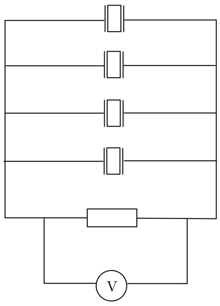

Figure 3.4: Circuit Diagram

The piezoelectric elements were connected in parallel in addition with a $470k\Omega$ resistor. As represented in Figure 3.3 the voltmeter was then parallel connected to the resistor.

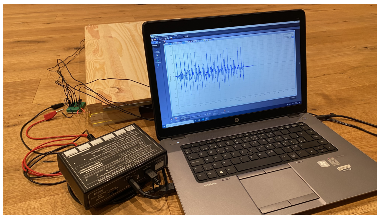

Figure 3.5: Laptop and Pasco Interface 500

For the measurement, a Pasco 500 Interface was used to measure the voltage. A laptop logged the data and plotted graphs.

3.1.1 Theoretical Calculation of the Experiment

The formula $U = g \cdot \frac{F \cdot t}{A}$ can be used to calculate the voltage output of the four piezoelectric elements.The impact force is estimated to be 730 ± 2 N. This results in a voltage of 10.81 ± 0.03 V.

$$U = g \cdot \frac{F \cdot t}{A}$$

$$\begin{aligned} U &= \frac{U_{\max} + U_{\min}}{2} \pm \frac{U_{\max} - U_{\min}}{2} \\ &= 10.81 \pm 0.03V \end{aligned}$$

With the voltage calculated, the formula $P = \frac{U^2}{R}$ can now be used to calculate the predicted power output. Hence, the power output is 249 ± 14 μW.

$$P = \frac{V^2}{R}$$

$$\begin{aligned} P &= \frac{P_{\max} + P_{\min}}{2} \pm \frac{P_{\max} - P_{\min}}{2} \\ &= 249 \pm 14\mu W \end{aligned}$$

3.2 Results

Time in s	Voltage in V
0	-0.083
0.05	1.353
0.1	9.995
0.15	-1.562
0.2	0.459
0.25	0.781
0.3	1.646
0.35	0.908
0.4	0.068
0.45	-0.156
0.5	-0.596
0.55	-0.19
0.6	0.234
0.65	0.205
0.7	0.122
0.75	-0.029
0.8	0.049
0.85	0.098
0.9	0.044

Table 3.1: Values of Voltage Graph 1

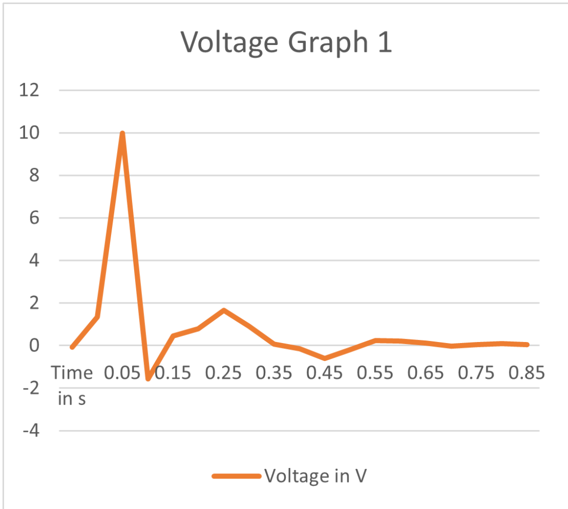

Figure 3.6: Voltage Graph 1

Time in s	Voltage in V
0	-0.151
0.05	-0.107
0.1	-0.088
0.15	-2.334
0.2	9.995
0.25	-1.401
0.3	-0.137
0.35	0.181
0.4	0.723
0.45	1.533
0.5	1.86
0.55	1.24
0.6	0.415
0.65	-0.02
0.7	-0.063
0.75	-0.273
0.8	0.249
0.85	0.195
0.9	-0.156
0.95	-0.054
1	0.088
1.05	0.166
1.1	0.132
1.15	0.215
1.2	0.093

