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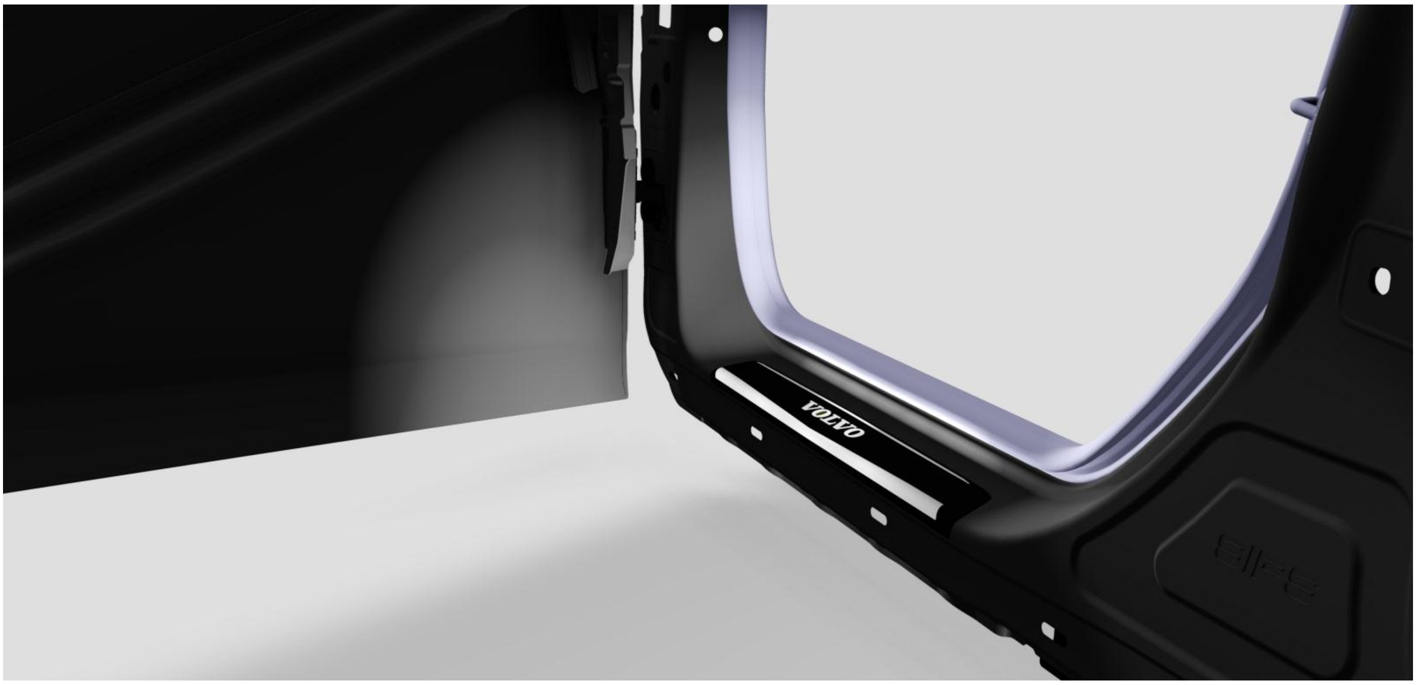


# An alternative energy source for interior accessories

- Harvesting vibration energy to power step-in-spline lights

*Master of Science Thesis*

Matti Halonen

Department of Product and Production development
Division of Product development
Chalmers University of Technology
Gothenburg, Sweden 2012

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Cover: A digitally produced image that shows an illuminated step-in-spline within the chassis of a Volvo V60

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# Abstract

This report describes the development work of examining an alternative way of powering lights within a step-in-spline is. More specifically the purpose of the project was to analyze the possibility of having a piezoelectric energy harvester within the step-in-spline in order to make the system a closed plug-and-play product. What became evident during the literature studies was that the current state of piezoelectric development is in a stage where almost every new application requires a custom-tailored solution in order to work within the intended environment. Further the project itself made clear the area of perfecting a piezoelectric solution requires knowledge within a wide range of sub-disciplines. These factors resulted in a project that from the early beginning until the very end had to be balanced between theory and practical testing in order to make the best choices along the development path.

The project resulted in a proof-of-principle prototype that shows the potential in having a piezoelectric energy harvesting system implemented within a step-in-spline. The result provides an approximation of how much energy a piezoelectric solution could scavenge from the ambient vibrations that originates from different road conditions when driving a Volvo V60. These ending test-results shows that piezoelectricity is a viable option when designing the power supply of less power demanding electronic components that otherwise proves difficult to power in traditional ways. The project was heavily focused on the step-in-spline, but should be seen as guidance and supporting tool when developing other small scale electronics struggling with power supply issues.



Keywords: Interior accessories, Piezo, Piezoelectricity, Power harvesting, PZT, Self-powered, Sill moulding, Step-in-spline, Vibration energy harvesting

## Preface

This report is the result of a technical investigation that was aimed to lower the assembling and support costs of an interior accessory.

The project was outlined as a master's thesis of 30p at Chalmers University of Technology in Gothenburg, Sweden, and is a result of collaboration between Chalmers University of Technology, Rücker Nord AB and Volvo Car Corporation.

First of all would like to thank my supervisors; Peter Aminoff (Rücker Nord AB), Göran Brännare (Product Development, Chalmers University of Technology) and Stefan Hill (Interior Accessories, Volvo Car Corporation) who has offered me support when I have needed it the most and inspired to progression throughout the project.

I would also like to thank Jan Möller (Applied Mechanics, Chalmers University of Technology) for invaluable discussions and insights. Furthermore a special thank you is given to Ann-Charlotte Kårhag for assistance at the test track (Analysis & Validation Engineer at Interior Accessories, Volvo Car Corporation).

Finally I would like to thank my family, friends and beloved girlfriend who have supported me during my entire study time at Chalmers.

Gothenburg, November 2012
Matti Halonen

# Nomenclature

| | |
|---|---|
| **Bimorph** | A bimorph is a cantilever that consists of two active layers: piezoelectric and metal |
| **d31** | Cantilever mount |
| **d33** | Stack (piezo plates stacked on each other) |
| **Energy harvesting** (also called power scavenging) | The process of deriving energy from external sources, such as wind, solar or vibration energy. In this thesis the energy harvesting refers to energy harvested from vibrations |
| **GTDS** | Global Technology Development System, a method used for implementation of new technology at Volvo Car Corporation |
| **PSD** | Power Spectral Density |
| **PVDF** | A polymeric piezoelectric material (Polyvinylidene fluoride) |
| **PZT** | A ceramic piezoelectric material (Lead Zirconate Titanate) |
| **RoHS** | Regulation of hazardous substances |
| **Sill moulding** | Alternative name for the step-in-spline, it may be used in certain images or documents from Volvo Car Corporation |
| **SoC** | System on a Chip |
| **VCC** | Volvo Car Corporation |
| **VEH** | Vibration Energy Harvesting |

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# 1 Introduction

This chapter provides a description about the intentions of the project itself. The aim is to give an overview about the framework and what the main ideas are and why the project was initiated.

## 1.1 Background

In order to maintain a strong position within the market as a car manufacturer Volvo Car Corporation (VCC) has to offer products that are groundbreaking. The need to offer the latest technologies in combination with current and coming trends is a key ingredient to success. One part of being able to do this includes studies, analyzes and implementation of (new) technologies already being used within other markets or product categories. For this specific case and project VCC has noticed a growing trend of interest to have an increased amount of light sources within the car interior. Today VCC cannot offer a variety of light sources within the interior to a reasonable price due to technical limitations.

Today the accessories within the category of interior light sources are few and come at a high price; one of these is light sources within the step-in-splines. The department of interior accessories questioned if a better solution could be achieved with an alternative solution that could lower or eliminate the high costs of today. The high price tag is a direct result of the chosen power source where two solutions are used today. One has a direct cost of cable mounting involving disassembly of parts; the step-in-spline lights are mounted during after-assembly, which means that the car has passed the main production line. Therefore all mounting requiring access to underlying parts of the car needs disassembly, which in turn is time consuming and a cost driver. The other solution of today is to power the lights with batteries, which has limited power and needs to be maintained and replaced by VCC at service shops. The solution including batteries uses 4 non-rechargeable Li-Ion batteries, which after a period of use gets depleted and therefore needs to be replaced with new ones. This swap of batteries occurs each third year (Hill, 2012), where the service and administration of consumable materials is the cost driver. It was during the development of a step-in-spline with built in light sources the idea of piezo elements as energy harvesters was born. The idea is to use piezo elements as an energy harvester, which can use the vibrations and/or mechanical forces from the car when it is driven. The department responsible for interior accessories within Volvo initiated the project with one main question in mind;

- Does it fit within the desired field of use?

The question will be in focus throughout the report, even though it will be broken down into sub-questions to give an opportunity to structurally consider and analyze the defined question from different angles.

Besides of managing the project mainly as a technology exploration test, space will be given to discuss interest areas for VCC. Examples of these areas are questions about economic feasibility and to compare the technology against what is used today. Even though the technology itself still offers the same experience for the customer, whether the light source is powered by a battery, central electric generator or piezo electricity, the goal is to get rid of waste during production and the product itself. Waste is defined as activities that do not add value to the customer (Burenius & Lindstedt, 2003). By implementing a piezoelectric solution the waste reduction might be achieved by a product that could be installed as a closed solution with no need of cabling. Unlike the solution of today that demands power from a central power source. The same principle is also eligible for waste due to service and maintenance costs due to battery replacements, which is a solution that is intended to replace todays powering solution by cabling. With the goal of getting rid of waste in mind, the project also undertook the task of following a traditional product development structure in order to explore and discuss the possibility of other competitive solutions.

The initiator companies of this project were; in first hand Volvo Car Corporation, since the project originates from an idea during the step-in-spline development. The project itself was outsourced to Rücker Nord AB who offers consultant services. Below follows a very brief description of the companies activities.

*Rücker Nord AB*

Rücker Nord is one of the leading companies in the area of advanced product and process development in western Sweden. The company offers technical consultancy services within the areas of energy, telecom and automotive- and aeroindustry (Rücker Nord AB) .

*Volvo Car Corporation*

Volvo Car Corporation is one of the car industry's strongest brands, with a long and proud history of world-leading innovations. The company was founded in Gothenburg, Sweden, by Gustaf Larson and Assar Gabrielsson, 1927 (Volvo Personvagnar).

## 1.2 Purpose

The purpose of the report is to review the possibilities of having piezo technology as an energy harvester mounted within the car. Not only with the function of powering light sources assembled within the step-in-splines, but to review the technology itself in order to discover the possibilities of it being an energy harvester powering other functions as well. The desired result is to develop a solution that offers higher production efficiency, a product with prolonged lifetime and/or to offer the customer a better product.

## 1.3 Delimitations

The focus of this thesis is on implementation of the technology on a step-in-spline even though other similar product categories could be equally or more adaptable/beneficial of the technology they will not be evaluated within this project. Another limitation is a result from the choice of considering the technology as a tool, which means that the analysis will lack a highly detailed description of the underlying functions of piezoelectricity. If a prototype is feasible then it will most likely be tested in a separate vibration simulation bench with the goal of demonstrating the technological possibilities. Thereby development resources are focused on hardware and not to develop the software in order to make it compatible within a functional vehicle.

The project does not possess the resources or the needed access to documentation within VCC to give a definite answer to the question *"How does the technology and planned type of solutions compare against the solution used today?"*. The reason for not removing it from the question formulation below is that an estimated value will be presented, and it should give a hint about the potential of the technology and other competing solutions even though the answer lacks a detailed cost analysis or a total life cycle cost. Further the focus is on exploring and testing new technology, and when it comes to the technology itself one has to remember that it is built up by a wide range of scientific sub-disciplines. Knowledge within elasticity, electricity, physics of crystals and crystallography is required to build up a deeper understanding on how piezoelectricity functions (Katzir, 2003). This in turn put a limitation to the knowledge gathering time frame that had to be balanced against the time needed of applying the technology in a prototype.

## 1.4 Methodology

Even though the piezo effect has been known for a long time, the technology itself is adapting and finding its way into new applications. With the ever-changing state of development and research within the field of piezoelectricity the first phase was focused on literature studies, where a pre-literature (see 1.4.1) study was performed prior to this methodology chapter in order to increase the probability to achieve a successful work-plan. These literature studies were strictly focused on piezoelectricity and; how it works, when it works and can it work within the desired field of use? When a firm knowledge base had been established, an initial development phase of the piezo implementation began. The initial plan did not emphasize the knowledge phase as much as it proved to demand in reality. The development and implementation required basic knowledge within vibration mechanics, piezoelectric materials and electrical circuit theory. Further, the development relied on contact with companies that offered piezoelectric products and thereby evaluating possible ways of testing the equipment on the field.

When a holistic piezoelectric concept finally was coming into view and the puzzle pieces were falling together, a parallel development of a competing solution was going to be initiated. The development of a competing solution was planned to follow the product development steps proposed by Ulrich & Eppinger (2008):

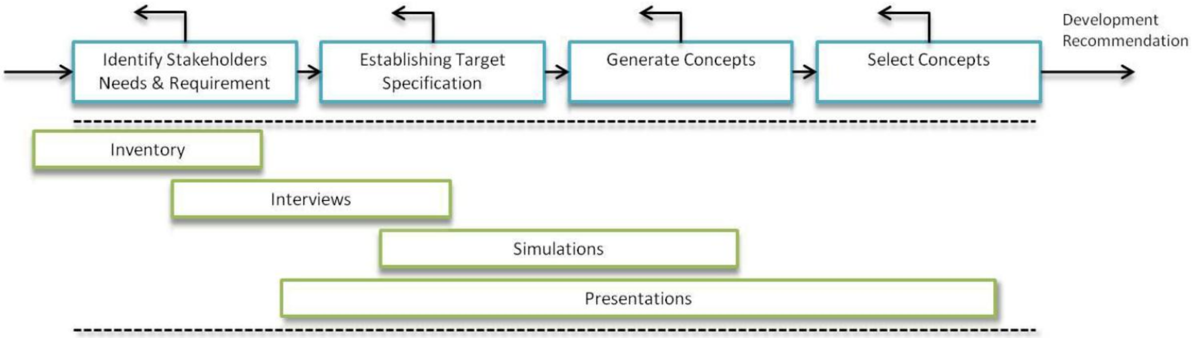



**Figure 1: Product development steps, by Ulrich & Eppinger, 2008.**

With focus on the development of a piezoelectric solution, the idea was to also allow some attention for alternative solution discussions. The purpose of allowing these discussions was that both project supervisors (VCC and Chalmers) kept discussing possible alternative solutions throughout the project, where many of the ideas had vague or no connection to piezoelectric solutions. The focus was kept on developing a piezoelectric solution throughout the project, but since the implementation work required knowledge of the product requirements and investigation of the system it would have been a waste of resources not to consider competing solutions. These thoughts resulted in a revised project description, described below, which also contains a proposed backup plan if piezo technology would have proven un-applicable. Later the backup plan was modified and implemented into the actual development; this step was taken due to the high possibility of an elongated review of the piezotechnology, which only would have forced a rushed development of an alternative solution in order to fit the timespan of the project.

### 1.4.1 Pre-literature study

The first step was to carry out a pre-literature study about available piezoelectric technology that provided enough knowledge to draw a conclusion if there was a chance of applicability within the desired field of use. The information sources were a combination of qualitative primary research with both a pre-study and a follow up on secondary research sources; with a pre-literature carried out the aim was to gain a greater understanding of the technology itself and thereby it allowed to easier combine a plan of former familiar product development methods with VCCs own GTDS template. The contribution from the GTDS template was to add stages that were suggested and recommended, such as; "Delivery Risks" and "Backup Plan", which were implemented in the early planning stages. The pre-literature study provided enough material to develop a pre-analysis about the biggest risks facing the project. The purpose of having this step was to get an insight of the risks and thereafter develop a backup plan.

For the planning of the piezo technology the guide of "phases of the thought process" (Friberg, 2006) was used as a template. Fribergs guide is shown in Figure 2, where a pre-literature study is done before the problem is formulated in detail. The pre-literature study was never intentioned to solve the problems of implementation; instead it was a combination of planning according to how successful the implementation of the technology could be and what to do if it does not apply as a feasible solution.

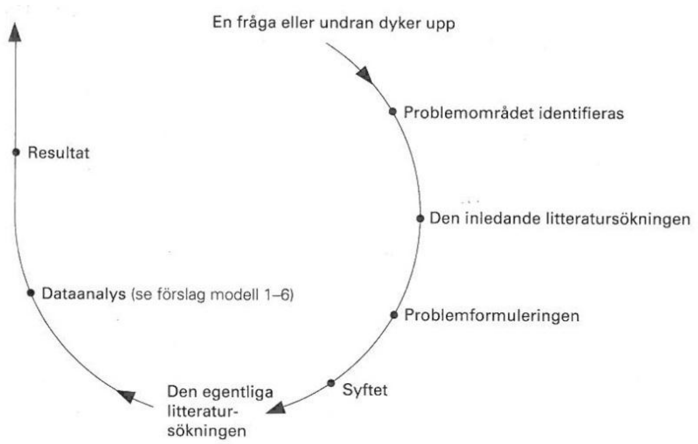



Figure 2: Fribergs phases of the thought process

### 1.4.2 Revised project description

The pre-literature study early made it evident that the technology offers many great advantages, but they may be out of reach if the technology proves un-applicable within the automotive applications in its current state. Since VCCs main issue with today's solution is the resource demanding after-assembly-line mounting, the solution should not be as strictly technology constrained as it was; it lacked a high degree of development freedom, which also prevented the use of many tools that Chalmers Technical University teaches engineering students. Therefore, the project was slightly widened and revised to; continue the development of a piezoelectric solution, while also having a backup plan ready where the knowledge built up around the step-in-spline could be used to review and develop alternative solutions. This offered VCC a technical review of the piezoelectric possibilities, and if applicable; a solution, while at the same time also considering alternative solution that might be worth looking into at further development projects.

Due to the uncertainty of the piezoelectric capabilities a combined development approach of two different methods was used as a foundation for the development. Where the initial development of a piezo based solution was of a literature based nature, with the intention to review if a piezoelectric solution within the step-in-spline was unfeasible and if so; shift resources and focus towards the development of competing solutions. The two phases were jointly connected in the early phases; to identify stakeholders, needs & requirements and to establish a target specification as illustrated in Figure 3. After these initial stages the focus was shifted to the piezoelectric solution since a solution could be envisioned.

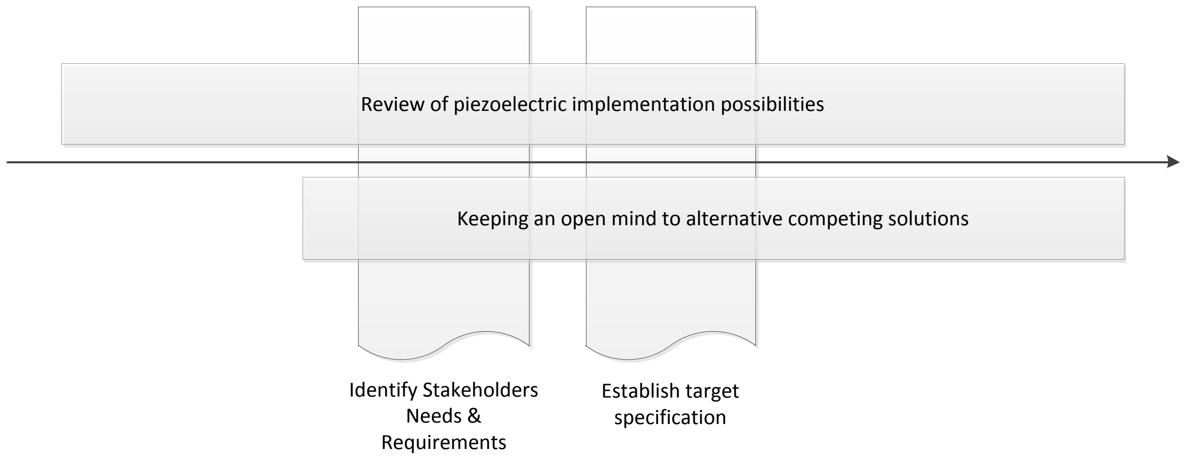



Figure 3: The development of a piezoelectric solution with doors left open to competing solutions

### 1.4.3 Revised methodology plan

In conclusion, the methodology followed 6 major segments. These segments can roughly be split into phases that could belong to either a strictly piezoelectric solution or others that could be categorized as development work for an arbitrary solution;

- Building up a knowledge base of piezo technology (piezo)
- Building up a technological understanding of the step-in-spline and its constraints (arbitrary solution)
- Set up targets and analyze market (arbitrary solution)
- Develop/ test piezo applicability (piezo)
- Develop concept (s) (piezo)
- Deliver concepts and prototype (piezo)

### 1.4.4 Product development methodologies

The first stage was to clarify the problem and to define sub-functions, from where solutions for each function were generated. This step was somewhat exaggerated for the development of a solution where the type of solution already was chosen (piezoelectric). The idea of doing this step early in the development was to increase the understanding of the product and the problem at a deeper level, and to gain a greater understanding of possible alternative solutions to piezoelectricity. The development of the piezoelectric solution focused on what Ulrich & Eppinger (2008) calls rational methods (and external solution searching), where the search for a solution was done in a systematic way by relying on gathered information.

The next step was to identify the needs and desires of interest parties in collaboration with proper departments within VCC. It was important to describe the project and to bring forth a discussion that not only included the complex issues, but also revealed the most basic and unspoken needs that needed to be considered. In order to gain insight into all needs Burenius and Lindstedt (2003) recommends a method using three principles; “asking the customer”, “studying the customer” and “being the customer”. The last principle was achieved by a visit to the assembly plant where insight of the current products assembly and installment was obtained. The plan was to follow Cohen and Crabtrees (2006) guide in order to extract as much information as possible from the interviews through; a keen understanding about the topic had been achieved, which would have made it possible to state meaningful research questions for semi-structured interviews. These interviews were intended to be with persons who possessed piezoelectric knowledge with the goal of getting detailed technological answers to open ended questions. But as it proved hard of finding interview persons with expertise only a few interviews could be conducted and a bigger effort had to be put into the segment of secondary market research. Here the aim was to obtain information and guidance about the availability of the technology. The research was conducted through external secondary market research to a great extent where internal research was mostly used to obtain references to external market information.

Before the development of a concept could begin a product specification was formulated. The piezoelectric requirements was in focus, but needed to be astricted with Volvos own technical regulation for a sill moulding (Volvo Car Corporation, 2011). When developing the prototype the goal was to reach a level of functionality that offered a demonstration of the main function, and thereby enhance the discussions about a possible final product and to get an answer to the main question stated in the background chapter (1.1):

- Does it fit within the desired field of use?