Table 3.2: Values of Voltage Graph 2

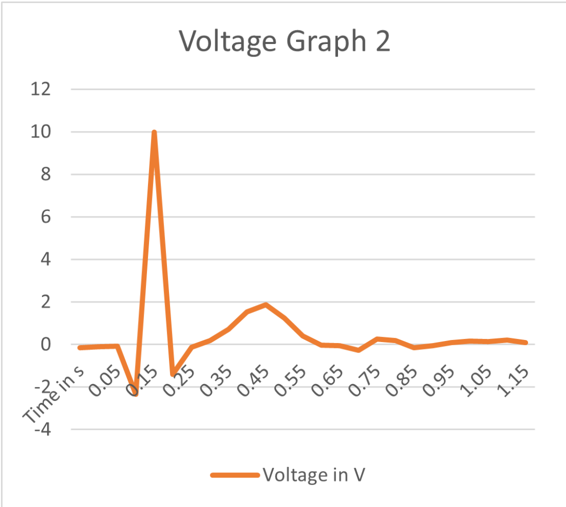

Figure 3.7: Voltage Graph 2

Voltage in V	Time in s
0	0.283
0.05	4.844
0.1	-4.932
0.15	-4.673
0.2	-2.393
0.25	-1.045
0.3	-0.479
0.35	-0.259
0.4	-0.171
0.45	-0.122
0.5	-0.098
0.55	-1.826
0.6	9.995
0.65	-2.822
0.7	0.591
0.75	0.19
0.8	0.62
0.85	1.143
0.9	1.396
0.95	0.869
1	-0.034
1.05	0.122
1.1	-0.088
1.15	0.01

Table 3.3: Values of Voltage Graph 3

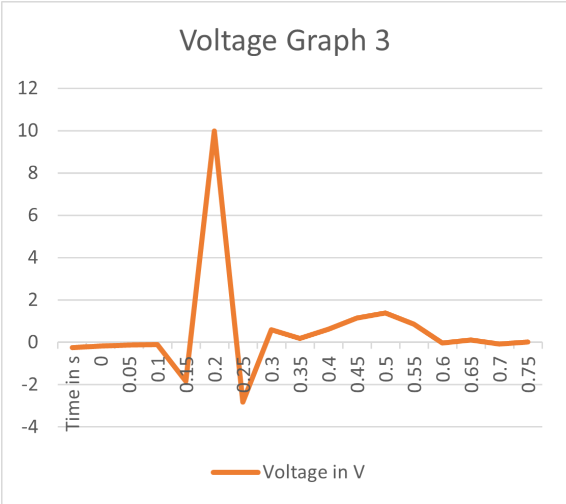

Figure 3.8: Voltage Graph 3

The table and graphs above show that the voltage output by the piezoelectric elements varies between -2.822 ± 0.001 V and 9.995 ± 0.001 V with a discrepancy of $7.54 \pm 2.485\%$.

Time in s	Power in W
0	1.46574E-08
0.05	3.89491E-06
0.1	0.000212553
0.15	5.19116E-06
0.2	4.48257E-07
0.25	1.29779E-06
0.3	5.7645E-06
0.35	1.75418E-06
0.4	9.8383E-09
0.45	5.17787E-08
0.5	7.55779E-07
0.55	7.68085E-08
0.6	1.16502E-07
0.65	8.94149E-08
0.7	.16681E-08
0.75	1.78936E-09
0.8	5.10851E-09
0.85	2.0434E-08
0.9	4.11915E-09

Table 3.4: Values of Power Graph 1

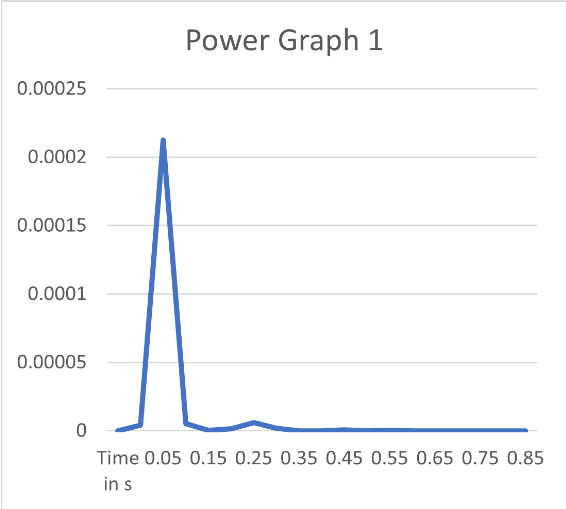

Figure 3.9: Power Graph 1

Time in s	Power in P
0	4.85128E-08
0.05	2.43596E-08
0.1	1.64766E-08
0.15	1.15905E-05
0.2	0.000212553
0.25	4.17617E-06
0.3	3.9934E-08
0.35	6.97043E-08
0.4	1.11219E-06
0.45	5.00019E-06
0.5	7.36085E-06
0.55	3.27149E-06
0.6	3.66436E-07
0.65	8.51064E-10
0.7	8.44468E-09
0.75	1.58572E-07
0.8	1.31917E-07
0.85	8.09043E-08
0.9	5.17787E-08
0.95	6.20426E-09
1	1.64766E-08
1.05	5.86298E-08
1.1	3.70723E-08
1.15	9.83511E-08
1.2	1.84021E-08