The project repeatedly followed the cycle of "plan, do, study, act" (represented in Figure 4), which meant that the results accomplished and the project itself was reviewed at each of the projects interim targets. The reason of implementing the PDSA cycle was that it provided a widely applicable and helpful tool (Moen & Norman, 2009), but especially since it needed to be kept in mind that a "no-go" gate could have been reached without notice if the project was not reviewed at given points.

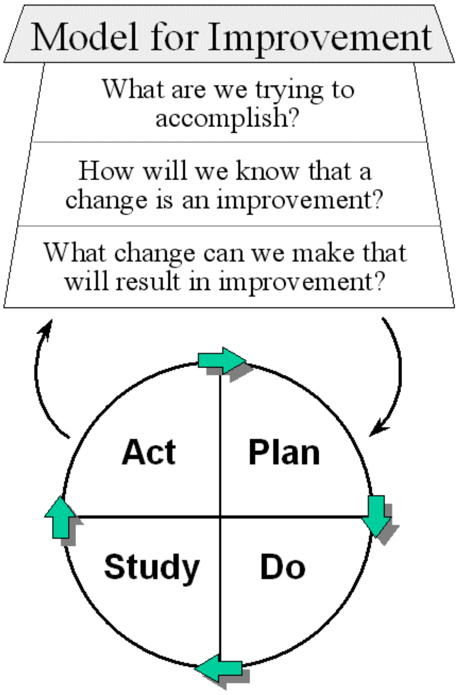


Figure 4: PDSA cycle

## 1.5 Question formulation

In order to achieve a structured workflow for the review of piezoelectric possibilities a set of questions was formulated. These questions were derived from the question stated within the Background chapter:

- Is it theoretically and practically feasible to use the vibrations and/or mechanical forces caused by the car during normal use for energy harvesting?
- Do they offer enough electricity to power light sources in the step-in-spline?
- In which parts of the car are the vibrations and/or mechanical forces of such magnitude that the energy can be used for the intended use?
- Is it possible to have the product as a closed system?
- What is the life-span of the elements during normal use together with a battery or other power conserving technologies?
- Which suppliers are there today that offer piezo elements and are these products usable within the car industry?
- Are these within the range of economic feasibility of the intended field of use?
- Are there relationships to other accessories sold today and how would they be affected?
- Which are the issues (time and cost) of implementation within VCC?
- Are other car manufacturers using the technology and are there patents to seek or patents that hinder?
- How does the technology and planned type of solutions compare against the solution used today?

With preliminary answers given to the first four questions the theoretical preparatory work was considered done, thereafter the development of a concept was in focus. The main objective of developing a prototype is to verify the preliminary answers that were given to the first four questions stated above.

# 2 Literature study

After a comprehensive literature study it became obvious that piezoelectricity's main field of use today is to provide energy to applications that has ultra-low power demands. This can be observed by visiting resellers' energy harvesting product descriptions (this can be seen at APC International, Ltd. or Linear Technology Corporations piezoelectric product portfolios). A result of this was that it became hard to convert piezo-applications already in use to the projects intended field of use. This in turn forced the research and development of a piezoelectric solution highly dependent on research articles as the main source of information.

## 2.1 About piezo and the piezoelectric effect

Piezoelectricity is the conversion from mechanical pressure to electrical energy, achieved by subjecting an object to pressure which at release of stress produces an electrical current flowing through the material. The piezoelectric effect was discovered as early as 1880 by Jacques and Pierre Curie. It took 35 years for the technology to reach applications outside the laboratory testing. Today, more than a century later the piezoelectric effect only seem to have begun expanding its field of use. The technology is wide spread and almost everyone in the west encounters devices based on piezoelectric technology daily. Some well-known examples would be click lighters and wristwatches (Katzir, 2003). The word piezoelectricity has its roots in the Greek word piezo which means pressure and the effect is described in several papers with an analogy to a sponge and water: "Like a water sponge, piezoelectric materials charge when squeezed" (Solvay, 2012).

## 2.2 Piezo today and tomorrow

As stated, the piezoelectric technology is spreading with a growing interest due to its low-impact capabilities. Katzir (2003, p. 61-91) states that in the year 2000, more than 3000 published papers were dealing with the piezoelectric phenomenon. But still, the main fields of use are within ultra-low power applications. As Qiu et al. (2009) states; if the expanding of piezoelectric applications is going to continue, a raise in the efficiency of piezoelectric harvesters is becoming increasingly important. But the efficiency of piezoelectric harvesters is not the only part of the system to make more effective. The chosen piezoelectric solution of the project at hand has to be viewed from a holistic perspective, where each part can be improved and made more effective. Jia and Liu (2009, p. 42) claim that the biggest gains in efficiency will be achieved through decreasing energy consumption thanks to the continuing scaling down of devices. As the vibration driven piezoelectric devices are gaining ground in expense of the micro-battery solutions (Jiang et al., 2010) there have been many controversial attempts of implementation in other areas. It is from these attempts the inspiration for a functioning piezoelectric driven solution is being kept as a viable solution of powering the lights within the step-in-spline. Some of these controversial solutions or ideas are presented below.

One of the most famous and attention drawing piezoelectric driven applications are a few dance-clubs where the energy of dancing people on the dance floor powers the LED lights. The dance clubs have implemented piezo as a tool to become more eco-friendly. Some of the clubs claim that as much as 60 percent of the total energy required to operate the club comes from the dance floor, where a single dancer can generate around 5–10 watts (Club 4 Climate, 2012). Some similar solutions include implementation of piezoelectricity within sidewalks to power streetlights, railways to power ticket stations, under railroad tracks and inside highway sections (Discovery Communications, LLC, 2011). These are all under experimental stages and it remains to be seen if the solutions will be implemented widely.

An application idea that could be transferred to the solution within this project is the development of a microscale energy harvesting system that could recharge portable devices. The goal was to develop a case for a laptop with built-in piezoelectric elements, which during transportation would use the low resonance frequencies to recharge a computer. The aim for targeting low-resonance frequencies has been tested in a few applications, mainly because they are available during typical daily activities, such as walking, running, cycling and going by car. In the laptop case design the results showed that a 900 mAh Li-ion battery would only be able to charge the battery at a rate of 16–26% of the ideal trickle-charging[1] rate depending on activity. The result was achieved by a 1.2 cm thick computer case, with length and width being respectively 31 and 26 cm (Fain, Hopcroft, & Wright, 2009).

Further, multiple development projects focused on garments, mainly shoes, harvesting energy from human movement is under development or has been finished. One of the first attempts were done by Trevor Baylis, as he walked 100 miles in the African desert in his piezoelectric shoes in order to charge his phone, from which he then made a call (Drake, 2001). DARPA[2] had a goal to harness 1–2 watts from continuous shoe impact while soldiers were walking, but the project was abandoned due to discomfort and impracticality when wearing the shoes (Belfiore, 2009). These charge rates are not assuring neither deterring that an implementation within the step-in-spline is going to work. However, the most comparable experiment was done by Sodano et al. (2005) when they successfully experimented with different ways of charging batteries by piezoelectricity. The goal was to recharge batteries by vibrations in an engine compartment where the results were quite encouraging as an 80 mAh battery was recharged under or within 2 hours by simulated engine compartment vibrations. As the development of a piezoelectric solution begins to form, the hopes are that vibrations within the engine compartment are somewhat transferrable to the automobile chassis, which would make the experiments made by Sodano et al. (2005) more pertinent when developing a piezoelectric solution for the step-in-spline. The citation below shows that the experiments could be transferrable to this project;

> “ *the finding that piezoelectric materials can be utilized for recharging batteries brings power harvesting significantly closer to the commercial market and opens up many doors for its applications ... Without a method of storing energy more effective than the capacitor, power harvesting will never become a viable power supply in commercial applications”*
> (Sodano et al, 2005, p. 18-19)

[1] Trickle charging = Charging of a fully charged battery under no-load at a rate equal to its self-discharging rate, thus enabling the battery to remain at its fully charged level.
[2] Defense Advanced Research Project Agency

## 2.3 Piezoelectricity as a part of interior design

During the startup meeting of the project the implementation of a piezoelectric solution within the step-in-spline was roughly stated as; develop a step-in-spline with built in piezoelectric elements, which in turn generate power to the light sources (LEDs) mounted within the step-in-spline. This description still describes the main purpose and idea of the project, but as with any other projects, requirements has to be stated in order to have distinct and measurable goals. The following requirements are extracted from a technical regulation for the step-in-spline (Volvo Car Corporation, 2011). The step-in-spline with built in lights of today is a styling element that emphasizes the sill area and gives a unique appearance to the vehicle when any front side door is open/opened. The product (LED's) shall be lit up softly when the door is opened (supply voltage) and then stay lit and follow the interior light dimming process. The illumination of each function shall appear homogenous without spots, streaks or other conspicuous variations. No dark areas on the illuminated surface, minimum when looking in a 45 degree angle relative to cars line.

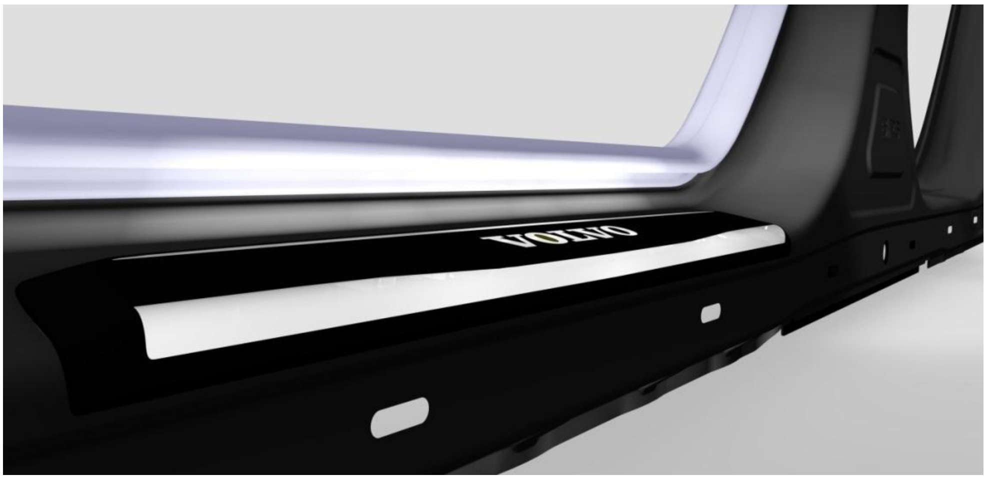



**Figure 5: The illuminated step-in-spline as part of the interior styling**

The mentioned requirements are stated for the solution of today. The development of a piezoelectric solution will have to include work that determines if the requirements can be kept unaltered or if some has to be redesigned in order to function with a piezoelectric solution. After the literature studies it became evident that it would be a too extensive task to consider all existing sill moulding requirements within this technology review. Especially within a company with global development that could increase the time needed to pinpoint the needed information. Thereby the focus was once again narrowed down to evaluate how a piezoelectric solution technically could work within the step-in-spline. The technology focus was needed, and as Shu (2009, p.80) states in his work *Performance Evaluation of Vibration-Based Piezoelectric Energy Scavengers*: one has to gain a good understanding of piezoelectric energy harvesting systems in order to build one. The optimum design and setup depends on the surrounding kinetic energy (amplitude and frequency) and the electrical application that is to be powered. These two areas became the main areas of focus from this point on. Shu (2009, p. 80) also states that it is necessary to use model-based design methods instead of using try-and-error schemes. Which is the reason for the project turning out to be more of a theoretical analysis with more time spent on the literature studies than actual prototype testing.

One example of this is that it would have been impossible to make a good choice of a piezoelectric material before the whole system was planned for. Further, one has to be reminded that without the vibrations from the vehicle a VEH-system would be useless. Which somewhat is in conflict with the development of cars as a whole, where the aim is to lower vibrations in order to make the ride as comfortable as possible. The more the car is damped, the less useful vibrations available to harvest, which also is linked to the fact that piezoelectricity is bound to be a sub-system within a bigger one since its main function is to harvest energy from other power sources. Rincón-Mora (2009) writes about this in his work *Harvesting Microelectronic Circuits*: *"the harvester cannot replace the power source in a microscale system, only the energy source".*

# 3 Piezoelectric solution development

It is the dark areas of the step-in-spline that are lit up by the LEDs in Figure 6. From observing the figure an obvious question is raised; how much volume does a piezoelectric solution demand, and how much volume inside the step-in-spline is available for such a solution? The question is thoroughly analyzed in chapter 4.2 (Dimension constraints), but considering the earlier literature studies an interesting idea would be to place the piezoelectric element in a location with more available space and heavier vibrations, such as the engine compartment.


**Figure 6: The step-in-spline with lights, the dark areas are illuminated.**

The idea originates from the already mentioned article by Sodano et al. (2005) where a few piezoelectric materials ability to charge batteries when placed within the engine compartment of a Mitsubishi eclipse was studied.  They were able to recharge batteries at a rate which would be more than enough to power a few LEDs, as can be seen in Table 1.

**Table 1: Piezoelectric battery charging times as measured by Sodano et al. (2005) when using a random signal**

| Battery size [mAh] | PZT |
|---|---|
| 40 | 1.6 |
| 80 | 2 |
| 200 | 1.2 |
| 300 | 9.8 |
| 750 | 8.6 |
| 1000 | 32 |

*Specific power needs for the step-in-spline can be found in: The building blocks - The battery (3.4.4)*

The reason for not choosing to follow this idea was that VCC initiated the project with the goal of minimizing costs. Either VCC chooses to implement batteries to power the LEDs, which has a cost driven by having to replace batteries each third year in every car with illuminated step-in-splines. Alternatively the solution is to continue using cabling to a central power source, which is the solution used today, with high after assembly costs. The issue is applicable to many other areas also, and is stated by Priya below:

> *”A large network with several sensor nodes and data acquisition components requires a centralized energy source that has to be charged or replaced over time. In remote applications, such as ... battery replacement or wiring can be very tedious and expensive task.”*
> (Priya, 2007, p. 166)

Priya emphasizes piezo as the problem solver in these kinds of situations, and by reading the encouraging results achieved in experiments by Sodano et al. a vision of having a piezoelectric solution began to form.

## 3.1 The System

Before analyzing possible energy harvesting solutions a block diagram of the functions that needs to be fulfilled was defined. The analyze resulted in the block diagram presented below (Figure 7).


**Figure 7: Energy harvesting system as a block diagram**

A piezoelectric solution could be implemented in several ways. But since the envisioned solution of VCC is a plug-and-play system the first attempt of implementing piezoelectricity will be to pack the whole solution inside the step-in-spline. There are two possible ways of getting the energy needed for a piezoelectric solution when considering a solution that is built inside a step-in-spline;

*Closed piezoelectric system*: The ambient vibrations obtained from driving a car will be converted to electricity by a closed piezoelectric system, as illustrated in Figure 8. The base is excited to ambient vibrations which are converted to energy by the piezo element. All components of the system are enclosed within the step-in-spline.

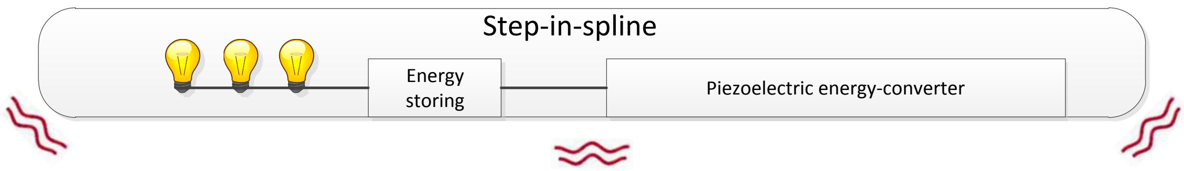



**Figure 8: Closed piezoelectric system**

*Open piezoelectric system*: The vibration energy is an input from a relative mass to the piezoelectric element, as illustrated in Figure 9. The applied force is a relative movement to the element itself. The vibrations within the step-in-spline will be of lower frequency than the frequencies inside the engine compartment, maybe even too low for sufficient energy harvesting. One way to overcome this obstacle could be to use the relative movement of the door against the step-in-spline which might be of a higher frequency and the movement against the piezo element only needs to be within the range of some micrometers (µm).

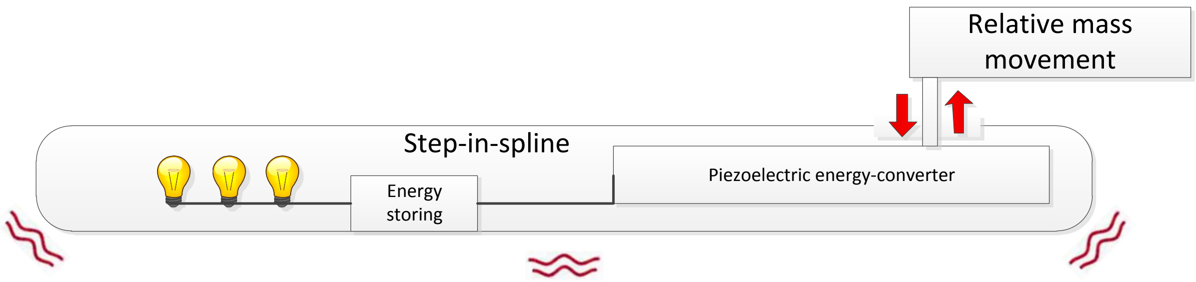



**Figure 9: Open piezoelectric system**

The open piezoelectric system requires more development work compared to a closed solution before a prototype could be put together. It would also require a higher degree of modification of the door and step-in-spline in order to only allow the desired amplitudes get in contact with the piezo element. Thereby the closed system is desirable to test at first and if it fails then an open system would be shortly evaluated theoretically, with a discussion of further development.

The closed piezoelectric system would provide a solution closer to the one VCC had envisioned a solution that would not require modification to other components and could be implemented as a plug-and-play component in the after assembly. Thereby the focus will be to evaluate the possibilities of accomplishing such a solution. Fortunately the initial idea of implementing a piezoelectric element inside the step-in-spline has been tested by others and provides guidance in the planning:

> *"It has been found in previous studies that piezoelectric material attached to a beam with cantilever boundary conditions provides an effective configuration for capturing transverse vibrations and converting them into useful electrical power."*
> (Sodano et al., 2004)

## 3.2 Vibrations and frequency characteristics

In order to harvest energy from a vibrating source one needs to study the nature of the vibrations. It is of great importance to know the system characteristics in order to chose the right material and operating mode to maximum power output. The frequency data is from vibration studies made by VCC. This information data was supplemented by having an interview with Robert Höglind, a vibration engineer at VCC (Höglind, 2012). The ambient frequencies within the car are presumed be of same frequencies as the ones that the step-in-spline is exposed to. The vertical acceleration over time and acceleration density over a frequency band (PSD) has been measured, the measurements are from a point rigidly attached to the chassis (next to the gear stick). The measurement data is presented in Figure 10 and Figure 11 (more frequency data can be found in Appendix I: Test drive and frequency data).

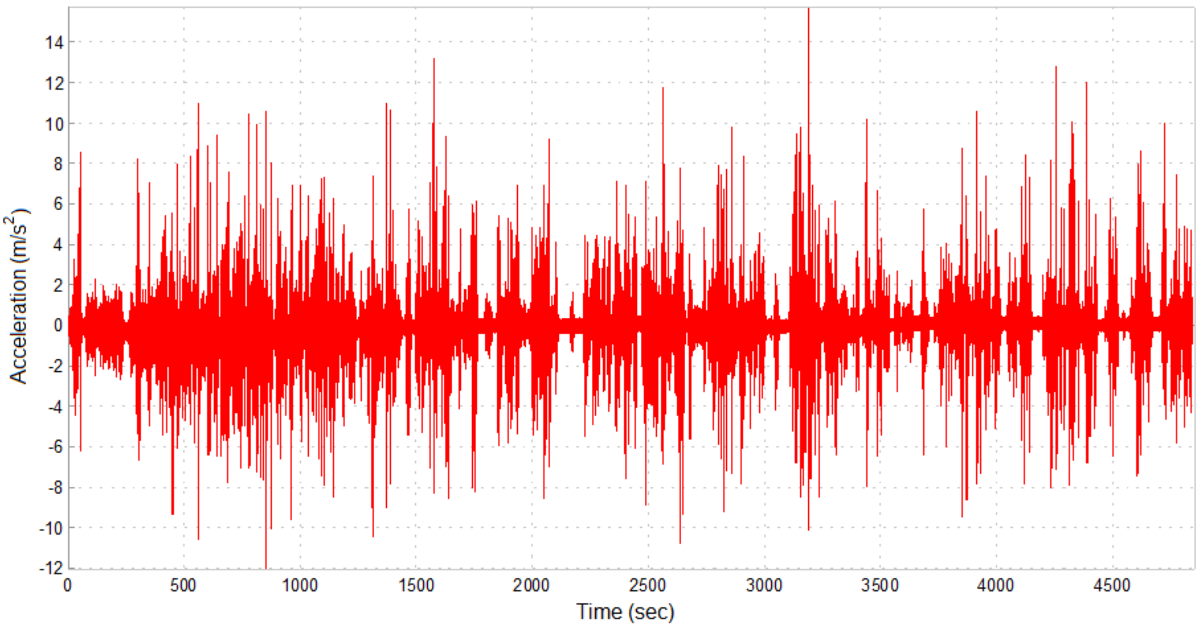



**Figure 10: Vertical acceleration data – city driving 35km, car model: S80, year model 2000.**

In Figure 11, the above vertical acceleration data has been sampled in a PSD that gives the "power" carried by a wave per unit frequency. Further, the frequency value given in $a^2$/Hz refers to a bandwidth rather than to the frequency in Hz along the X-axis (Irvine, 2007). The PSD is done since random vibration is complicated and has no simple relationship between the peak value and rms-values, where the peak value typically can be 3 or 4 times the rms-value.

The units can vary between different measurements, and in this test the squared acceleration ($a^2$) versus frequency (Hz) has been used. That gives an acceleration density (as in; power or acceleration) at given frequencies (American Environments Company, Inc). It gives sort of a mean value of the content per frequency region, it does not say anything about the amplitude since it is a mean value over the measured timespan. As an example, if one would compare the below PSD, which is from a test drive around a track, with another PSD from the same track with a pause in the middle of the track the value of the y-axis would be lower (Höglind, 2012).

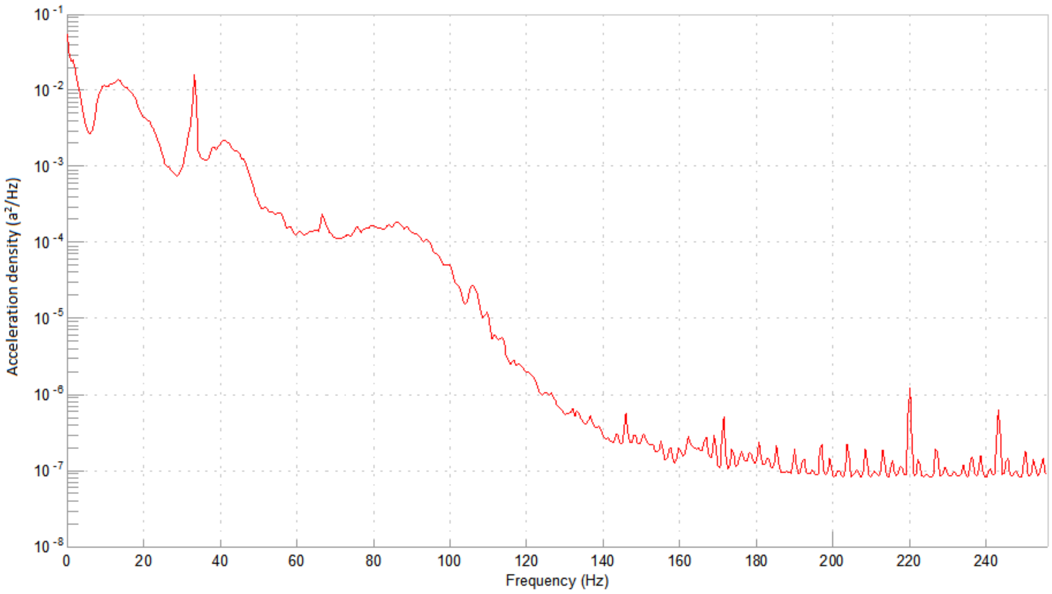



Figure 11: PSD derived for the whole signal from Figure 37

In this case, the PSD tells us that there are low frequencies that have relatively high acceleration density from which energy could be harvested. It would nevertheless be wise in later development efforts to verify these measurements with ones made within the step-in-spline to see if they differ from these measurements. Especially since discussions at VCC pointed towards ambient vibrations that could have a frequency bandwidth being as low as 1-2 Hz. It is hard to find certain frequencies that would work for one allround VEH-system since the peaks are related to tire imbalance, engine vibrations, rotational vibrations from drive train system, the alternator and air conditioning unit. There is however one frequency typical for many cars; the low spectral peak (around the mentioned 1-2 Hz) is the fundamental frequency related to the car mass and its suspension system (Priya, 2007). This could provide a piezoelectric operating frequency to aim for.

## 3.3 Question formulation wrap-up

As mentioned earlier, the development of a piezoelectric solution will begin after the question formulation has been revisited. This chapter contains a summarizing wrap up of the questions that already can be given answers.

- Is it theoretically and practically feasible to use the vibrations and/or mechanical forces caused by the car during normal use for energy harvesting?

Yes. Several studies that have been reviewed within the report have shown that mechanical vibrations are suitable sources for energy harvesting. To be more specific, experiments has proven that it is possible to recharge batteries relatively fast with energy harvesting from ambient vibrations within the engine compartment of a car (Sodano et al., 2005).

- Is it possible to have the product as a closed system?

Probably yes. As long as the vibrations are of such frequency and magnitude that allows the piezoelectric plate to operate at a frequency where it effectively converts mechanical to electrical energy (often equal to the its resonance frequency where it vibrates most readily). Further the space within the step-in-spline has to be able to contain circuitry, piezoelectric plates with enough bending space (matter of millimeters).

- Which suppliers are there today that offer piezo elements, and are these products usable within the car industry?'

Without going deeper into the subject; the resellers found during the project are listed below.

### *Resellers*

The suppliers offering piezoelectric solutions are still a niche market and finding national resellers could not be achieved. However, online resellers tended to be located within USA. During the literature study some questions required personal contact with the resellers, where three of the resellers proved helpful; APC International Ltd., Piezo Systems Inc. and Advanced Cerametrics Inc. Beside these three companies the following companies were found and might be helpful when searching for a supplier of piezoelectric components.

- Advanced Cerametrics, Inc. - *http://www.advancedcerametrics.com/*
- APC International, Ltd. - *http://www.americanpiezo.com/*
- Face® International Corp. - *http://www.faceinternational.com/*
- Fuji & Co. - *http://www.fuji-piezo.com/*
- Linear Technology Corp. - *http://www.linear.com/products/*
- Lumedyne Technologies Inc. - *http://www.lumedynetechnologies.com/*
- Midé Technology Corp. - *http://www.mide.com/*
- PI Ceramic GmbH. - *http://www.piceramic.com/*
- Piezo Systems, Inc. - *http://www.piezo.com/*
- PiezoTech S.A.S. - *http://www.piezotech.fr/*
- Smart Material Corp. - *http://www.smart-material.com/*

## 3.4 The building blocks

As in any project evaluating new technology, the system model is conceptually represented with as low complexity as possible. As the system undergoes testing the model will increase in detail and include more design parameters. At the same time it is desirable to estimate the energy harvesting systems capabilities before building a physical model in order to confirm the possibility of energy harvesting giving a power output that could match the needs.

The building blocks of the system can be broken down to; the circuit, which is the node of the building blocks, the piezoelectric material that converts energy from mechanical to electrical, the battery that stores the energy harvested, and finally the main power draining component, the light source. In this chapter these building blocks are analyzed separately and then put together into one system that will be evaluated theoretically.

### 3.4.1 The energy harvesting circuit

How should a piezoelectric circuit model be obtained? In their book *Energy Harvesting Technologies*, the editors Priya and Inman (2009, p. 107) discusses the matter. The reason for having a circuit models is to be able to analyze and design the piezoelectric system so that it matches the application it is intended to serve. The models in turn require input to give an output estimation, which can be obtained either experimentally  or numerically. The aim within this project is to attempt a numerical estimation, and thereafter complement these estimations with experimental values. If the numerical models prove useful VCC will have a guide/manual to easily benchmark piezoelectric solutions in comparison to other solutions.

#### *3.4.1.1 A functional model*

In order to address the function of the piezo-electric circuitry within the step-in-spline a functional model was conducted. As one can see in Figure 12 the system is being kept as compact as possible, with few components and functions to keep track of. The simplicity is desired since the electronics in the system adds complexity to the system exponentially; each component put in the system will be contributing to changes in the system properties. The functional model presented in Figure 12 has three steps; harvest energy, take care of harvested energy, use the energy.

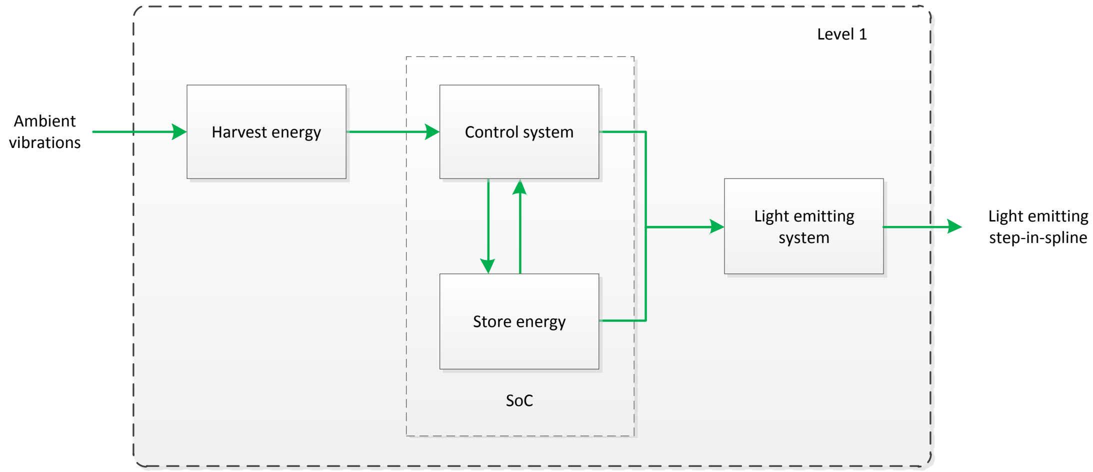



**Figure 12: First level of the functional model for a piezoelectric solution**

As one digs deeper into the simple SoC presented in the first level of the functional model it becomes apparent that the energy harvesting function is not the most demanding part in the development of the solution. In Figure 13 the SoC is being analyzed. Within the SoC the amount of components needs to be kept at a minimum in order to keep the energy consumption as low as possible, both in standby and when operating. As discussed in the introduction of this chapter where the circuit functions were shown in a block diagram (see Figure 7: Energy harvesting system as a block diagram), the goal was to show the necessary steps that needed to be taken in the process. The following functional model (Figure 13) in combination with Figure 12 is an attempt of including the smallest amount of functions needed to fulfill the operations of a VEH step-in-spline.

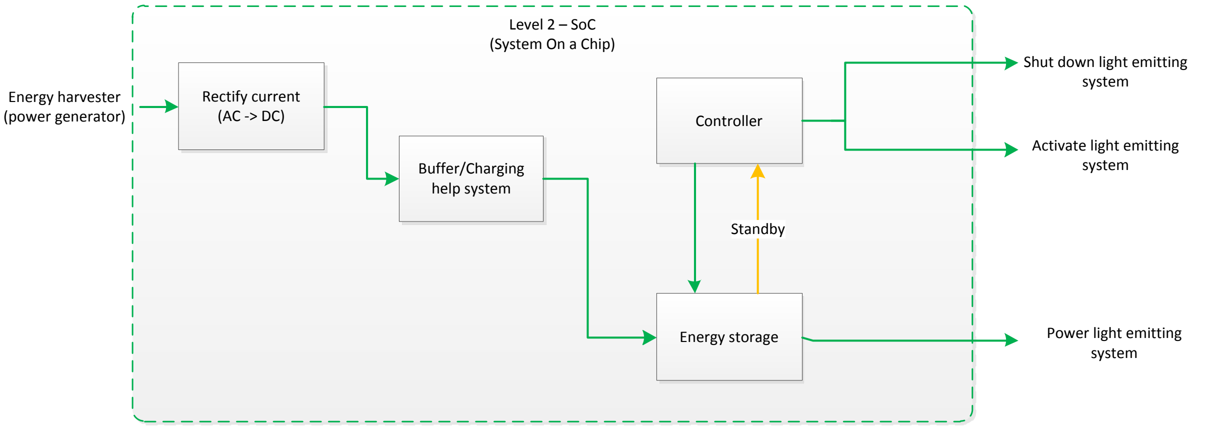



**Figure 13: Level 2 of the functional model, where the circuitry is in focus**

The rectifier is a necessity in the circuitry since piezoelectric materials work like pendulums where the energy is harvested by a stress of alternating direction. Thereby the circuitry cannot directly be borrowed from solar or thermal energy harvesters that produce a steady flow of charge carriers. The issue of rectifying the alternating current requires energy, either by the rectifier or a controller that switches controls in order to obtain the charge current. The voltage on the other hand needs to be controlled to be high enough to drive the components (such as diodes and if implemented, metal-oxide semiconductor (MOS) switches), and low enough to avoid breakdown of the components.

### *3.4.1.2 The circuit*

The circuitry requires a balance between functionality, effectiveness and simplicity. A complex circuitry would be hard to accomplish with the time constraints and resources given, while the circuitry would be in its simplest form when only using the absolute minimum of needed components. The plan is to start with the simplest possible circuitry, and to gradually add circuitry if time allows with the hope of reaching a higher efficiency (which unfortunately leads to higher complexity). To achieve the simplest circuitry an interview/discussion was conducted with Jan Möller (Möller, 2012), the outcome was a circuitry with a minimum amount of components that should make charging of a battery possible, as presented in Figure 14. Note that the circuitry only shows the energy harvesting scheme, and does not include any controller that is mentioned in the functional models.

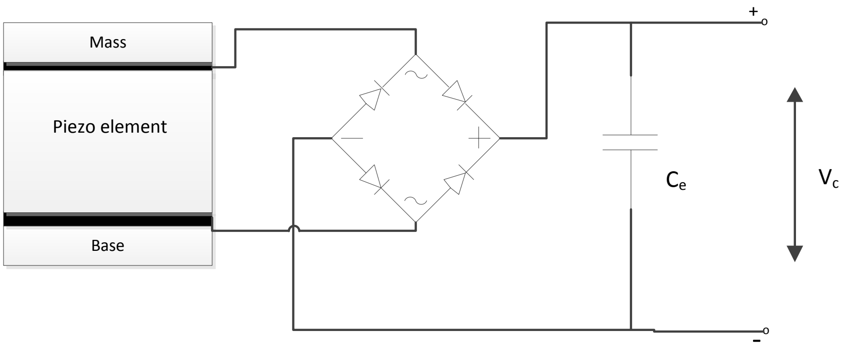



**Figure 14: The energy harvester circuit to begin the tests with**

As mentioned before, the voltage needs to be controlled, which here is done by assuming the capacitor ($C_e$) to be large enough so that the output voltage is basically constant (where the battery is connected). As explained by Pedersen in his work "*Low Frequency Low Voltage Vibration Energy Harvesting Converter*": The piezoelectric voltage needs to be greater than the output capacitor voltage and diode bridge forward voltage, only then energy will be harvested (Pedersen, 2011). This makes the capacitor a necessity in a harvester-charger system, and means that it is only the current flowing out of the capacitor that charges the battery (Rincón-Mora, 2009).

Even when only designing on resistive components the complexity is high, and requires additional circuitry presented in order to have a chance to represent the systems capabilities theoretically. In Figure 15 the scheme of a “typical” energy harvester is presented, which is used in a wide range of literature. The purpose of implementing a resistor is to illustrate the parallel resistance to the load and leakage resistances, and by studying the resistance Renno et al. claims that a maximum flow of energy can be found by choosing the optimal resistance (Renno, Daqaq, & Inman, 2009). The study presents a formula that among other requires precise frequency ratio data, damping ratios and an optimization problem with a 12$^{th}$ degree polynomial of the optimal frequency ratio. This proves that even in this simple scheme there are many dependencies between the components, and to examine them in detail theoretically in order to give a precise mathematical description of the system would steal focus and time from the main task.

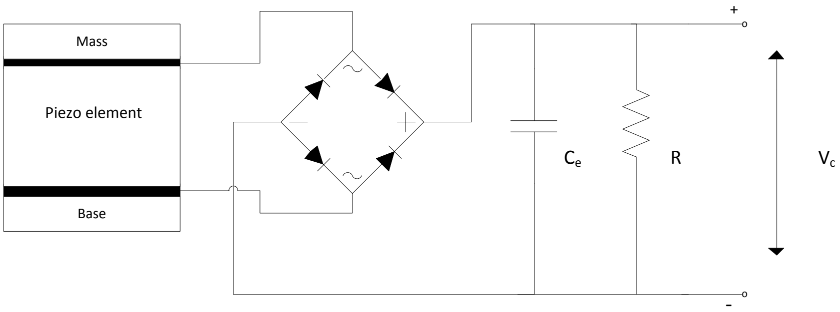



**Figure 15: A ”typical” energy harvesting circuit, same as above but with an added resistor that represents the system resistance**

Further, a “backup” circuitry should be ready for testing, that is; if there is time and resources for more testing the further work will continue smoothly. The criterion of simplicity still has a high weight in the choice of a secondary circuit. First the possibility of testing a system with a control circuit was evaluated. Unfortunately most of the control circuits are under development and are complex to implement efficiently. This can be seen in articles about recent research within the area, where one test of a control circuit used when harvesting energy with an active control circuit based on ultra-low power ICs and a synchronized switch for harvesting on inductor was tested (Pedersen, 2011). The test was successful and showed increase in power factors between 2–8 times (depending on the energy level of the source of harvesting) compared against full rectifiers, but even in this test that was a pure circuit experiment the power consumption of the power control circuit was too high and the output power was lost.

Literature studies of circuitry models and the evident complications of implementing a control circuit resulted in a secondary circuitry evaluated by Priya and Inman (2009, o. 286). In their book *Energy Harvesting Technologies* they argue; by adding an inductor to the circuit a new degree-of-freedom is achieved. The frequency ratio does not need to be precisely chosen to match the natural frequency of the material and other affecting factors, by tuning the inductor and resistance of the energy harvesting circuit it is possible to harvest power more effectively over the frequency domain. Which could come in handy considering the frequency plots presented in previous chapter (3.2). Further, Priya and Inman (2009, p. 189) suggests that the inductor should be connected in series with the resistor (system load) if a high current is favored (which is needed when charging a storage device). And in parallel configuration if a high voltage is favored (e.g. when using wireless sensors). This gives the circuitry presented in the schematic below Figure 16. Most circuits in the literature study did not involve inductors, but an attempt of implementing it will be made (if resources allows it) to validate the benefits from it due to the car chassis varying frequencies.

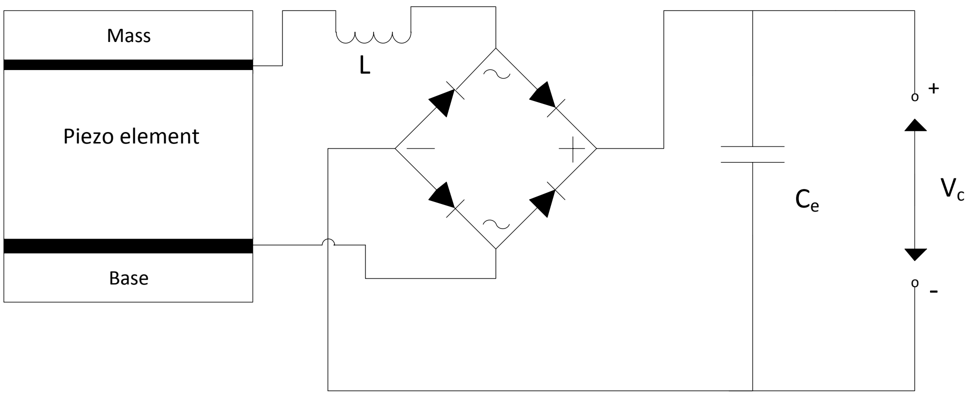



**Figure 16: The ”typical” energy harvester with an inductor implemented in the circuitry**

Priya and Inman does not provide a schematic for the inductor in combination with a battery. In Figure 16, the inductor has been included in the main circuitry in a simple way that hopefully could raise the effectiveness of the systems capability of harvesting energy over a wider range of frequencies.

### 3.4.2 Choice of piezoelectric material

Before choosing a piezoelectric material one has to know what type of mounting on the vibrating source is to be used. The most common ways of mounting a piezoelectric material to the power source are shown in Figure 17. In this implementation project the dimension constraints, the nature of the vibrations and the step-in-spline being a rigid body where its hollow body is used for energy scavenging the choice falls on a cantilever mount.

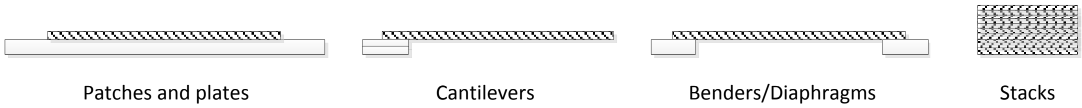



**Figure 17: Different ways of mounting piezoelectric material(s) to the power source**

The cantilever mount is proven to be most efficient when operating in small force and low-vibration environments. Further, the cantilever mount has a low resonance frequency, which increases the chances of being able to tune the system mechanically to match the low fundamental frequencies of the car (Clark & Mo, 2009). The tuning could give a great performance boost if the resonance frequency of the energy harvester could be matched with the structural resonance (Cornwell, Goethal, Kowko, & Damianakis, 2005). Note that in the literature the cantilever mount is often referred to as d31 mode and d33 mode refers to a stack.

When applying a piezoelectric material to harvest energy from vibrations (with a mass attached to the tip) a strain or deformation is caused by the movement. In this chapter the aim is to choose a material that has the best matching properties of energy harvesting linked to the character of the mechanical vibrations. As the piezoelectric materials are gaining attention within many areas, new combinations of the available materials are hitting the market. The common existing materials come in the form of polycrystalline ceramics, textured ceramics, thin films and polymers. Of further notice is that the market offers two extreme cases of high-energy density material, PVDF and PZT. Both of these materials are commercially available, which is a requirement since it allows the construction of a prototype. It should also be noted as an advantage that using piezoelectric energy harvesters in a system has the same effect as a shunt damper (Sodano et al., 2004). The piezoelectric system removes energy from the system, with the difference that the energy is stored for electrical components rather than dissipated. The effect of added damping in form of piezoelectric elements as energy harvesters within the step-in-spline will not be noticeable by the driver. But in the future, if the technology surpasses some technological holdbacks it might be implemented for use within a wide range of applications within the car, and maybe then the effect would be noticeable.

A difficult part of choosing the material was to decide when to order it, the more time spent on research about choosing the right material; the less time there would be to build a prototype and to test it thoroughly. Further, the curie temperature of piezoelectric materials defines the temperature at which the material loses its spontaneous polarization, and usually lies around or above 200°C. It was thereby not an issue and was not taken into account when comparing the materials. Also the operating life time was left outside the comparison since it is hard to pinpoint, many sources give their own life-time that unfortunately differs in most cases. The range is mostly given from 10^6 cycles to infinity, but as Jia & Liu (2009) mentions in an article about *human power-based energy harvesting strategies for mobile electronic devices*, it is important to notice that the operating life and piezoelectric properties are nonlinear and depend on age, stress and temperature. In the case of having piezoelectric energy harvesters within private vehicles, the operating life needs to be tested thoroughly due to the irregular motion conditions it will be exposed for before it could be implemented within mass production.

#### 3.4.2.1 PVDF

The advantages of Polyvinylidene fluoride (PVDF) are great, it is mechanically strong, withstands many chemicals, is relatively easy to manufacture and due to the advantages of the polymers flexible nature it is believed that it will have a significant importance since it can be integrated in almost any structure (Priya, 2007). Further, the piezoelectric effect is strong within PVDF, and it even shows response at microwave frequencies (Priya & Inman, 2009). But in contrast to ceramics it makes a relatively weak electromechanical transmitter, especially at resonance and in low frequency applications (Measurements Specialties, 1999). In combination with a magnetic mass the energy harvesting capabilities could have been raised to higher levels at low frequencies, unfortunately the outer boundaries of the step-in-spline prohibits the use of magnetic generators due to size constraints (Jiang et al., 2010). Thereby PVDF materials were disqualified as a suitable material to use within the step-in-spline.