Table 3.5: Values of Power Graph 2

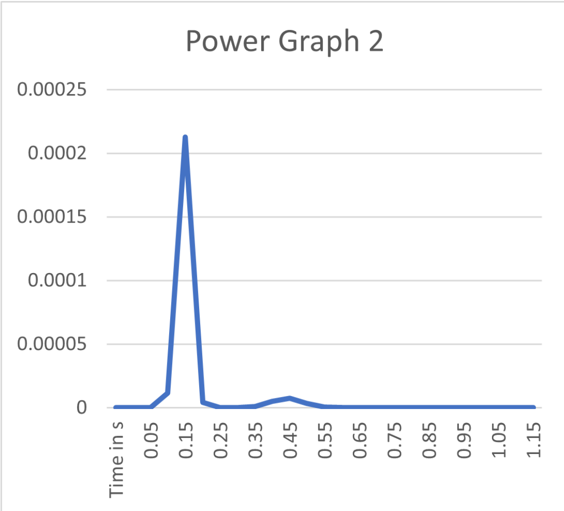

Figure 3.10: Power Graph 2

Time in s	Power in W
0	1.42726E-07
0.05	6.22149E-08
0.1	3.16681E-08
0.15	2.0434E-08
0.2	7.0942E-06
0.25	0.000212553
0.3	1.6944E-05
0.35	7.43151E-07
0.4	7.68085E-08
0.45	8.17872E-07
0.5	2.77968E-06
0.55	4.14642E-06
0.6	1.60673E-06
0.65	2.45957E-09
0.7	3.16681E-08
0.75	1.64766E-08
0.8	2.12766E-10

Table 3.6: Values of Power Graph 3

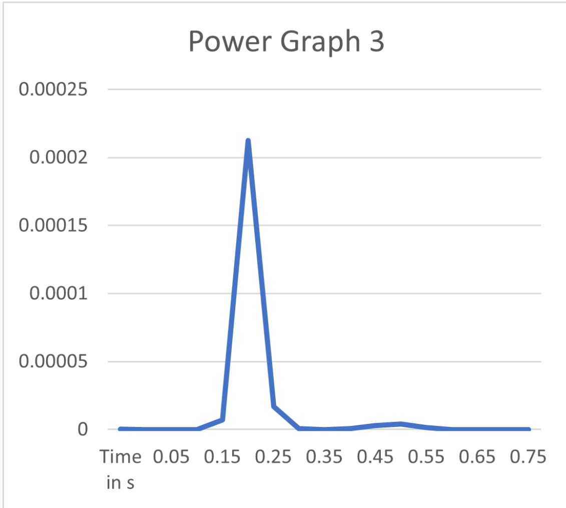

Figure 3.11: Power Graph 3

From the table and graphs above, one can see that power produced by the piezoelectric elements varies between $2.18 \cdot 10^{-10} \pm 0.53 \cdot 10^{-10}$ W and $2130000 \cdot 10^{-10} \pm 107000 \cdot 10^{-10}$ W with a discrepancy of $8.53 \pm 4.72\%$.

Chapter 4

Comparison with other papers

The concept of implementing piezoelectric elements in roads, railways, and highways has been around for a while now. That is why it is apparent that there has been much research done about this concept. However, there has been much skepticism about this concept regarding many aspects such as the costs and the energy harvested by the piezoelectric elements. On the one hand, a scientist from khplant predicts that 12 meters of road could produce 1 kWh when a car drives over it. There is also a team from Lancaster University, who are very confident about this concept and are preparing to deploy tests in the United Kingdom and Italy. They believe that they could harvest 1 – 2 MW per kilometer road. This seems very doubtful as on the other hand, Rex Garland from Stanford University claims that 1 km of read contains 1.54 MJ which is miles away from the 1 kWh or the 1 – 2 MW. Nonetheless, how much power could a busy road produce?