#### 3.4.2.2 PZT

Does the PZT offer advantages that make it suitable to use within the step-in-spline? Many PZT[3] ceramics have great functionality at kHz frequencies, but within this project the aim is to find a material with as low operating frequency as possible (or at least closing in on the bandwidths presented in the chapter about Vibrations and frequency characteristics). On the lower end PZT has an operating frequency range reaching between 10-200 Hz and external force amplitudes of 0.1-3 Newton (Priya & Inman, 2009). These operating frequencies suits the frequencies much better. As a bonus PZT has low dielectric losses, which in turn facilitate the development of the envisioned closed system solution by allowing the material to be used continuously in resonance mode with only low intrinsic warming of the components (PI Ceramic GmbH, 2012). PZT is not an optimal material in every aspect; a drawback is that PZT is made of lead zirconate-lead titanate compounds which are hazardous substances, and even though an exemption for use of the material exists in the EU directives to reduce hazardous substances (Electronicsweekly.com, 2011) it would be preferable for VCC to have an alternative with a guaranteed future. And besides the lead containment, the fragile nature of PZT could make it hard to implement with ease. But it still does offer the most suitable combination of properties in this implementation study.

[3] PZT is an abbreviation of a chemical compound, $Pb[Zr_xTi_{1-x}]O_3$ ($0 \le x \le 1$) and is also known as "Lead zirconate titanate".

#### 3.4.2.3 Alternative materials

Some interesting alternatives are being developed or are already available, with either comparable material properties, performance in terms of energy harvesting, or with other tradeoffs instead. Three of these materials are mentioned below:

- Aluminum Nitride (AIN): Comparable results to PZT (Fain et al., 2009), with the advantage of being lead free.
- Quick Pack: Outperforms PZT when operating in resonance, but hard to make efficient when the frequency varies (Sodano et al., 2005).
- Macro-Fiber Composite (MFC): Has many advantages, but offers low current output compared to PZT (Sodano et al., 2005).

The possible material selection does not end at these mentioned materials, it ranges from the mentioned PZT family to other ceramics like modified lead titanate, barium titanate, lead metaniobate, lead magnesium niobate (PMN) based relaxor compositions, and a multitude of ceramic/polymer composite types such as Piezoelectric Fiber Composites (PFC).

#### 3.4.2.4 Prototype material

When choosing a PZT material for testing, a high conversion rate of the mechanical input to electrical output is obviously desirable, what makes the choice a bit more difficult is that the material needs to be picked for the specific environment it will be working in. Due to inconsistencies in mass production of the cars at VCC one cannot rely on that same frequencies will be generated from the same driving conditions, furthermore, the cars will not be driven in the same way by all the customers. This is a holdback that hinders easy implementation of vibration based energy harvesters that works within a strictly specified frequency bandwidth. Yi-Chung Shu claims that a vibration based scavenger achieves maximum power when the resonance frequency matches the driving frequency, and if the frequency deviation is more than 5% from the resonant frequency the scavengeable power is almost negligible. (Shu Y.-C. , 2009) This statement in combination with the frequency plots available in chapter 3.2 made it difficult to choose a material since it should combine easy testing at a low frequency range, it proved to be time consuming to compare the PZT materials available at resellers. Most materials had a frequency bandwidth above 100Hz, which complicated the selection since it would be desirable to have the peak-conversion at 1-20Hz. Further, the selection was complicated due to the issue of being forced to select a material fairly quickly because; (1) no domestic branch offering piezoelectric solutions was found and thereby prolonging the shipping time, and (2) an inquiry had to be sent to VCCs purchasing department for processing before the material could be ordered.

The material for the prototype was chosen to be PZT from Piezo Systems Inc. To ease and save time of the installation an energy harvesting kit that is pre-wired and comes with an on-board capacitor bank that stores energy was ordered. The material properties are presented in the table below and the kit can be seen in Figure 18.

**Table 2: Material specification for piezoelectric material 5A4E from Piezo Systems, Inc.**

| | | | |
|---|---|---|---|
| Material | 5A4E | | |
| Weight | 10.4 | [g] | |
| Stiffness | $1.9 \times 10^2$ | [N/m] | |
| Capacitance | 232 | [nF] | *(Parallel operation)* |
| Rated tip deflection[1] | ± 2.6 | $[mm_{peak}]$ | |
| Max. rated frequency[1] | 52 | [Hz] | *(Resonant frequency)* |
| Open circuit voltage[1] | ± 20.9 | $[V_{peak}]$ | *(At rated deflection)* |
| Closed circuit current[1] | ± 57 | $[\mu A_{peak}/Hz]$ | *(At rated deflection / cycle)* |
| Rated output power[1] | 7.1 | $[mW_{rms}]$ | *(At rated deflection and frequency)* |

[1] *Cantilever mount. Force applied at the outermost tip of the mount.*

The bending generator is delivered as a "double quick mount" that allows easy fastening of the element as a cantilever (Figure 18 right side) to a power source, more information about the material and the energy harvesting kit can be found in Piezo Systems catalogue (Piezo Systems, Inc.). Priya writes that bimorphs can be easily mounted into several configurations, providing a high degree of adaptability to the available vibrations (Priya, 2007).

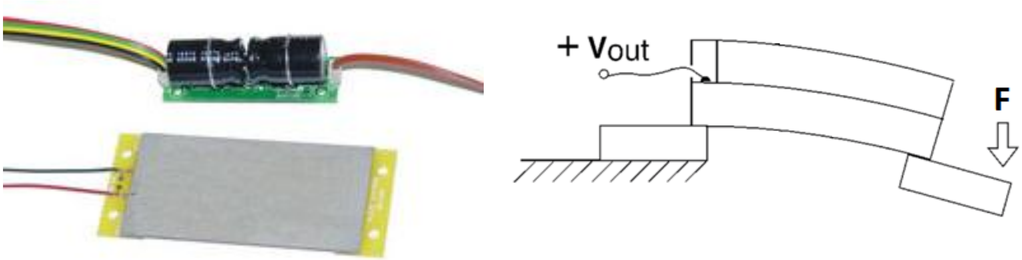



**Figure 18: Energy Harvesting Kit with a double quick mount from Piezo Systems Inc.**

As mentioned above, it is desired to have a material that harvests energy most effectively at low frequencies. The resonance frequency is determined by the composition of the ceramic material, the shape and volume of the element; generally, a thicker element has a lower resonance frequency than a thinner element of the same shape (APC International, Ltd, 2012). With that in mind the resonance frequency could be lowered by adding more layers of piezoelectric material. But within this project the frequency adjustments has to be made in other possible ways before considering to order more layers of the piezoelectric material.

### 3.4.3 Choice of light source

When the battery has been charged and the system is in a state where no charging is done (the car stands still), the system switches from a state of scavenging energy to depleting the energy source. The stored energy of the battery will mainly be used to power 14 light emitting diodes (LED), which are of type SWCA05 from Seoul Semiconductor (see Figure 19). VCC has chosen to operate these with a microcontroller from Microchip Technology Inc., type PIC16(L)F1507 (Microchip Technology Inc., 2012).

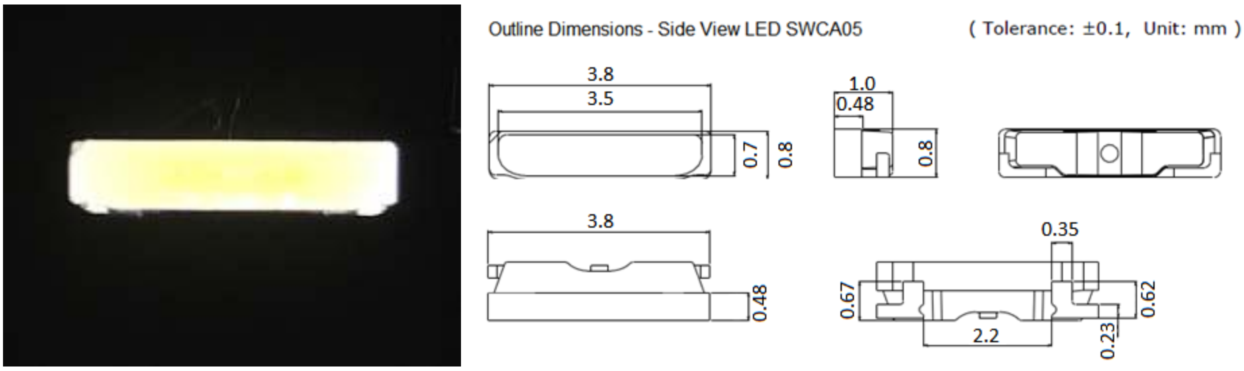



Figure 19: The side view LED used within the step-in-spline today

The diodes require 20 mA each to reach required illumination rates, which makes the system quite power demanding when compared to other ultra-low applications powered by piezoelectricity. The efficiency of the piezoelectricity is developed to the better at a rapid pace, but as long as the system is built up by components with high power demands it will be hard to implement energy harvesting systems within new applications. As Jia and Liu claims in their work *Human power-based energy harvesting strategies for mobile electronic devices* when comparing the past evolution of batteries and electronic technology;

> *"it is in the part of electronic consumption where there are most possibilities for closing the gap between generated energy and consumed energy"*
>
> Jia and Liu (2009, p. 42)

The development of a step-in-spline with (or simply a switch to) other LEDs would lower the power consumption by large, but it will have to be a task of further projects. Nevertheless an estimation of LEDs with a current of 5mA will be done when evaluating the system in a following chapter. This is done since the lower power demand from the LEDs is seen as a valid and required power saving assumption and by switching from the diodes presented here, to diodes that require less power the system can be made significantly less power demanding.

### 3.4.4 The battery

When choosing a battery the same principle applies as in the choosing of circuitry. The battery has to allow a simple electric circuit for testing, high enough efficiency for allowing it to store enough energy in a not too big container, with functionality that makes recharging possible with the piezoelectric output. Unfortunately it has been proven that direct charging of many battery types is pretty slow without a suitable controller, with the main reason being that the equivalent electrical resistance of a battery is much smaller than the optimal electrical resistance (Shu & Lien, 2006). Further, since the space available inside the step-in-spline is limited one should study and compare the energy density of the battery when developing the final solution. The energy density gives the amount of energy stored per unit volume (Wh/l) or per unit weight (Wh/kg); the higher it is the more energy one can store in a given space. In addition to that there are other important parameters to consider, such as; Cost, rechargeability, operating life by charge and discharge, the rate at which the cell can be charged/discharged and environmental impact.

Before choosing a battery to include in the circuitry, a pre-calculation of the energy storage need is approximated. To get a grip of the power consumption the required illuminating time was taken from the technical regulation for a sill moulding (Volvo Car Corporation, 2011), see Table 3.

**Table 3: Common use of the LEDs within the step-in-spline**

| 20 activations/day + 0,5 long-term activations/day + standby current consumption | |
|---|---|
| Activation | = Sill moulding shall be illuminated for 8 sec |
| Long-term activation | = Sill moulding shall be illuminated for 120 sec |
| Standby current consumption | = Shall correspond to leak current |

This specifies the illuminating time of the LEDs to 220 seconds per day. The following are estimations from datasheets, which were forwarded from VCC. The step-in-spline has 14[4] SWCA05 LEDs from Seoul Semiconductor that requires 20 mA each to reach required illumination rates (Seoul Semiconductor, 2012). Further a rough estimation of current need of the circuitry with an added microcontroller (Microchip Technology Inc., 2012) for diode operations is made and it reaches a need of 1 mA + ~0.2 mA standby. This gives a system current of ~280 mA, which in turn specifies the amount of mAh needed to fulfill the required illumination time just above 17 mAh[5] + standby. These calculations provide a result which tells that the system does not have the need of a large bulky battery if it can be charged at an acceptable rate.

The choosing of a battery is a science on its own; in many cases the battery must be matched with a proper power conditioner, much owing to the oscillating nature of piezoelectric energy harvesting with the resulting voltages and currents. In this project the power conditioner has been chosen to be a full wave rectifier, which comes at the cost of ohmic power losses and voltage drops. Further, overloading or overcharging the battery is destructive and decreases in many cases the battery's capacity; therefore the load has to be matched to the battery. The energy from the harvester, through the battery, and to the load needs to be matched to suppress the effects of voltage and current variations in both the harvester and the battery so they do not affect the load. (Rincón-Mora, 2009)

[4] Based on a CAD model of the step-in-spline for a V60 with illuminated sill moulding
[5] Required time [hours] * current [mA] gives the required level of charge in mAh

Lithium-ion (li-ion) batteries have only a few disadvantages, and are recommended for use in most of the literature. As it is discussed in *Materials for High-energy Density Batteries* by Manthiram (2009), li-ion batteries among the group that offers highest energy density when compared with other rechargeable battery systems known to date, as can be seen in Figure 20 (Woodbank Communications Ltd). Unfortunately the requirements of li-ion are more stringent in microsystems. Besides of requiring additional charge controllers or voltage regulators (Sodano et al., 2005) Rincón-Mora explains in his work on *Harvesting Microelectronic Circuits* the li-ion restrictions in microsystems as; *"light loading conditions are pervasive and any power losses associated with the circuit, irrespective of its magnitude, decreases operational life"*. As a result of these restrictions it seems to be wise to mimic the tests by Sodano et al. (2005) by choosing a nickel-metal hydride battery (Ni-MH), at least during initial testing to evaluate battery charging capabilities. The Ni-MH battery has a relatively high charge density and is claimed to not require additional charge controllers and charge controllers (unlike li-ion batteries). Further, an option of using supercapacitors has been evaluated, but due to their tendency of high rate self-discharging, being an energy source that provides short but high power output and not being able to store as much energy as batteries (Halper & Ellenbogen, 2006) it does only fit as an option when estimating power output and validating a piezoelectric solution, but it would not fit as an energy storage system within the final piezoelectric step-in-spline. As a final recommendation within the choice of energy storage system for a piezoelectric solution it would be wise to keep an eye on the ongoing parallel development of piezoelectricity where a new group of batteries are developed. Thin film batteries seem to be a promising energy storing solution to pair together with piezoelectricity; they are already being tested with full integration with energy harvesting devices. (Dudney, 2009)

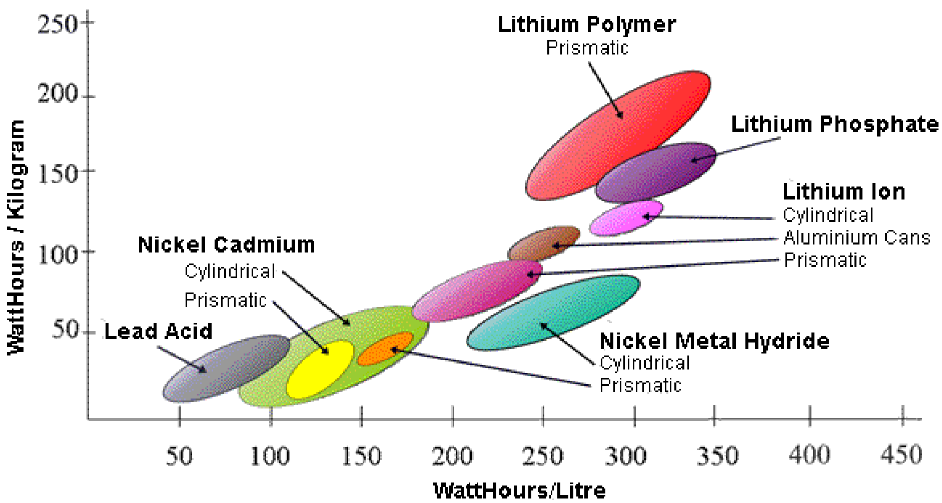



**Figure 20: Relative energy density of some common secondary cell chemistries (from Woodbank Communications Ltd.)**

# 4 Evaluation of the system

The aim of this chapter is to evaluate the level of required output from the system, and to find a way to approximate a possible output.

## 4.1 Charging time to fulfill illumination requirement

If the LEDs that are specified by VCC for use within today's step-in-spline solution are to be used in a piezoelectric solution, then the 17 mAh required to fulfill the illumination time (see 3.4.4) has a charging time that is dependent on the outer forces affecting the system, the power output of the piezo element and the complex electric dependencies within the circuitry. Unfortunately these factors cannot be specified at this time; therefore simpler estimations are made using different piezoelectric efficiency rates and estimates. Below is a description of factors that affects the charging time, these factors are thereafter summarized in Table 4 and Table 5.

To begin, the approximation uses the maximum output energy given for the piezoelectric material chosen for the prototype (presented earlier in this chapter) as a starting-point. The maximum rated frequency occurs at 52 Hz with an output of 57 $\mu A_{peak}$ / Hz. It is rated as output (ampere) per peak and since each hertz (wave) contains two peaks the maximum provided output current could reach a level of 5.928 mA; this is the absolute maximum current-output that can be achieved at any point. This maximum output relies on simulated conditions, e.g. an acceleration that swings the element both up and down at its maximum rated frequency of 52 Hz in order for it to reach its rated tip deflection of ±2.6 mm. If this optimal operation mode could be maintained, no losses would occur and the battery charging voltage would be fulfilled, then the battery would be charged to a level of 17 mAh in under 3 hours. But then again, the optimal mode can only be simulated and is thereby a case that never could be achieved during normal conditions. Thereby an evaluation of the charge time has been done by varying the output. The charge-outputs presented in Table 4 are (1) the maximum output of 5.928 mA, (2) 50 % of the maximum output and (3) 25 % of the maximum output.

Together Table 4 and Table 5 presents a variety of different charge scenarios, the variables that influence the result of different charge times are; (1) the charge-rate/output current, (2) the required level of charge due to 20 mA or 5 mA diodes and (3) the number of piezoelectric plates within the step-in-spline. In these predictions the battery charging voltage is considered fulfilled.

**Table 4: A theoretical analysis of charge times to fulfill required illumination time with a PSI-5A4E plate**

| No. of plates | Output current [mA] | % of max. | Required charge level [mAh] | Charge time |
|---|---|---|---|---|
| 1 | 1.482 | 25 | 17 | 11h 29m |
| 1 | 2.964 | 50 | 17 | 5h 44m |
| 1 | 5.928 | 100 | 17 | 2h 52m |
| 1 | 1.482 | 25 | 4.25 | 2h 52m |
| 1 | 2.964 | 50 | 4.25 | 1h 26m |
| 1 | 5.928 | 100 | 4.25 | 43m |

A way of increasing the power output is to have more piezoelectric elements inside the step-in-spline. If the amount of power generated can be multiplied by the amount of piezoelectric elements inside the step-in-spline, four piezoelectric plates would shorten the charge time by a factor of 4. The required charge time could then be even further lowered by the already mentioned switch from 20 mA to 5 mA diodes.

**Table 5: A theoretical analysis of charge times to fulfill required illumination time with 4 PSI-5A4E plates**

| No. of plates[6] | Output current [mA] | % of max. | Required charge level [mAh] | Charge time |
|---|---|---|---|---|
| 4 | 5.928 | 25 | 17 | 2h 52m |
| 4 | 11.856 | 50 | 17 | 1h 26m |
| 4 | 23.712 | 100 | 17 | 43m |
| 4 | 5.928 | 25 | 4.25 | 43m |
| 4 | 11.856 | 50 | 4.25 | 21.5m |
| 4 | 23.712 | 100 | 4.25 | 10m |

If these charge-rates could be accomplished and combined with the current development of piezoelectricity that could lead to even shorter charge times due to higher efficiency, then a piezo powered solution that fulfills the requirements could be within reach. It has to be kept in mind before experimental results has been made that many of these estimates could be hard, if not impossible, to achieve with ambient vibrations within the step-in-spline.

Three main issues can be seen directly; (1) the natural/fundamental frequency of the chassis during driving is probably lower than 52 Hz with only sporadic bumps that gives the piezo element a chance to operate at its resonance frequency for shorter times, (2) even if the element could be placed in such a way that it could reach those frequencies more often the scavengeable power decreases drastically already when the frequency deviation is more than 5 % from the resonant frequency (Shu Y.-C. ,2009 & Midé Inc.) and (3) these approximations does not pay interest to circuitry losses or realistic charge efficiencies. The charging efficiency of Ni-MH that is closer to 66 % of the theoretical maximum charging rate (Lund) and considering that li-ion batteries needs additional charging regulators to allow charging a similar charging efficiency is considered for such a systems even though the charge efficiency in high current states are higher than the ones of Ni-MH.  Further the batteries does not follow a linear charging efficiency rate, this should be considered when developing a prototype with a Ni-MH battery, since most experiments of charging Ni-MH batteries with piezoelectrics define a full charge as 90 % of the maximum capacity. The remaining 10 % requires long charging time and is in many cases even impossible to achieve with the low current available from piezoelectric energy harvesting. (Sodano et al., 2005) Thereby, if an energy storing buffer of 100 mAh is preferred, a Ni-MH battery of 110 mAh should be implemented in the system.

[6] The resistance of the system rises when adding piezoelectric elements due to more wires and electronics. In these estimations the losses are ignored and a linear relationship has been assumed.

## 4.2 Dimension constraints

Since the initial and main goal of implementing a piezoelectric energy harvesting system is to have the product as a closed self-powering system with easy after assembly mounting, the step-in-splines capabilities of containing a built in energy harvesting system is analyzed with the dimension constraints limiting the boundaries being in focus.

### 4.2.1 Area constraints

The most obvious question related to the dimension constraints is directly related to the power output, the more piezo elements one can fit inside the step-in-spline the more power the system can generate. The available length and width (area) define how many plates one can fit into the system; Figure 21 shows the area that could be used for piezoelectricity if the circuitry would be kept as it is today.

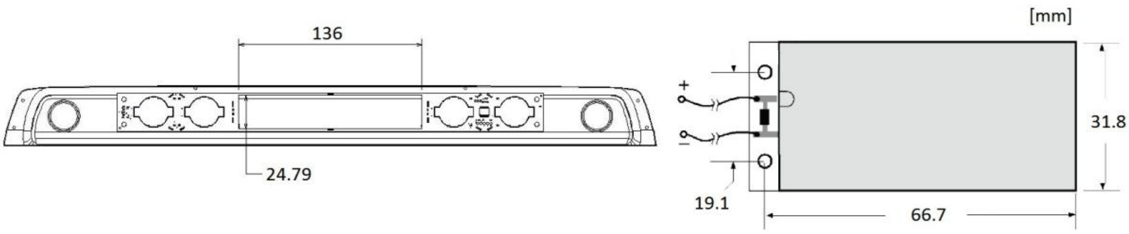



**Figure 21: The available space for piezo plates within the unmodified step-in-spline (left), and 503-standard piezo-plate dimensions from Piezo Systems Inc. (right)**

In order to visually evaluate and confirm the implementation of piezoelectric plates with appropriate circuitry within the step-in-spline a model has been created, the model is a modified representation of the circuitry within a step-in-spline belonging to a Volvo V60 (Volvo Car Corporation, 2012). The goal is to visualize a piezoelectric solution within the step-in-spline with, allowing no changes that would affect the outer boundaries. The original electric circuitry has been used as a guideline of the piezoelectric circuitry, and thereby the piezoelectric plates in the model have been made slimmer than the standard sized piezoelectric plates found at Piezo Systems Inc., further the model does not include a capacitor or an eventual inductor since these are yet to be selected.

The unaltered circuitry can be seen to the left in Figure 21 and at the top in Figure 22 when compared to modified circuitry solutions. In Figure 22 the electric circuitry has been modified in two different approaches. As mentioned, the electric circuit at the top represents the solution that is used with batteries today (with no modifications made to it); in its current shape it could carry two slightly modified 503-standard size piezoelectric plates. The circuitry in the middle represents a slightly modified solution; where the four li-ion batteries have been stripped away and replaced by one rechargeable battery and four full bridge rectifiers, while leaving all other electric components unmodified and at same locations. In comparison to the solution of today, it could pack three bigger piezoelectric plates and a smaller one. The idea of having different sizes of piezoelectric plates opens up the possibility to tune the energy harvesting to a wider frequency domain since the plates naturally has different resonance frequencies (where the plate vibrates most readily and should give the highest energy output).

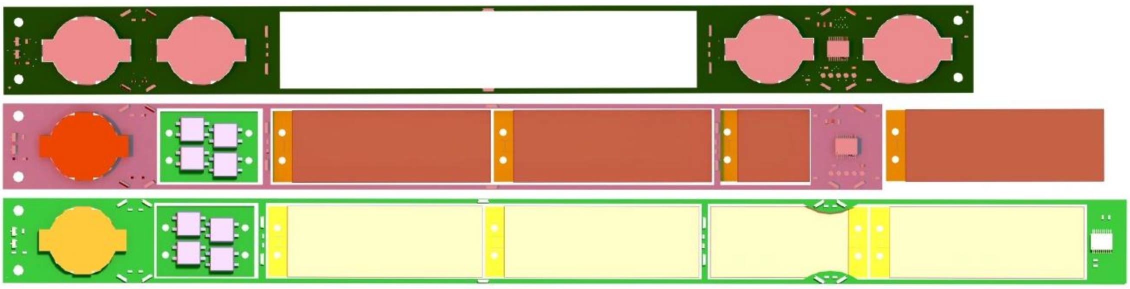


**Figure 22: Electric circuitry of today (top) compared to a slightly modified piezoelectric solution (middle) and a longer circuitry proposition that can contain four big piezo-plates (bottom).**

The last electric circuitry presented in Figure 22 packs four big piezo plates, the four full bridge rectifiers and the rechargeable battery. The difference to the previous solutions is that this solution has bigger modifications made to the circuitry plate, in order to keep the LEDs at the same positions while having the possibility to have four big piezo plates the electric controller had to be moved to a location where it was not blocking the piezo plates. Still the electric circuitry would fit within the step-in-spline (with a margin of 3.77 mm in length direction), as can be seen in Figure 23 when comparing it to the unmodified circuitry placed within the step-in-spline. The width of the circuitries is unmodified in these alternative solutions.

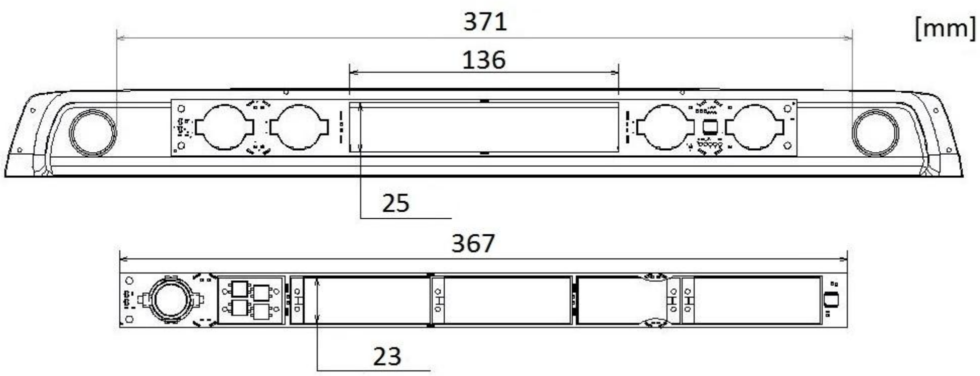



**Figure 23: A modified circuitry compared to the unaltered circuitry within the step-in-spline**

The piezoelectric plates can be purchased in dimensions that comply with the step-in-spline, but in order to have a prototype ready for testing as fast as possible a standard plate size was ordered for testing. Further, special interest has been given to keep the LEDs at the same locations in every modification model in order to keep the same illumination scheme.

### 4.2.2 Height constraints

The second dimension constraint problem is related to the small amount of space available in height dimension within the step-in-spline. As one can see in Figure 24 the available height is between 3,9 and 4,5 mm, luckily the piezoelectric plates are thin, and the piezoelectric plates that are of ceramic nature (PZT) only requires small deflections in order to generate electricity.

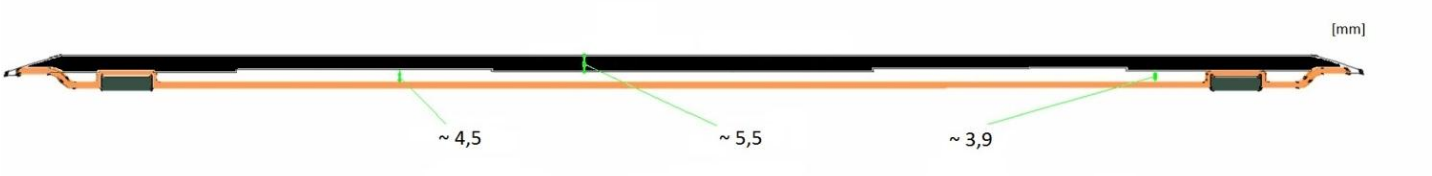
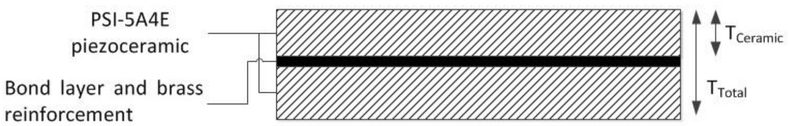



**Figure 24: Cross section that displays the available space in height within the step-in-spline**

The piezoelectric plate generates energy when it is presented to a force that bends it; therefore the tip deflection needs to be accounted for when considering the available space in height. For the PZT material of standard 503-size and brass reinforcement from Piezo Systems the max rated tip deflection is ± 2.6 $mm_{peak}$, which would require 5.2 mm of free operating height for the piezo element. The mounting and material height would add between 0.38–0.86 mm to the needed space of tip deflection.




| TTOTAL mm | TCERAMIC mm |
|---|---|
| 0.38 | 0.13 |
| 0.39 | 0.19 |
| 0.48 | 0.19 |
| 0.51 | 0.19 |
| 0.58 | 0.19 |
| 0.66 | 0.27 |
| 0.86 | 0.27 |

**Figure 25: Height information of the piezo material chosen for the prototype**

The whole range of tip-deflection does not fit within the given space, but it is close enough to be believed as a problem that can be solved with relatively easy means (change of material or design changes of the step-in-spline). However, since the energy harvesting circuitry requires a capacitor being part of the circuitry the height dimension is once again reviewed. The range of the capacitor size vary; the tests using small capacitor seizes, varying between 47 nF to 1 µF, has been used in combination with microcontrollers, step-down converters or has switched the battery to a supercapacitor as the energy storing bank (Ottman et al., 2003) (Cossio, 2008) (Jiang et al., 2010). But when it comes to testing of battery-charging within specific applications, the test circuits have usually had a capacitor size of at least 1000 µF or larger (Sodano et al., 2005). The energy harvesting circuit provided by Piezo Systems Inc. has a built in capacitor that is not specified in the product specifications and probably has to be expanded manually later (see left side Figure 18). If a mockup prototype would be manufactured, the height constraint limits the choice of capacitor, considering a capacitor larger than 1000 µF is requested and it should fit within the height constraint of 4,5 mm.

## 4.3 Calculations

Calculations for piezoelectric systems and materials are in a grey-zone, where attempts of agreeing upon standardized equations for comparing piezo-systems efficiency just recently has been in the spotlight within the area (Center for Energy Harvesting Materials and Systems). During the last five years many different models of energy harvesting systems have been developed, where some are heavily simplified and when the different approaches gives different end-results with the same input variables it is hard to make a trustworthy estimation without conducting own experiments. Another hinder for estimating piezoelectric solutions applicability within a given function is the end results high dependency of the circuitry; thereby it is hard to make simple tests to see if piezoelectricity is a feasible solution without building a prototype. Building a prototype that will operate within an area that has no plug-and-play solutions to test is comparable of doing research within the area, which in turn requires knowledge within vibration mechanics, constitutive behavior of piezoelectric materials and electrical circuitry theory. In order to get some estimates before building a prototype, some estimations of the work done bending a beam has been made, which hopefully could be converted to possible power output.

## 4.4 Power output estimation

The first step of estimating a possible power output will be achieved by combining beam bending calculations and product data sheets. By using known theory of beam bending on cantilevers the intention is to get an insight of the amount of work done by bending a piezoelectric plate, this energy should be the maximum available energy that can be converted between mechanical and electrical energy. When a beam (in this case a piezo element, see Figure 26) with a mass placed at the tip is subject to vibrations that originates from the base the mass is exposed to acceleration (Newton's third law). The acceleration and mass produces a force that with a moment bends the piezoelectric "beam", which in turn is used in an equation of equilibrium. The work done when bending the element provides the opportunity to do an estimation of power output by multiplying it with piezoelectric systems conversion efficiency.

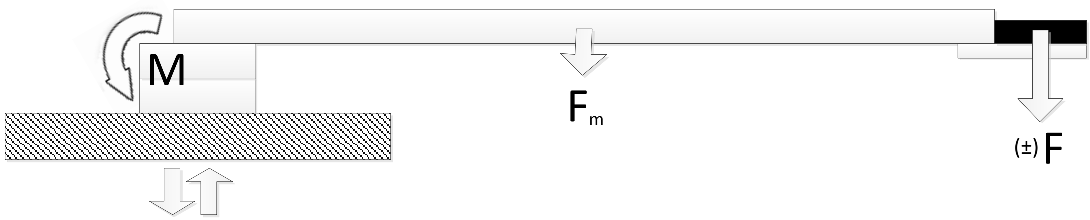



**Figure 26: The cantilever mount of the piezoelectric material 5A4E with its affecting forces illustrated**

The work done when bending the prototype material (5A4E) with given properties, with a varying tip mass (1-20 g) is given in Figure 27 (next page). The issue in these estimations is that the work affecting the beam bends both the piezoelectric material 5A4E and its reinforcing brass layer, in these estimates only the mass from the piezoelectric material is considered to generate work that can be converted and thereby the mass of the brass layer is neglected. Furthermore, Piezo Systems Inc. suggest that the values are to be seen as guidelines since the material properties vary in production and thereby the final power output has to be pinpointed experimentally for the actual work piece. The affecting forces on the cantilever are illustrated in Figure 26. Figure 27 only displays tip mass weights up to 20 g, since at a certain weight limit the fatigue life of the piezoelectric material begins to shorten.

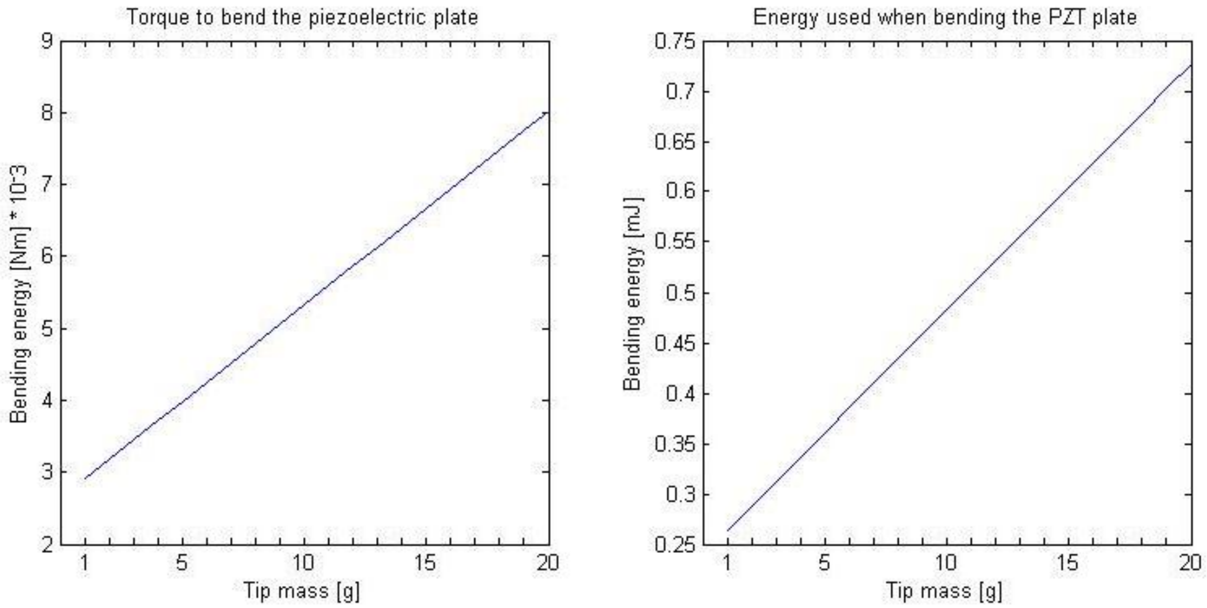



**Figure 27: Beam bending energy with varying tip mass**

If the maximum energy that can be harvested per bending of the plate lies between ~0,3-,7 mJ, and this could be achieved at the max rated frequency of 52 Hz. Then the work done bending the plate lies between 15,6 to 37,44 mW. The maximum specified rated output power is given to 7.1 mW at rated deflection and frequency (found in Table 2: Material specification for piezoelectric material 5A4E from Piezo Systems, Inc.) and hints about a relatively high conversion efficiency. The task is to see how close this figure one could get with the ambient vibrations within a car. Unfortunately there are quite a few losses that have to be accounted for, such as; energy loss bending the brass layer, energy that is dissipated back to the system, energy that is converted to heat, energy that is lost in the circuitry, standby current and internal battery losses. The rest of the energy should be available for storage in the battery; that is, if the output current and voltage are within the charging requirements of the battery. But as long as the charge activity and a current flow can be measured in the testing phase the result could be used to extrapolate the number of elements needed to fulfill the requirements of the illuminated step-in-spline in a given time. The time frame for assuring the knowledge needed to complete reliable calculations is outside the scope of this project, which also implies that the calculations that have been made so far have not been verified and are thereby only a starting point for further development of theoretical work in the area of piezoelectric solutions. That is also the reason not to present them as results within the report, instead they can be found within the appendix for assistance in further studies.

## 4.5 Establishing a product specification

The product specification will be a modified specification from VCCs technical regulation for a sill moulding (for car model S60 and V60), where the most important differences, constraints and similarities will be brought up for inspection. An added part for piezoelectric requirements is added to enlighten the differences in the product functionality with advanced electric circuitry inside the casing. The requirements have been modified throughout the project and will continue to change as long as the project is active. One of the first decisions made due to the specifications was taken as soon as knowledge about the piezoelectric capabilities grew; if the step-in-spline with lights is to be a self-containing unit without affecting the step-in-splines capabilities to shield its electronics from outside elements, then modifications of the outer casing are outside the project scope. Thereby an open system solution (described in earlier chapters) is undesirable not only due to higher complexity, but also due to casing restrictions. Further, the product specification with its requirements is a guideline for the development of a piezoelectric solution, and if a prototype is to be built, the goal of its existence will not be to provide answers to most of the requirements stated in this project, and certainly not the requirements VCC has for its sill moulding.

### 4.5.1 Piezo-related requirements from the technical regulation of the sill moulding

The goal is to retain as much as possible of the current step-in-splines shape, with the same materials and design of the outer case. By doing so time can be saved in some areas; Chemical resistance and moisture resistance in tropical cabinet provides the possibility of relying on that the inner electronics will be protected from outer elements such as; moisture, dust, water and dirt. As an example the technical regulation for an illuminated sill moulding for S60/V60 says that: “The unit shall be designed so that moisture will not be in contact with non-insulated current carriers such as soldering areas” (Volvo Car Corporation, 2011). For elements like temperature, stress and impact resistance tests should be made when a prototype fitted inside a mockup is constructed. Further, within the technical regulation sheet for the step-in-spline one can find a vast variety of requisites and requirements. Within this project only the ones with high association will be discussed.

When developing the piezoelectric step-in-spline some of VCCs requirements have to be considered, even though many will remain unaltered due to same outer casing. Changes made to the step-in-spline are especially not allowed to alter the occupant safety, side impact or interior safety factors. Further, VCC has stated that the product shall follow the interior light dimming process. The test method for the LEDs of today will have to be seen through, because today the LEDs are put through a test where they are supposed to be lit up 12 ± 2 times/min during a period of 60 minutes. There is a conjectural probability that the battery chosen for the purpose will lack the power of illuminating the LEDs for the amount of time it takes to accomplish the test. As a suggestion the test should be split up in two parts, where the LEDs and piezoelectric functionality will be tested separately.

# 5 Concept realization

The concept within this project is a proof-of-principle prototype, with the intention to assist when deciding if a piezoelectric solution should be further developed or not. The first step was to put together the components for some pre-testing in order to verify if an output could be achieved through ambient vibrations within the step-in-spline.

## 5.1 Generating a piezo powered concept

In order to begin tests to verify the potential of having piezoelectricity as the energy source within the step-in-spline the energy harvesting kit from Piezo Systems Inc. (described in chapter: Prototype material) was ordered and prepared for testing. The energy harvesting circuit surprisingly came with a relatively large energy storage bank in form of two 3300 µF capacitors. These capacitors and output measurements with a multimeter might suffice for enough testing to estimate the potential of PZT as a conversion material when trying to power a few LEDs from VCC. From these tests a decision can be made on how to proceed with the testing, or if more testing is required.

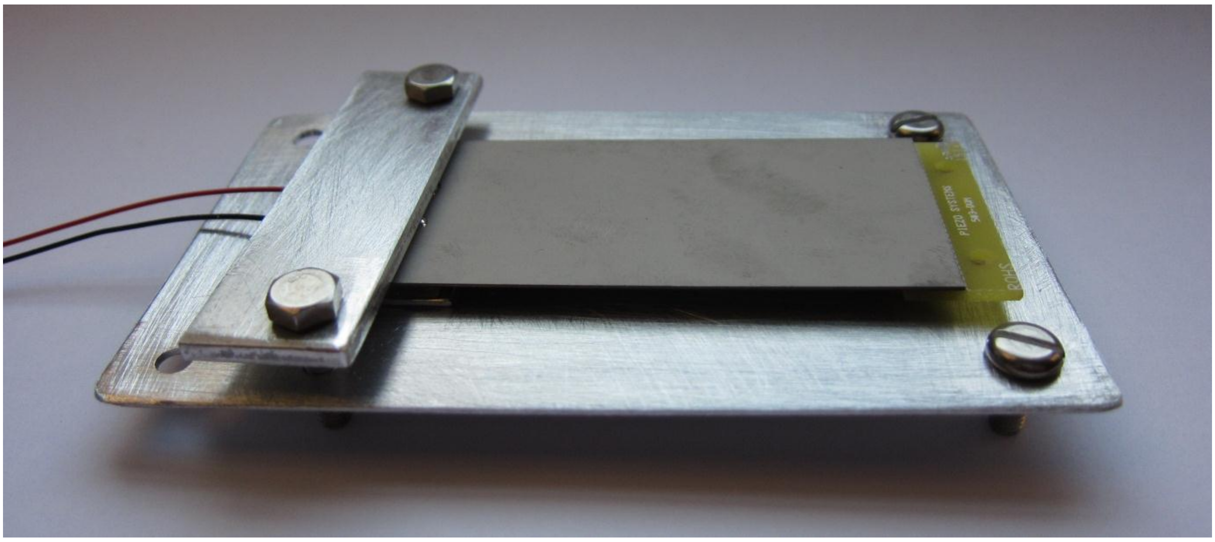


**Figure 28: The PZT plate with a mount that enables testing by fastening points and also protects the plate from too large tip deflections**

Since the PZT material is fragile a protecting test bench was put together, the test bench prevents the PZT plate from extreme bending amplitudes during tests. The high amplitudes might occur if the PZT plate is loaded too heavily when trying to achieve a low resonance frequency, which in turn could result in a crack and put an end to the testing. The test-bench can be seen in Figure 28, where the fastening point of the piezo element easily can be raised in order to allow larger tip deflections.

## 5.2 Preparations for the test

The test system in Figure 29 Figure 1 consists of the PZT plate mounted to its protecting test bench, the plate was connected to the energy storage bank, which in turn was connected to a piece of a circuit board with four outputs; (1) ground, (2) LED and resistor in series (resistor of 130 Ω to lower voltage over the LED), (3) a switch to control the output signal and (4) a pin to monitor the capacitor charging process. The system was measured with a multimeter, which in Figure 29 is connected to ground and the capacitor charging pin. The system was tested during eight short measurements, initially on a tumbler drier and thereafter within a Volvo V70 (year model 2007) where it was clamped together with the rail on which the seat is connected. The rail is fixed together with the chassis and thereby the vibrations are considered to be of same magnitude and frequency here as within the step-in-spline.