M. Vázquez-Rodriguez, F. J. Jiménez, and J. De Frutos published a paper in 2011 where they measured the voltage and power output a public road could create using a contraption and different piezoelectric materials. They concluded that the power output depended on the speed of the cars and the frequency with which the cars drive over the piezoelectric element. Nevertheless, the voltage only peaked between 0.455 and 0.900 Volts. In the end, the paper also showed the estimated power output of 48.3 W.
In the paper by Hiba Najini and Arumugam Muthukumaraswamy published in 2017, they used a DC-DC Booster in addition to the capacitor, which would increase the power output. Theoretically, they could have an output for a 1 km road of 187 kWh considering that there are 3280 piezoelectric elements implemented into the road and that there were 500 cars per hour travelling at 100 km/h. They also included theoretical calculations including the time where the traffic density was lower than 500 cars per hour. However, the power outcome is imense ranging from 20.8 to 93.81 kWh.
According to Flurin Solèr's research paper from 2017, it had a similar result as the experiment of this paper. In fact, he was also limited by the maximum voltage output of the piezoelectric element. He measured the voltage output and calculated the theoretical power output a person could generate while walking. Even though the concept of gener-

ating power during walking sounds promising, he was only able to generate an estimate of 0.247 mW. He also calculated that it would take 6.2 years to charge an iPhone with this method.

Chapter 5

Analysis and Conclusion

5.1 Analysis

Looking at the theoretical calculations, the voltage seemed to be promising since the piezoelectric element is such a small device, which could produce a lot of voltage just by using pressure. Nevertheless, the theoretical calculation of the power output showed, that the concept is nearly impossible to use in day-to-day life since the power output would not be sufficient to power anything. Even if a car drove over the piezoelectric element, the power produced would not be sufficient.

The experiments also show similar results to the theoretical calculations. The measured voltage which leads to a power of 0.213 ± 0.011 mW, leads to the fact that this power cannot be used in daily life because tt is too little to be used as conventional electronical appliances use more power.

Interestingly, the opinions about piezoelectric elements in roads, railways and pathways are quite split when looking at the papers. On the one hand, the papers show that the power output is very little and not considerable to be used. On the contrary, the paper of Hiba Najini and Arumugam Muthukumaraswamy shows that the power output can be significant, once a DC-DC Booster is used and even profitable. Although considering the fact that 20 km of highway would be needed to power a house in Switzerland for a whole year, the question arises whether it is worth implementing this concept in the highways of Switzerland. To put this into contrast, merely 4 houses could be powered if 500 cars travelled at a speed of 120 km/h from St. Gallen to Zurich.

So how can the piezoelectric element be used rather than as a source of energy? On the one hand, the piezoelectric elements could produce power for a sensor measuring data. Furthermore, the piezoelectric element has better functionality when used as a sensor. One could monitor the voltage of the piezoelectric element to sense very little forces and even calculate the theoretical force. Moreover, the piezoelectric element can be used as a loud speaker since it vibrates according to specific voltages.

5.2 Conclusion

From the results of our research, one can derive two conclusions.
Firstly, one could observe that the piezoelectric element is limited by the maximum voltage output it can generate due to its thickness. This leads to the fact that the piezoelectric element will only produce its maximum voltage no matter how high the force is. Therefore, it is important to note that the formula is a theoretical approach to the voltage output of a piezoelectric element.
Finally, the experiment, the theoretical calculations, and the research papers showed that the power gained by the piezoelectric elements is not sufficient and not worth the costs as the revenue would not be profitable enough to cover the cost to implement piezoelectric elements. Furthermore, other sources producing renewable energy are far more profitable and generate more power. As for now, our technology is not sufficient for the use of piezoelectric elements as a source of renewable energy but perhaps in the near future, there will be a possibility where the piezoelectric element will function as a renewable energy source.
So, are piezoelectric elements a new renewable energy resource applicable in roads, railways, and pathways? Overall, the possibility of using piezoelectric elements as a renewable energy source is better understood. After simulating similar events where this concept could be used and understanding the limitations, one can now explain why this concept in our present will not be profitable enough to be used. Nevertheless, there are still many problems which have to be covered in this research.
The experiment is based on theoretical calculations due to the fact that the power produced is too small to be measured (Table 3.4, 3.5, 3.6). In addition, the experiment is based on a very low frequency. This raises the question whether the theoretical calculations are applicable to the real results. Additionally, since the voltage output of the piezoelectric element used here is limited to 10 Volts, the experiment will never be able to provide the full potential of a piezoelectric element. This brings up the question whether the results from the experiment (Table 3.1, 3.2, 3.3) are valid despite the theoretical calculated voltage having a discrepancy of $7.54 \pm 2.485\%$ from the measured voltage. As we are limited to these materials, an experiment similar to the paper of M. Vázquez-Rodriguez, F. J. Jiménez, and J. De Frutos is not possible even though it would be more precise.
All in all, the research question could be answered. In our present time it is not worth implementing piezoelectric elements in roads, railways and pathways. Notwithstanding, its potential as a sensor is worth considering.

List of Figures

Listings

Appendix A

Declaration of Original Work

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