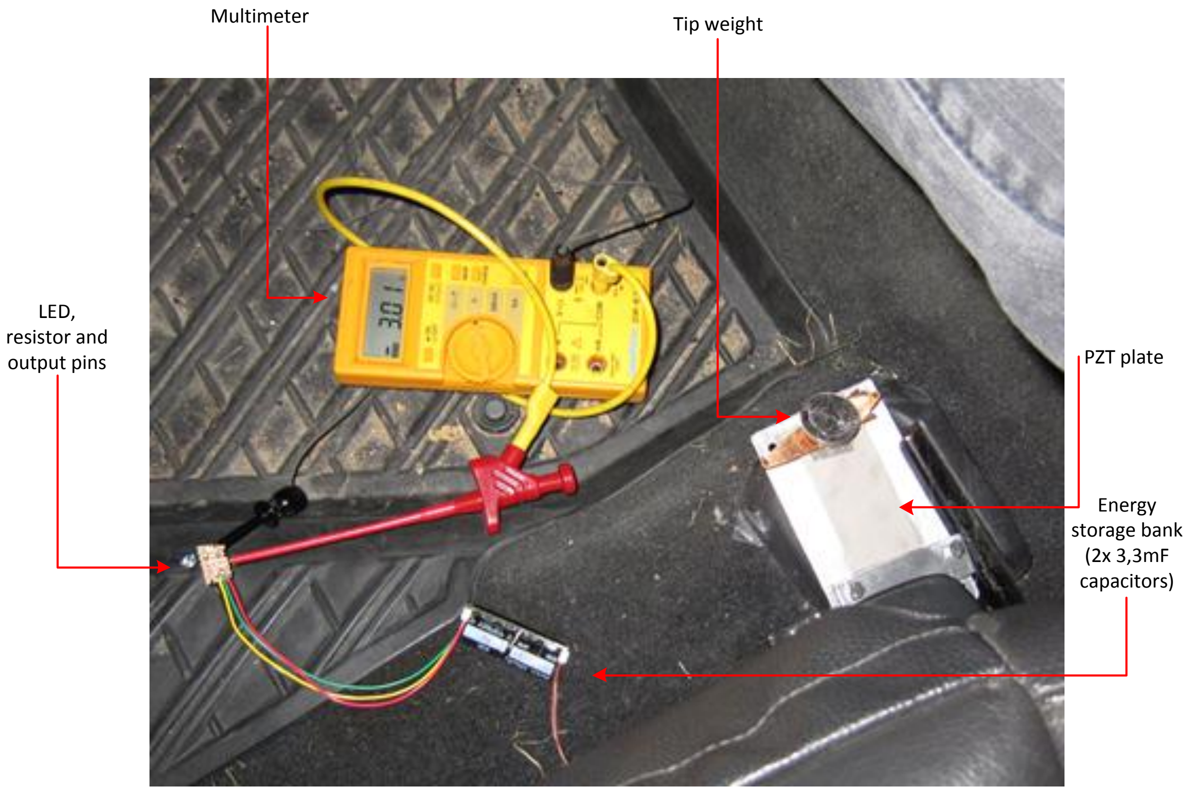



**Figure 29: Initial test system**

The tests did not give any output even though the vibrations were heavy (especially the ones when clamped to the tumbler drier). When testing the system within the Volvo V70 the tip weight was slowly increased until charging activity could be measured. As one can see in Table 6 the piezoelectric plate did not charge the capacitors until a substantial weight was added to the tip.

**Table 6: Initial testing of the piezoelectric plate**

| Test | Duration | Tip weight | Capacitor voltage charge | | Vibration source |
|---|---|---|---|---|---|
| **#** | **[min]** | **[g]** | **[V]** | **[V/h]** | |
| 1 | 5 | 0 | 0 | - | Tumbler drier |
| 2 | 5 | 3 | 0 | - | Tumbler drier |
| 3 | 5 | 10 | 0 | - | Tumbler drier |
| 4 | 12 | 10 | 0 | - | Volvo V70 |
| 5 | 9 | 0 | 0 | - | Volvo V70 |
| 6 | 8 | 10 | 0 | - | Volvo V70 |
| 7 | 4 | 18 | 0 | - | Volvo V70 |
| 8 | 15 | 24 | 0.03 | 0.12 | Volvo V70 |

These initial tests (especially the latter ones having the Volvo V70 as vibration source) show that a weight should be added to the tip when testing the system. The weight lowers the resonance frequency/eigenfrequency and allows the piezoelectric plate to operate in the resonance frequency more often, and thereby allowing a higher output. The system will be tested on a test track, which allows enhancement of the vibrations and thereby the full capabilities of the energy harvester will be revealed. The test track tests will not be directly convertible to normal driving and if a higher charge output is achieved then maybe more optimizations and testing will be recommended in order to raise the efficiency when driving on regular road. But due to time-limitations a test track simulation will have to suffice within this project.

Since the time on the test track is limited and each test takes its time to complete a measurement form was put together. In these test forms the tip-weights was predefined to 21–26–30 grams. These weights were chosen in accordance to the pre-tests and can shortly be described by; it was desirable to see if a firmer mounting of the piezoelectric element could allow charge at a lower weight (21 g), and to see if a similar weight (26 g) would give a greater output and to see if a larger weight (30 g) would give an even greater output.

### 5.2.1 Discharge rate of capacitors and the weight adding system

An important note considering the initial tests is that those tests did not pay attention to the self-discharge of the capacitors. The charging of the energy bank was slow and thereby the discharge rate should have been evaluated in order to have a way of calculating the total charge-rate of the system. The discharge rate of the capacitors was measured at different occasions, level of charge and varying conditions, where the actual level of charge when beginning the test was of greatest importance. Thereby the level of charge when starting the vibration tests should be the same for every single test in order to allow an easy way of adding the discharged power to the total charging sum. This is done since the self-discharge would not be a problem if a battery with low discharge rate would have been implemented in the test system, which is recommended if further development would take place.

The measurements of the capacitor discharge for the system can be seen summarized in Figure 30. As the table reveals the discharge rate loses its linear discharge rate when charged above 1.2 volts. The discharge rate was smaller in the pre-tests; the higher leak is the result of a malfunctioning logical circuit, which unfortunately broke one day before the test track was booked for tests which made the discharge rate measurements even more important. Parts for a new circuitry were not an option due to the short time left to the tests, thereby the current leak was measured at different charge levels.

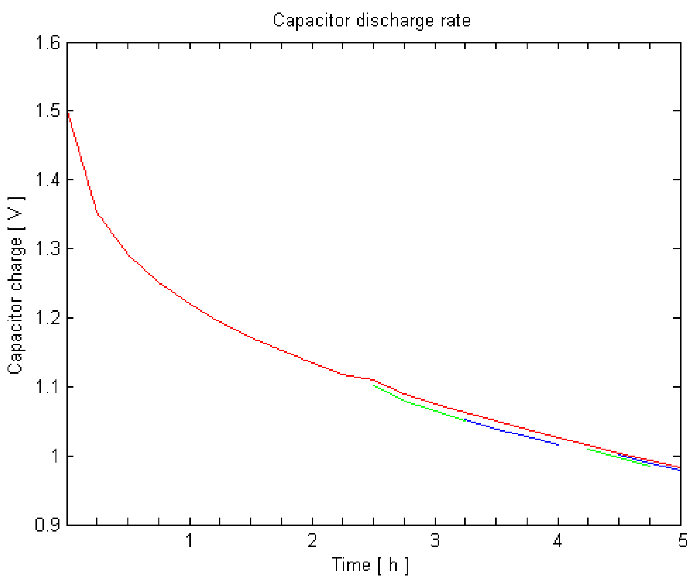



**Figure 30: Discharge rate of the capacitors after the logical circuit malfunctioned (a plot with larger time frame can be found in the appendix)**

Fortunately the relation of the discharge and time became linear enough when dropping below 1.1 volts, and thereby the tests should be started as low as possible. As one can see in Figure 30 the linear relation below 1.1 was tested several times and can be seen as blue and green line plots. Another problem was that the logical circuit made it ineffective and time consuming of discharging under 0.63 volts, which gives a stable charge window between 0.63 and 1.1 volts when measuring the charging during the tests. From the discharge measurements one can calculate that if the tests are carried out within the given charge frame and each test had a maximum time-limit of 15 minutes, then a charge drop of maximum 0,012 volts would occur.

When the higher discharge rate due to the malfunctioning logical circuit could be managed, a weight adding system that allowed easy adding and removing of weights had to be put together. Due to the time loss of troubleshooting the malfunctioning logical circuit the weight system was chosen to be composed of simple standard components, more specifically nuts and screws. The piezoelectric plate has an energy conversion frequency high above the frequencies found within the step-in-spline. A way of lowering the energy conversion frequency is to add weights to the tip, and due to the aim of harvesting energy from low frequencies in this project a permanent fastening system weighing in on 6 g on its own was considered acceptable.

Three nuts of different sizes were glued to the clamping area at the tip of the piezoelectric plate (total weight 6 g). To these nuts one could add screws and nuts in order to fine tune the tip-weight; in Figure 31 the tip-weight is 34.47 g which shows that there is additional room for testing with weights that probably would exceed the tolerated limit of a breakage.

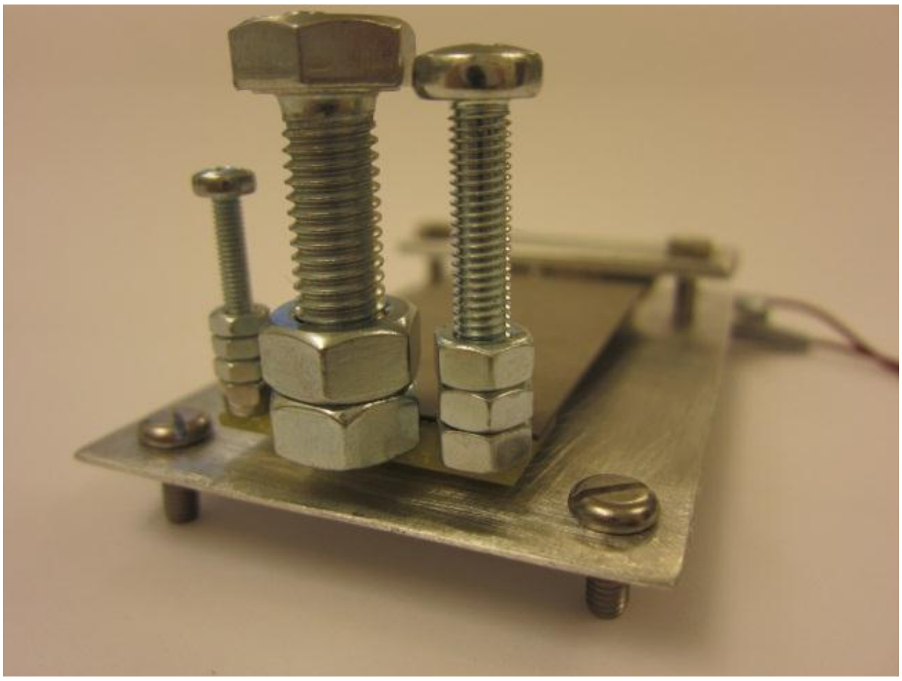


**Figure 31: The weight system, current weight 34.47 g**

## 5.3 Piezoelectric solution test

The test was carried out on VCCs test track at Volvo Torslanda TLA. The piezoelectric test-system was clamped to the seat rail fixture as before, now using cable ties and duct tape to avoid damping due to loose fastening which could have been an issue in the pre-tests. The test track consisted of 10 different surface materials, as seen in Figure 32, where the hope was to achieve faster charging than on regular country road asphalt and thereby see if the charging rate was of a magnitude that could give power to the step-in-spline lights.

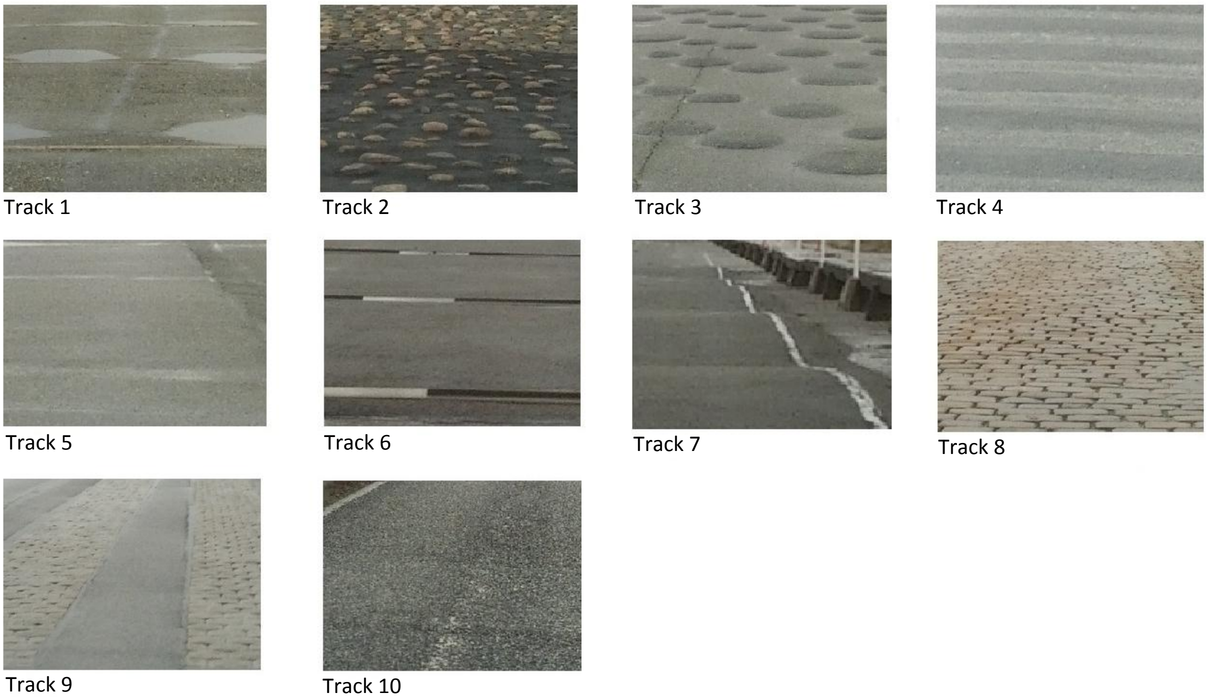



**Figure 32: The different surfaces of the test track**

When the discharge of the energy bank occurred at 5.2V it released 55 mJ of energy during the drop to 3.1 V (see Appendix III: Energy Harvesting Kit specification sheet). When having a 20 mA diode in the circuitry the diode was powered for 1,09 seconds. This drop of 2.1 volts and the given ampere gives an energy release of 26,19 mJ / V. Further, knowing that the circuitry discharge is a direct current (DC) and that the circuit is purely resistive the needed relationship was achieved to give the charge rate in amount of energy and effect in the following tables.

The results presented within this and the next chapters are derived from the measurement charts that can be found within the appendix.

The test track was driven seven times, where four of the laps where driven through all of the different surfaces and three laps when avoiding the vibration enhancing surfaces (trying to simulate regular country-road driving). If only paying attention to the different surfaces at first, the highest output was obtained on track 2, 4 and 8. One could assume that all highest charging rates would apply to the same tip-weight, but surprisingly all top four outputs had different tip weights (see Table 7).

**Table 7:** Highest effect by track and weight

| Track no. | Tip weight [g] | Effect [µW] |
|---|---|---|
| 4 | 30 | 412,5 |
| 4 | 26 | 406,4 |
| 2 | 26 | 385,0 |
| 8 | 21 | 323,0 |

These results strengthen the assumption of that an effective energy harvester needs to be able to work over a broad frequency range to be able to take advantage of many different operating conditions. In order to optimize the power output one would have to analyze the relationship between tip weight (resonance frequency) and the actual frequency when driving on a specific track, which lies outside the scope of this project. Further, it is not only the highest output when driving a specific track that is interesting; the highest mean charging rate shows which of the weights works best over a variety of frequencies. The output mean by weight can be seen in Table 8.

**Table 8: Mean output by weight**

| Tip weight [g] | Effect [µW] |
|---|---|
| 26 | 162,6 |
| 30 | 130,1 |
| 21 | 115,5 |

The charging mean was highest when having 26 grams of weight on the tip, which is less than half of the fastest charging rate of the weight. Having the highest charging mean at 26 g shows that a maximum should occur when having a tip weight somewhere between 21 to 30 g, such optimizations has to be left for further development efforts. Unfortunately the mean charging rate cannot be directly converted to normal country road driving where the vibrations are of a different nature.

Test 5 to 7 has more relevance when compared to normal driving conditions, the results achieved here are far more optimistic than the pre-testing results obtained within a Volvo V70 (the reason could be connected to a wide range of factors). The results gained from driving the test track on regular asphalt are presented in Table 9.

**Table 9: Test drive - simulated country road driving**

| Speed [km/h] | Weight [g] | Output [μW] |
|---|---|---|
| 90 | 26 | 41,8 |
| 90 | 30 | 38,8 |
| 90 | 21 | 35,6 |
| 40 | 21 | 15,4 |

The average speed when driving around the test track (in simulated normal conditions) was around 90 km/h, which can be compared to a later test where the average speed was 40 km/h with a tip-weight of 21 grams, where stops and starts were part of the driving session. In the latter test the average output dropped to 15,4 μW, which is below half of the charging rate achieved when driving 90 km/h which shows that the vibrations gets more scavengeable when driving at higher speeds. The result drawn from this test is that the charging rate is related to the speed and finding an optimal tip weight (if the size of the plate is fixed). Other than that it is interesting to see that rugged asphalt (track 10) did not improve the charging rate when compared to normal asphalt; the highest charging rate achieved on rugged asphalt was 39 μW with a tip weight of 30 grams, compared to the charging rates of normal country road asphalt as presented in Table 9.

# 6 Results

In order to convert the test results from the experiments to evaluate the possible performance of a piezoelectrically illuminated step-in-spline the test drive results were combined with the illumination time from the pre-tests. Combining these two gave the opportunity of extrapolating an end result that shows an approximation of drive time needed to fulfill the required illumination time.

As already stated before; when the discharge of the energy bank occurred at 5.2V it released 55 mJ of energy during the drop to 3.1 V (see Appendix III: Energy Harvesting Kit specification sheet). When having a 20 mA diode in the circuitry the diode was powered for 1,09 seconds. This drop of 2.1 volts at the given ampere gives an energy release of 26,19 mJ/V. Further, knowing that the circuitry discharge is a direct current (DC) and that the circuit is purely resistive the needed relationship was achieved to give the charge rate in amount of energy and effect in the following tables. The circuitry is built up by a standard 20 mA (red) diode and a resistor of 130 Ω as seen in Figure 33). This gives a relationship between charge and time for this specific circuitry; to illuminate the diode for 1 second with the given energy bank and circuitry requires an energy level of 50,46 mJ.

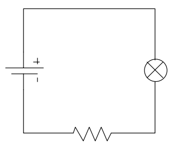


**Figure 33: The circuitry used to get a relationship between charge and illumination time**

The relationship can be used to approximate how much time it would require under different output rates to illuminate a varying number of diodes for the required illumination time of 220 seconds per day (see 3.4.4 for illumination time requirements). The calculated result ignores the fact that the charging of a capacitor is non-linear and depends on the charge level; neither do later approximations consider the increased resistance when adding diodes. Thereby an increased level of uncertainty needs to be accounted for when evaluating the performance of a complete solution based on the results presented here. The calculations are made to get an evaluation of how long it would take to charge an arbitrary energy storage medium with the charge rates the tests provided.

At first the required charge time is evaluated, the charge time is calculated for illumination of one single diode (20 mA) for 220 seconds with only one piezoelectric plate. As predicted the charge times are long and nowhere near the region of a result that encourages implementation within a commercial vehicle in its current state. Table 10 summarizes the required charge times for different driving conditions. These results can be compared to the estimations made in chapter 4.1 (Charging time to fulfill illumination requirement) that shows the required charging times to reach a required charge-level that would fulfill the illumination time (see Table 11). The theoretical charge times depends on three output efficiencies (100%, 50% and 25%) and number of diodes (1 or 14).

Table 10: Test results: Illumination of one 20 mA diode for 220 seconds

| Surface / Groundwork | Effect [µW] | Energy stored per hour [mJ/h] | Charging time |
|---|---|---|---|
| Best regular road output | 41,8 | 150,3 | 105h 24m |
| Best mean output (test track) | 162,6 | 585,4 | 18h 58m |
| Best output (test track) | 412,5 | 1485,0 | 7h 29m |

Table 11: Theoretical best case scenario: Charging time with PSI-5A4E plate (estimation from chapter 4.1)

| No. of plates | Output current [mA] | Required charge level [mAh] | Charging time 1 diode | Charging time 14 diodes |
|---|---|---|---|---|
| 1 | 1.482 (25 %) | 17 | 49m | 11h 29m |
| 1 | 2.964 (50 %) | 17 | 24m | 5h 44m |
| 1 | 5.928 (max.) | 17 | 12m | 2h 52m |

As one could expect, the vibrations are not in the optimal area for vibration energy harvesting and it could even be impossible to find a location outside the engine compartment where the vibrations are of such frequency that could vibrate one single piezoelectric plate in its optimal frequency. Due to the wide frequency band the output efficiency is far from the theoretical maximum.

The following pages will focus on the required charging times under various conditions. The outputs obtained from the test-driving session are the starting point. These output results are presented in combination with possible combinations of the diodes within the step-in-spline. The end result should then easily show if any combination fulfills the requirements, and which part further development should focus on.

Table 12 shows charging times that could be achieved by varying the number of PZT plates and if a switch from a 20 mA to a 5 mA diode could be implemented. Note that the table only shows the results for having no more than one diode to illuminate.

**Table 12: Charging time when using more PZT plates and lower current diodes**

| Surface / Groundwork | No. of PZT plates | Diode current [mA] | Energy stored per hour [mJ/h] | Required charging time |
|---|---|---|---|---|
| Regular road | 1 | 20 | 150,3 | 105h 24m |
| | 4 | 20 | 601,3 | 18h 28m |
| | 4 | 5 | 601,3 | **4h 37m** |
| Mean charging rate (test track) | 1 | 20 | 585,4 | 18h 58m |
| | 4 | 20 | 2341,6 | 4h 44m |
| | 4 | 5 | 2341,6 | **1h 11m** |
| Best charging rate (test track) | 1 | 20 | 1485,0 | 7h 29m |
| | 4 | 20 | 5940,0 | 1h 52m |
| | 4 | 5 | 5940,0 | **28m** |

In some of the cases the charging times are closing in on acceptable time frames, where the best case scenario has a charging time of only 28 minutes. However, the case has three main technological issues; (1) the calculations are made when illuminating one diode, (2) the case of only 28 minutes is achieved when driving on a specific track (track 4, see Figure 32: The different surfaces of the test track) and (3) the weights required to lower the resonance frequency of the plates take a substantial amount of space. The weight system has to be further analyzed in order to see if the required weights could be implemented within the step-in-spline or if they are a too bulky to fit within the step-in-spline. Another possibility could be to use several piezoelectric plates mounted in parallel in contrast to only one, which would make the length/width relation bigger and thereby the resonance frequency could be decreased with a smaller amount of tip weights.

If the piezoelectric solution was to be implemented in the step-in-spline as it is today, with 14 diodes, then the charging time would once again drop outside the acceptable time frame. The approximation of charging time is based on the earlier presented circuitry (see Figure 33), with the difference of more diodes added in parallel (as presented in Figure 34).

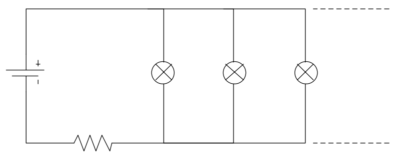


**Figure 34: The theoretical circuitry used when approximating the charging time with more than one diode**

The following two tables shows the charging time when the number of diodes is varied, which for example could be achieved by using other reflecting materials within the step-in-spline to reach the same level of illumination even though having fewer light sources. The scenario when only one PZT plate is used for energy harvesting is excluded from now on since it would be impossible to reach the needed charging times with only one plate. Instead all assumptions are made for four plates.

In Table 13 the charge time has been evaluated by varying the number of 20 mA diodes from 1 to 14.

**Table 13: Assumption of charge time based on a varied number of 20 mA diodes within the step-in-spline**

| Surface / Groundwork | No. of diodes at 20 mA | Required charging time |
|---|---|---|
| Regular road | 1 | 18h 28m |
| - Energy stored per hour: | 4 | 73h 51m |
| 601,3 [mJ/h] | 7 | 129h 14m |
| | 10 | 184h 37m |
| | 14 | 258h 28m |
| Test track - mean | 1 | 4h 44m |
| - Energy stored per hour: | 4 | 18h 58m |
| 2341,6 [mJ/h] | 7 | 33h 11m |
| | 10 | 47h 25m |
| | 14 | 66h 22m |
| Test track - best | 1 | 1h 52m |
| - Energy stored per hour: | 4 | 7h 29m |
| 5940,0 [mJ/h] | 7 | 13h 5m |
| | 10 | 18h 41m |
| | 14 | 26h 10m |

Table 14 shows the change in charging time when using diodes with otherwise same specifications but a lower specified current at 5 mA.

**Table 14: Assumption of charge time based on a varied number of 5 mA diodes within the step-in-spline**

| Surface / Groundwork | No. of diodes at 5 mA | Required charging time |
|---|---|---|
| Regular road | 1 | 4h 37m |
| - Energy stored per hour: | 4 | 18h 28m |
| 601,3 [mJ/h] | 7 | 32h 19m |
| | 10 | 46h 9m |
| | 14 | 64h 37m |
| Test track - mean | 1 | 1h 11m |
| - Energy stored per hour: | 4 | 4h 44m |
| 2341,6 [mJ/h] | 7 | 8h 18m |
| | 10 | 11h 51m |
| | 14 | 16h 36m |
| Test track - best | 1 | 28m |
| - Energy stored per hour: | 4 | 1h 52m |
| 5940,0 [mJ/h] | 7 | 3h 16m |
| | 10 | 4h 40m |
| | 14 | 6h 32m |

As the result shows; an acceptable charge cannot be achieved when the system consists of 14 diodes. The best case scenario has a charging time of six and a half hours when using the step-in-spline as it is today (14 diodes). Even when approximating the charging time based on the best case scenario the highest number of diodes that reaches an acceptable charging time lies between one to four diodes.

The tests made within this project are early output approximations and might hide the true potential of vibration energy harvesting capabilities mounted within the step-in-spline. This becomes evident when comparing the results from the theoretical evaluations and the experimental tests. Table 15 presents the percentage of harvested energy when compared to the maximum output one could harvest using the PSI-5A4E plate at maximum rated outputs.

**Table 15: Output efficiencies**

| Surface / Groundwork | Output efficiency[7] |
|---|---|
| Best charging rate of test track | 5,81% |
| Mean charging rate on test track | 2,29% |
| Regular road | 0,59% |

[7] Measured output divided by max. rated output of PSI-5A4E plate

# 7 Conclusion and discussion

The previous chapter presented possible outputs one could expect from a piezoelectric solution mounted within the step-in-spline. The experiments show that a piezoelectric solution could be implemented with further development; the end result is however not only depending on piezoelectricity. The piezoelectric step-in-spline would have to be developed from scratch where a few topics should be an equally big part of the development as the piezoelectricity itself. Piezoelectricity has already been proven to give an output that could suffice, but it does not reach the requirements that are needed and stated for a step-in-spline of today. It early becomes evident that the piezoelectric outputs achieved by vibration energy harvesting cannot meet the high power demand of the diodes used today. And thereby one of the most important questions that need to be answered is:

- *Is it possible to change the design of the step-in-spline in a way that fewer diodes could give a satisfying result?*

The result could be achieved by e.g. change of materials that reflects the light more efficiently and by switching to less power demanding diodes.

If the answer is yes, then a piezoelectric step-in-spline solution should be considered a viable option and further development investments could be the right way to go. But if the answer is no, then the piezoelectric energy harvesters would have to be put on hold until a higher system efficiency could be reached.

Some of the development topics that need to be analyzed before trying to fill a step-in-spline with piezoelectric energy converters are:

- Electronics with both low power demands and low losses
- Design that allows tip deflection and enhanced amplitudes due to larger tip weights
- A deeper analysis that proves or disproves that cantilever mount is the best way of harvesting the energy from vibrations within the step-in-spline
- Analysis and calculations of the optimal form of the piezo elements in order to match the vibrations of normal driving conditions
- A revision of the sill-moulding technical regulations to match both a piezoelectric solution and the customer without cutting away a big chunk of customer value
- Finding a suitable energy storage bank. Chapter 3.4.4 (The battery) should only be seen as assistance and a starting point of choosing an energy storage bank.

These are some of the main obstacles to overcome before a functioning prototype could be developed. Furthermore, point three and four are directly related to Table 15 that indicates the low output efficiencies achieved when harvesting vibration energy with a PZT plate mounted to the chassis. A possibility of improvement capabilities by frequency operating optimizations are evident, and in combination with a less power demanding system the piezoelectrically powered step-in-spline might just be the right solution to pursue.

## 7.1 Question formulation wrap up (part II)

The previous pages have given answers to most of the so far unanswered questions stated in the beginning of this report. The ones that have not been answered fall under the topic of economic feasibility, hindering patents and other natural questions that have to be answered by any company when considering new technology. These questions can be seen below:

- Are these within the range of economic feasibility of the intended field of use?
- Are there relationships to other accessories sold today, and how would they be affected?
- Which are the issues (time and cost) of implementation within VCC?
- Are other car manufacturers using the technology, and are there patents to seek or patents that hinder?
- How does the technology and planned type of solutions compare against the solution used today?

The questions were left unanswered since the piezoelectric solution demanded more time than expected. Mostly due to the state of development within piezoelectric energy harvesters being in a state of change, where the development just recently has shifted focus to also consider a future where products with higher energy demands could be powered by piezoelectricity. The state of development is also reflected within this project, where the first development idea thoughts circled around plug-and-play products which easily could be tested within the vehicle. Such development could not be achieved which resulted in a project that had to rely on literature studies on a much higher degree than expected. The remaining questions which do not neighbor to the area of economic feasibility and later delimited areas are shown below, the questions have already been given analytic answers throughout the project and the answers given here are greatly simplified:

- Do they offer enough electricity to power light sources in the step-in-spline?

Yes. But the power output is dependent on (followed by the choice made within this project/short description);

- The piezoelectric material: standard-size PZT plate from Piezo Systems Inc.
- How it is implemented and fastened to the vibrating source: cantilever mount.
- The vibrating source: pre-defined in this project.
- How many plates one can fit within the step-in-spline: 4 plates within step-in-spline.
- Room for movement within step-in-spline: doubtful case and requires small design changes in order to operate at full range (tip-deflection).
- The ability of choosing a material and modifying it in order to match it to the vibrations: tip-weights of around 30 grams might have to fit within the step-in-spline in order to effectively harvest the low frequencies found within the car chassis. Adding weights lies in conflict with the above stated requirement of “room for movement”. This could maybe be solved by using parallel plates with less width and thereby lowering the resonance frequency.
- Circuitry and energy bank: the circuitry needed within the step-in-spline has several functions to handle; control the time of illumination, sensors for door opening and closing etc. makes it more power demanding than the circuitry used in the tests within this project, which requires more development before a final answer can be given.

A deeper explanation, analysis and reason for these choices can be found in the relating chapters within the report.

- In which parts of the car are the vibrations and/or mechanical forces of such magnitude that the energy can be used for the intended use?

Since the step-in-spline is in direct contact with the chassis, on which the tests were done the whole chassis is presumed to be a possible energy harvesting location. As long as the piezoelectric plate and its surrounding case are fastened tightly and rigidly against the chassis one should be able to re-create the results shown in this report.

- What is the life-span of the elements during normal use (together with a battery or other power conserving technology)?

Many products found states a “virtually unlimited operating life” where others specify the operating life to a specific number of oscillations. This project has no chance of exploring this closer, the same goes for the operating life of different energy bank systems’ operating life which might possess restrictions making a piezoelectric solution impracticable.

# 8 Alternative solutions and ideas

During the project and the development of a piezoelectric solution the problem definition became clearer and a bigger understanding for the system was gained. This chapter is a short briefing of further development options and alternative solutions that could be investigated.

## 8.1 Further piezoelectric development

The piezoelectric solution tested in this project is not optimized in terms of frequency, acceleration, and finding a resonance frequency (or anti-resonance, being another optimal frequency (Renno et al., 2009)). The material was chosen according to specifications that had the best chance to conform to the vibration characteristics within the area of the step-in-spline, with the only degree of freedom of changing the resonance frequency being a tip mass. In future development a piezoelectric solution could be optimized and improved by allowing a higher degree of design freedom of the step-in-spline, where the step-in-spline could be made out material with less internal damping, or a small movement of the list could be allowed which in turn could enhance the vibrations of the base. Another solution, already mentioned in the report (see 3.1), is to incorporate a piezoelectric solution that works as an open solution, with an energy input from the vibrating door being directed directly on the piezoelectric plate (or even a piezoelectric stack). The piezoelectric output could be further improved by doing research on the area of low profile transducers; Priyas work of *Advances in energy harvesting using low profile piezoelectric transducers (2007)* offers a good starting point to see the possible capabilities of implementing low profile transducers. Larger response and low frequency operation are a few mentioned improvement areas.

The functional diagram of the system in chapter 3.4.1 can possibly be improved with a little design change. The change still keeps the system simple, but instead it consist of a diode rectifier (AC/DC), a DC-DC converter and a controller, see Figure 35. The DC-DC converter is added because it has been shown to improve energy harvesting by a factor of 7 (Priya & Inman, 2009). Further, there are many techniques used for obtaining a higher efficiency of the circuitry, such as Synchronized Switch Harvesting on Inductor (SSHI), stand-alone harvesting systems and self-tuning systems (which requires complex electronics with a programmable microcontroller) (Muriuki, 2004). These systems were however outside the scope of the project, but might be worth investigating in future development projects.

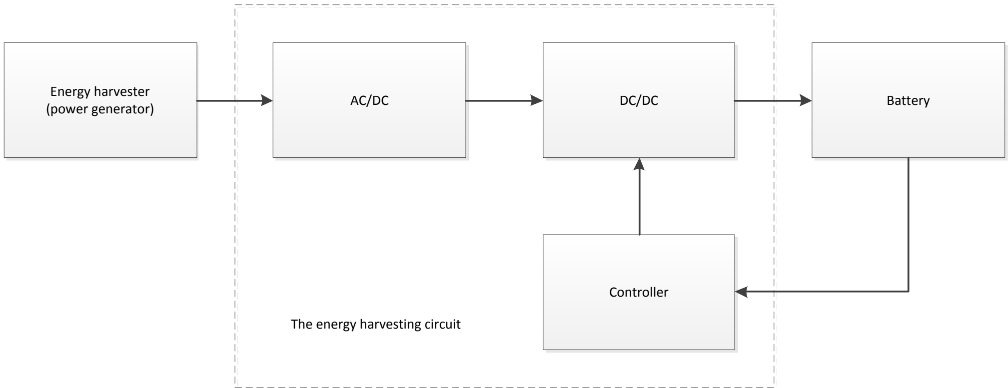



**Figure 35: An alternative circuit model**

## 8.2 Piezoelectric substitutes and other solutions

An improved solution does not have to consist of a different technological solution that already is in use. During the development and search for viable piezoelectric solutions one suggestion was applicable on the solution of today. The cabling could be re-routed and wired from the door electronics (window elevator) to the bottom of the door. At the bottom of the door wireless charging from the door to a battery placed within the step-in-spline could be used (same technology as used in most charging systems of electronic toothbrushes).

The piezoelectric effect is achieved by conversion from kinetic energy to electric energy. But the piezoelectric effect is not the only way we convert kinetic energy to electricity, two other kinetic energy converting examples are electromagnetic and electrostatic mechanisms (Priya, 2007). These two work in different ways to achieve the conversion; however, there is one highly similar effect that was discovered a few decades earlier than piezoelectricity. Pyroelectricity shares similar behavior as the piezoelectric materials with the exception of reacting to temperature changes, when exposed to temperature change an electric potential appears between its terminals (Solvay, 2012). Further, the idea of combining more than one energy harvesters is called multi-modal energy harvesting and could make energy harvesting more effective over a wider range of scavenging applications (Kim et al., 2009). In this way vibration energy harvesting through piezoelectricity, pyroelectricity, electromagnetic induction, photovoltaic and electrostatic could be combined with other energy harvesting systems such as; solar cells or to use the available air-flow during driving (e.g. small scale windmills).

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# Appendix I: Test drive and frequency data

## *Vibration and frequency characteristics data*

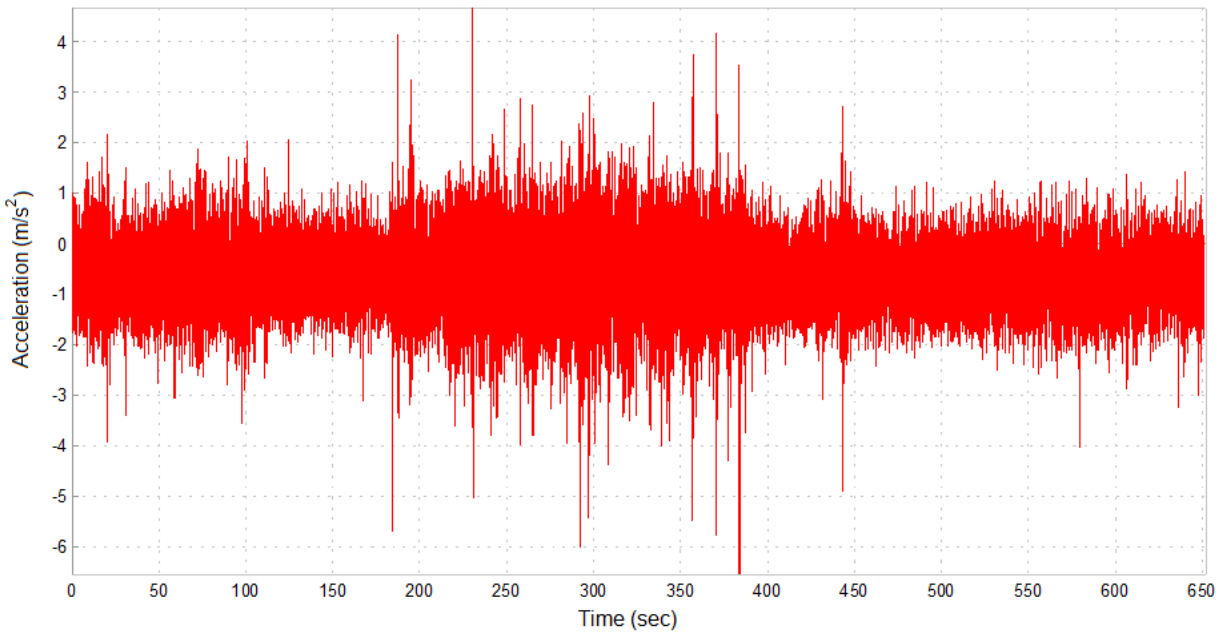



**Figure 36: Vertical acceleration data – motorway 22km, car model: S80, year model 2000.**

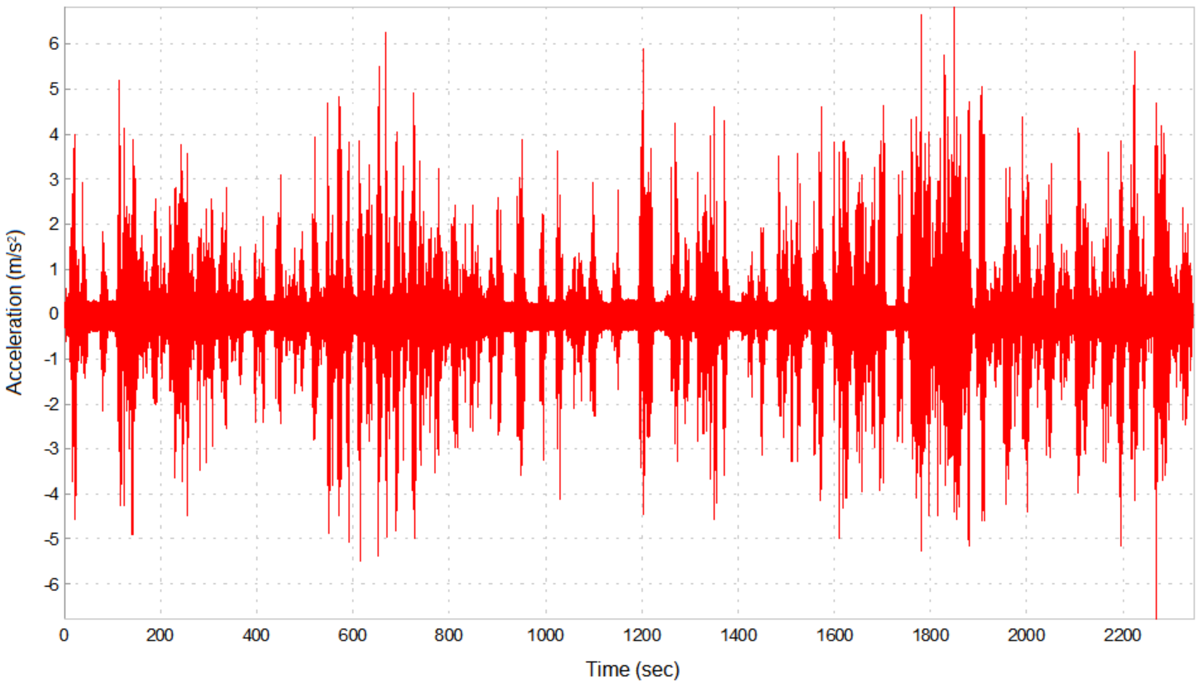



**Figure 37: Vertical acceleration data – regular driving, car model: S80, year model 2000.**

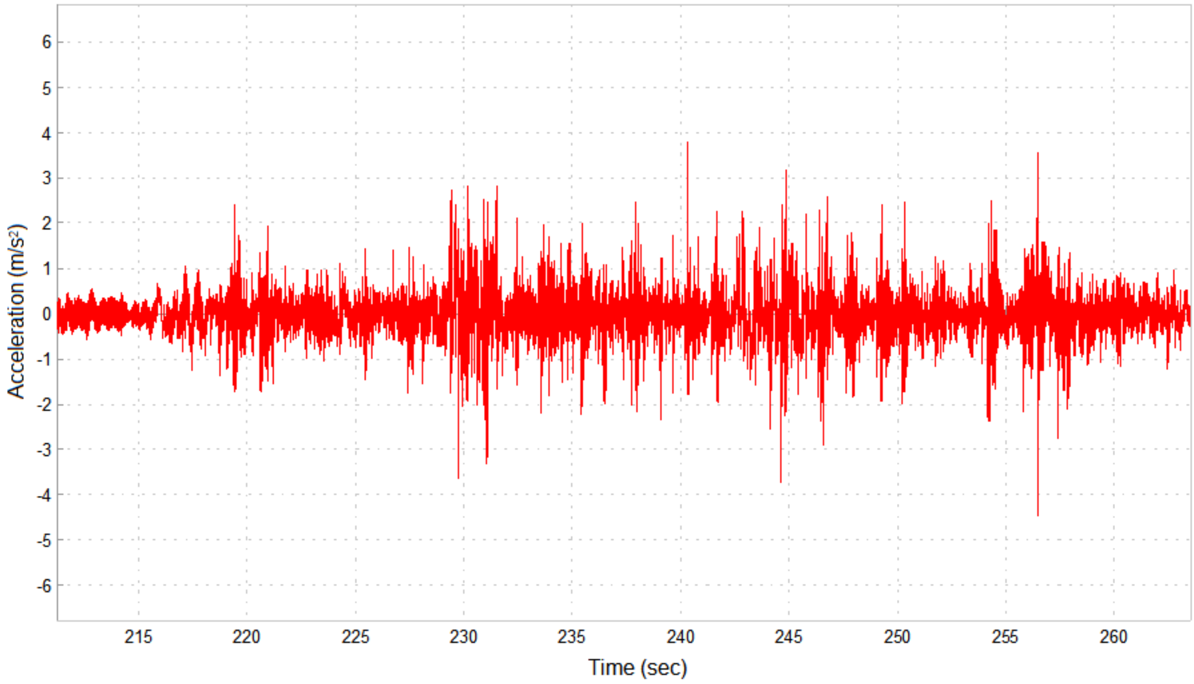



**Figure 38: A subset of the vertical acceleration data from Figure 37**

## Test-drive data

The following pages contains the data used within the approximations in the result chapter.

Volvo Car Corporation

| Document Type: | Document name: | Test #: 1 V60 chassi vibrations from seat fixture |
|---|---|---|
| Field test | Piezoelectrically illuminated step-in-spline | Tip weight: 21 [g] |

| Track # | Time From start*** | From last | Capacitor charge [V] | Difference [V] | Energy stored [mJ] | Effect [µW] |
|---|---|---|---|---|---|---|
| 1 | 22s | 22s | 1,189 -> 1,226 | | | |
| 2 | 1m 5s | 38s | 1,395 | | | |
| 3 | 1m 52s | 47s | 1,466 | | | |
| 4 | 2m 40s | 48s | 1,655 | | | |
| 5 & 6 | 3m 40s | 1m | 1,8 | | | |
| - | - | - | (Discharge to 1,78) | | | |
| 7 | 59s | 59s | 1,752 | | | |
| 8 | 1m 56s | 57s | 1,754 -> 2,05 **** | | | |
| 9 | 3m 10s | 1m 14s | 2,00 -> 2,04* **** | | | |
| 10 | 4m 34s | 1m 33s | 1,9 -> 1,86** **** | | | |

Comments: * = half of the long track, ** = rugged asphalt, *** = or last discharge
**** = Large current leak due to high charge
This first test leaked a lot of current, the test rig had to be inspected before more testing. Total length of test-track: 4.686 km

Issuer: Matti Halonen

Date Issued: 2012-11-01
Date Revised: 2012-11-20

Volvo Car Corporation

| Document Type: | Document name: | Test #: 2 V60 chassi vibrations from seat fixture |
|---|---|---|
| Field test | Piezoelectrically illuminated step-in-spline | Tip weight: 21 [g] |

| Track # | Time From start | / test | Capacitor charge [V] | Difference [V] | Energy stored [mJ] | Effect [µW] | Energy stored per hour [mJ/h] |
|---|---|---|---|---|---|---|---|
| 1 | 24s | 24s | 0,683 - > 0,723 | 0,04 | 1,05 | 43,8 | 157,5 |
| 2 | 1m 33s | 39s | 0,723 -> 0,876 | 0,153 | 4,01 | 102,8 | 370,2 |
| 3 | 2m 29s | 34s | 0,875 - > 0,948 | 0,073 | 1,91 | 56,2 | 202,2 |
| 4 | 3m 22s | 30s | 0,947 - > 1,277 | 0,33 | 8,64 | 288 | 1036,8 |
| 5 | 4m 58s | 20s | 0,683 - > 0,701 | 0,018 | 0,47 | 23,5 | 84,6 |
| 6 | 5m 47s | 27s | 0,702 - > 0,879 | 0,177 | 4,66 | 172,6 | 621,3 |
| 7 | 7m 11s | 48s | 0,878 -> 0,922 | 0,044 | 1,16 | 24,2 | 87 |
| 8 | 8m 34s | 30s | 0,673 -> 1,043 | 0,37 | 9,69 | 323 | 1162,8 |
| 9 | 10m 16s | 55s | 0,650 -> 0,91 | 0,26 | 6,81 | 123,8 | 445,7 |
| 10 | 13m 22s | 38s | 0,632 -> 0,687 * | 0,055 | 1,44 | 37,9 | 136,4 |
| | | Σ 345s | Σ 1,42 | - | Σ 39,84 | 115,48 | 415,72 |

Comments: * = rugged asphalt
Total length of test-track: 4.686 km

Issuer: Matti Halonen

Date Issued: 2012-11-01
Date Revised: 2012-11-20

Volvo Car Corporation

| Document Type: | Document name: | Test #: 3 V60 chassi vibrations from seat fixture |
|---|---|---|
| Field test | Piezoelectrically illuminated step-in-spline | Tip weight: 26 [g] |

| Track # | Time From start | / test | Capacitor charge [V] | Difference [V] | Energy stored [mJ] | Effect [µW] | Energy stored per hour [mJ/h] |
|---|---|---|---|---|---|---|---|
| 1 | 15s | 15s | 0,713 -> 0,801 | 0,088 | 2,3 | 153,6 | 553,13 |
| 2 | 51s | 20s | 0,8 -> 1,094 | 0,294 | 7,7 | 385 | 1385,97 |
| 3 | 1m 53s | 29s | 0,634 -> 0,879 | 0,245 | 6,42 | 221,3 | 796,54 |
| 4 | 3m 31s | 29s | 0,871 -> 1,321 | 0,45 | 11,79 | 406,4 | 1463,03 |
| 5 | 4m 55s | 20s | 1,308 -> 1,317 | 0,009 | 0,24 | 11,8 | 42,43 |
| 6 | 6m 7s | 24s | 0,645 -> 0,848 | 0,203 | 5,32 | 221,5 | 797,49 |
| 7 | 7m 28s | 46s | 0,848 -> 0,904 | 0,056 | 1,47 | 31,9 | 114,78 |
| 8 | 9m 7s | 30s | 0,631 -> 0,976 | 0,345 | 9,04 | 301,2 | 1084,27 |
| 9 | 10m 48s | 56s | 0,641 -> 0,869 | 0,228 | 5,97 | 106,6 | 383,87 |
| 10 | 13m 49s | 46s | 0,646 -> 0,683 * | 0,037 | 0,97 | 21,1 | 75,84 |
| | | Σ 315s | Σ 1,955 | - | Σ 51,22 | 162,6 | 585,37 |
| | | | | | | | |

Comments: * = rugged asphalt
Total length of test-track: 4.686 km

Issuer: Matti Halonen

Date Issued: 2012-11-01
Date Revised: 2012-11-20

Volvo Car Corporation

| Document Type: | Document name: | Test #: 4 V60 chassi vibrations from seat fixture |
|---|---|---|
| Field test | Piezoelectrically illuminated step-in-spline | Tip weight: 30 [g] |

| Track # | Time From start | / test | Capacitor charge [V] | Difference [V] | Energy stored [mJ] | Effect [µW] | Energy stored per hour [mJ/h] |
|---|---|---|---|---|---|---|---|
| 1 | 14s | 14s | 0,637 -> 0,707 | 0,07 | 1,83 | 131 | 471,42 |
| 2 | 1m | 30s | 0,706 -> 1,032 | 0,326 | 8,54 | 284,6 | 1024,55 |
| 3 | 1m 59s | 28s | 1,026 -> 1,222 | 0,196 | 5,13 | 183,3 | 659,99 |
| 4 | 2m 55s | 32s | 1,220 -> 1,724 | 0,504 | 13,2 | 412,49 | 1484,97 |
| 5 | 3m 44s | (24s) | 1,696 -> 1,685* | - | - | - | - |
| 6 | 5m 3s | 28s | 0,656 -> 0,887 | 0,231 | 6,05 | 216,07 | 777,84 |
| 7 | 6m 46s | 52s | 0,636 -> 0,710 | 0,065 | 1,7 | 32,74 | 117,86 |
| 8 | 7m 50s | 31s | 0,712 -> 1,070 | 0,358 | 9,38 | 302,45 | 1088,83 |
| 9 | 9m 33s | 56s | 0,637 -> 0,862 | 0,225 | 5,89 | 105,23 | 378,82 |
| 10 | 12m 9s | 36s | 0,705 -> 0,759 ** | 0,054 | 1,41 | 39,29 | 141,43 |
| | | Σ 307 | Σ 505,53 | - | Σ 39,93 | 130,07 | 468,23 |
| | | | | | | | |

Comments: * = high charge equals higher leak current, charge not readable/ reliable ** = rugged asphalt
Total length of test-track: 4.686 km

Issuer: Matti Halonen

Date Issued: 2012-11-01
Date Revised: 2012-11-20

Volvo Car Corporation

Test #: 5
V60 chassi vibrations from seat fixture

| Document Type: | Document name: | |
|---|---|---|
| Field test | Piezoelectrically illuminated step-in-spline | Tip weight: 30 [g] |

| Time From start | / test | Capacitor charge [V] | Difference [V] | Energy stored [mJ] | Effect [µW] | Energy stored per hour [mJ/h] |
|---|---|---|---|---|---|---|
| 0 | - | 0,62 | - | - | | * |
| 2m 59s | - | 0,885 | 0,265 | 6,94 | 38,77 | 139,58 |
| | | | | | | |
| | | | | | | |

Comments: *Clean drive around test-track
Total length of test-track: 4.686 km

Issuer: Matti Halonen

Date Issued: 2012-11-01
Date Revised: 2012-11-02, Time: 10:57:06

Volvo Car Corporation

Test #: 6 V60 chassi vibrations from seat fixture

| Document Type: | Document name: | |
|---|---|---|
| Field test | Piezoelectrically illuminated step-in-spline | Tip weight: 26 [g] |

| Time From start | / test | Capacitor charge [V] | Difference [V] | Energy stored [mJ] | Effect [µW] | Energy stored per hour [mJ/h] |
|---|---|---|---|---|---|---|
| 0 | - | 0,631 | - | - | * | * |
| 3m | - | 0,918 | 0,287 | 7,52 | 41,76 | 150,33 |
| | | | | | | |
| | | | | | | |
| | | | | | | |

Comments: *Clean drive around test-track
Total length of test-track: 4.686 km

Issuer: Matti Halonen

Date Issued: 2012-11-01
Date Revised: 2012-11-21

Volvo Car Corporation

| Document Type: | Document name: | Test #: 7 V60 chassi vibrations from seat fixture |
|---|---|---|
| Field test | Piezoelectrically illuminated step-in-spline | Tip weight: 21 [g] |

| Time From start | / test | Capacitor charge [V] | Difference [V] | Energy stored [mJ] | Effect [µW] | Energy stored per hour [mJ/h] |
|---|---|---|---|---|---|---|
| 0 | - | 0,631 | - | - | | |
| 2m 52s | - | 0,865 | 0,234 | 6,13 | 35,63 | 128,27 |
| | | | | | | |
| | | | | | | |

Comments: *Clean drive around test-track
Total length of test-track: 4.686 km

Issuer: Matti Halonen

Date Issued: 2012-11-01
Date Revised: 2012-11-21

Volvo Car Corporation

| Document Type: | Document name: | Test #: 8 V60 chassi vibrations from seat fixture |
|---|---|---|
| Field test | Piezoelectrically illuminated step-in-spline | Tip weight: 21 [g] |

| Time From start | / test | Capacitor charge [V] | Difference [V] | Energy stored [mJ] | Effect [µW] | Energy stored per hour [mJ/h] |
|---|---|---|---|---|---|---|
| 0 | - | 0,865 | - | - | | |
| 7m 26s | - | 1,128 | 0,263 | 6,89 | 1,54 | 55,6 |
| | | | | | | |
| | | | | | | |

Comments: *Drive back from test-track to PV, Length: 5km (4.987 km)

Issuer: Matti Halonen

Date Issued: 2012-11-01
Date Revised: 2012-11-21

# Appendix II: Calculations

## *First power output estimation*

The calculations provide estimates, which hopefully supports the implementation of a piezoelectric solution. As stated before, it was hard to access all the information needed, and some of the variables had to be given estimated values in order to obtain a statement of the possible power output. To begin, an estimation of possible output from vibrations within the step-in-spline mounted on the automobile will be calculated.

The first calculation follows an estimation made by Shu & Lien (2006), their goal was to analyze an AC-DC power output for a rectified piezoelectric harvester. The analysis was chosen as a valid comparison since the calculations are analyzed with electric compatibility in mind, where the generated AC voltage from the vibrating piezo element has been rectified, filtered and regulated. Within their studies a piezoelectric vibration energy harvesting system as made visible in Figure 40 has been used. The system is referred to as an open piezoelectric system since an outer force is applied on the beam. Unfortunately, the equation only apply on materials that have a ratio between its electromechanical coupling coefficient and damping ratio (electrical and mechanical) of $\frac{k_e^2}{\rho} \ll 1$. The damping ratio can be slightly changed with changes of the structural design, but will here remain the same since the model is to be used as a design guide for the first prototype. The electromechanical coupling coefficient will have to be fixed at the same value as in Shu & Liens experiment, since none of the PZT material resellers contacted has materials with an electromechanical coupling coefficient below 0.35. And thereby the ratio of $\frac{k_e^2}{\rho}$ would exceed the limit set for the equations capability to give a correct answer.

Shu & Liens experiments led to equation ( 1 ) for calculation of power output (P) for the piezoelectric vibration energy harvesting system presented above.

$$P = \left[\frac{M\omega}{F^2}\right]\left[\frac{k_e^2 r}{4\,\rho^2(\,r+\pi/2)^2}\right] \qquad (1)$$

M is the effective mass inside the piezo element, the values used by Shu & Lien is on a beam with dimensions of 40*20*0.36 mm and is considered to fit within a step-in-spline. The mass of the beam is 2.2509 g and the attached mass (M in Figure 40) is 0.4207, which gives the total mass of 2.6716 g (Shu & Lien, 2006, p. 1507). $\omega$ is the frequency of the input acceleration, which is calculated by:

$$\omega = 2\pi f \qquad (2)$$

The frequencies when driving a car is presented in Appendix I: Test drive and frequency data, where the majority of the frequency energy is around 20 Hz. F is the input force, in this case it is represented by the door frequently “bouncing” on the mass (M) placed inside the piezoelectric element. F is calculated by:

$$F = ma \qquad (3)$$

The acceleration of the exciting force is the vertical acceleration of the car. In this case the vertical acceleration from Figure 36 and Figure 10 is used, where the acceleration of 2 m/s$^2$ is used. The mass (m) of the door was obtained via VCC from a web-based benchmarking service (A2Mac1), which provided information of two models, the S60 model of 2010 and XC60 model of 2009. The door-weight used for calculations is the left rear door of an XC60, which is the lightest of all eight doors; weighing in at 28,440 kg. All eight doors are within the range of 28,4 kg to 36,8 kg. The whole weight of the door will not be calculated as the "bouncing" weight. The door is estimated to be carried up to 98 % by the joints, from the remaining 2 % an estimation has been made that almost all of the weight (80 %) is exciting the piezo element; leaving a total effective mass (m) of 454 g.

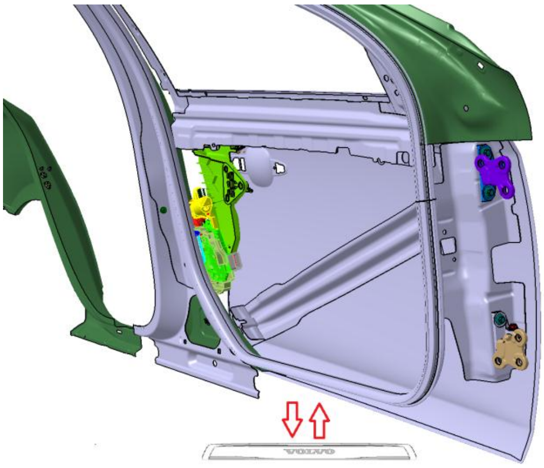


**Figure 39: The relative force from the door that "bounces" on the piezo element**

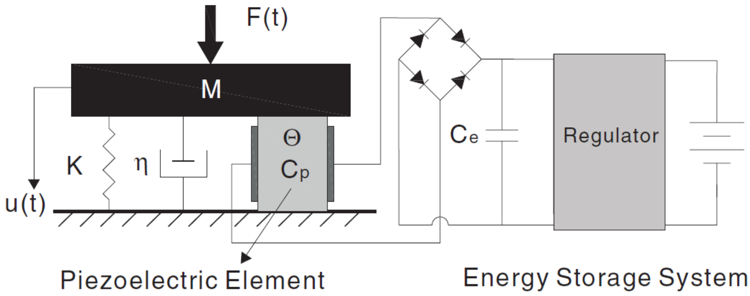



**Figure 40: The piezoelectric energy harvesting model used in calculations by Shu & Lien (2006)**

Further, $k_e^2$ is the electromechanical coupling coefficient[8] with a value set at 0.05, which in these calculations is borrowed from Shu & Lien. ρ is the damping ratio, which here is chosen as a constant of 0.03 (as in Shu & Liens testing). r is the normalized electric resistance. To be able to complete the calculations an optimal load resistance value is used, it was calculated by Shu & Lien as $r^{opt} = \pi/2\Omega$, which found an optimal value when $\frac{k_e^2}{\rho} \ll 1$ and $\Omega \approx 1$ (Shu & Lien, 2006, p. 1054). Thereby r is chosen as 1.57. The equation presented by Shu & Lien is claimed to be valid as long as $\frac{k_e^2}{\rho} \ll 1$.

Combining ( 1 ), ( 2 ) and ( 3 ) with the values above gives the power output (P) of 44mW.

The formula has been validated by experiments by Shu & Lien to work for the piezoelectric material PZT in a triple-layer configuration. It has to be remembered that the calculations often refer to a frequency that at all times is considered to be fixed at the frequency that allows the piezoelectric plate to operate in resonance, which gives the maximum power output.

[8] Electromechanical coupling coefficient is a numerical measure of the conversion efficiency between electrical and acoustic energy in piezoelectric materials (Kim et al., 2009, 12)

## *Attempts to find a standardized way of calculating the power output*

| | |
|---|---|
| First eigenfrequency without weight: | 143424.8616 Hz |
| First eigenfrequency with weight: | 482811.5297 Hz |
| Second eigenfrequency without weight: | 898893.1399 Hz |
| Second eigenfrequency with weight: | 3025946.5958 Hz |

These eigenfrequencies are with properties that assume a beam made of only PZT ceramic, thereby the high frequencies

| | |
|---|---|
| mAh needed to fulfill required light time: | 3.0556 mAh (@ rated frequency |
| Time_2_charge_by_specs: | 2.0618 h |

| | |
|---|---|
| <u>Power output by Shu & Liens model</u>: | 6.5043 mW |
| <u>Maximum power output by Roundys model (electromagnetic):</u> | 30.4201 mW * |

<u>Maximum power output by William & Yates simplified model</u>:
Vibration spectrum needs to be known for calculations
<u>Power output by William & Yates model</u>:
Housing vibration unknown
<u>Power output by Erturk & Inmans model</u>:
Unknown, testing required to obtain circuitry and mechanical dependencies

* Roundys model is for an electromagnetic system, and the answer given is an extremely seldom achieved peak, since it is only achieved when the system is resonant (our frequency varies the whole time

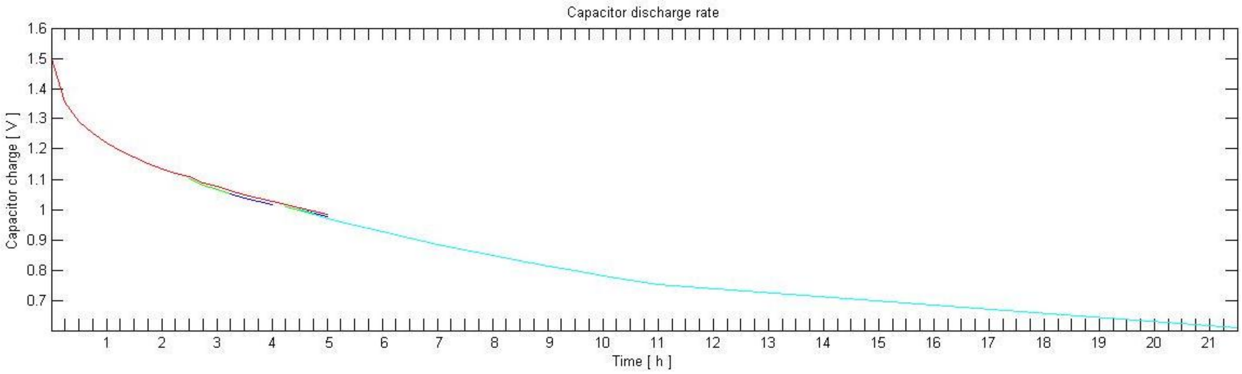
## Code used to generate the presented results on the previous page:

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Piezo power output calculation program (a work in progress) %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clc
clear all

% Mechanical system properties

%System constants

% Material (5A4E) & Outer system properties
Density = 7800;                          %material density
Length = 63.55;                          %piezo plate length in [mm]
Width = 31.8;                            %piezo plate width in [mm]
Height = 0.38;                           %Height in [mm], 2-PIEZO LAYER BENDING GENERATORS STANDARD-  RASS RE-INFORCED
Length_m = Length*10^-3;                 %Length of piezo element converted to [m]
Width_m = Width*10^-3;                   %Width of piezo element converted to [m]
Height_m = 0.2*10^-3;                    %Height of piezo element converted to [m]
Ro = 0.03;                               %damping ratio
Ke = 0.05;                               %Electromechanical Coupling Factor
r = 1;                                   %Normalized Electric Resistance
Piezo_volume = Length_m * Width_m * Height_m;  %Volume of the piezoelectric element
Inner_mass = Density * Piezo_volume;     %Inner mass of the piezo-element [kg]
Ep = 6.6 * 10^10;                        %Elastic modulus for material - 5H4E http://www.piezo.com/prodmaterialprop.html (3 direction = 5.0*10^10)
%Eb = 115 * 10^9;                        %Elastic modulus of brass (varies between 102-125)
I = (Length_m^3 * Height_m) / 12;        %Moment of area - http://en.wikipedia.org/wiki/Second_moment_of_area
Weight_beam = 0.0104;                    %Weight of the total beam (dual piezo + brass reinforcement)(http://www.piezo.com/catalog8.pdf%20files/Cat8.32.pdf)
Height_tip = Height_m;
Length_weight_tip = 0.007;               %Lenght of the tip where the weight is placed, in [m]
d = -320 * 10^-12;                       %System damping constant
k31 = 0.35;                              %Coupling coefficient (Material 5A4E), 31 direction
Mechanical_Q = 32;                       %32 for 5H4E, 80 for 5A4E material
Resonance_frequency = 52;                %Assumed that such a resonance frequency can be achieved by modifying the system properties
a = 4;                                   %Median peak-to-peak acceleration of the energy source
f = 2;                                   %frequency of the outer system
Omega = 2*pi*f;                          %Omega is the frequency of the input acceleration given in rad/s
Outer_mass = 0.2;                        %mass of the outer force [kg]
Outer_force = Outer_mass * a;

k = Omega^2 * Inner_mass;                %Spring constant
Damping_ratio = d / (2 * sqrt(Inner_mass*k));   %System damping ratio
Omega_n_square = k / Inner_mass;         %System resonant frequency

% for damping ratio: Calculate the logarithmic decrement d. This is the natural logarithm of the extent of two oscillations of the system.
% If your system is oscillating about a point x=0, using the ruler, measure the distance from 0 of two successive oscillations, x1 and x2.
% Take the natural logarithm of their ratio: d = ln(x1/x2). Do this a number of times to ensure you get an accurate result.
%
% Calculate the damping ratio. If you know k, m and c, you can use the above equation Z = c / (2*?(k*m)). If you do not know c, however,
% you can use the logarithmic decrement d by the equation Z = d/?((2*pi)^2+d^2). Now you have the damping ratio.
% From: http://www.ehow.com/how_5095037_calculate-damping-ratio.html

  %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
  % Mechanical properties of the system                  %
  %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

 %How much energy does it take to bend the piezo-element?

  %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
  % Varying tip mass             %
  %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

x = 1:1:20;
Weight_tip(x) = x*10^-3;                            %Weight placed at tip of beam
Tip_force = Weight_tip * a;                         %
Beam_force = Weight_beam * a;                          %
Bending_lenght = 57.2 * 10^-3;                        %Differs from beam_lenght since bending occurs after fastener
Tip_deflection = (2* 2.6) * 10^-3;                    %Rated tip deflection from material specifications for energy harvester (2 times since it bends
both up and down)
xAngle = (Tip_deflection / Bending_lenght);
Rated_Bending_Radians = atan(xAngle);
Rated_bending_Angle = Rated_Bending_Radians * 180 / pi;

%How much torque does it take to bend the piezo-element?

Moment = Tip_force * (Length_weight_tip/2 + Length_m) + Beam_force * Length_m;  %1Nm = 1Joule
Bending_energy = Moment * 10^3;
%disp(['Torque to bend the piezo-element: ' num2str(Moment)]);                  %
disp([' '])

subplot(1,2,1)
```

```
y = Bending_energy(x);
plot(x,y)
set(gca,'XTick',0:1:20)
set(gca,'XTickLabel',{' ','1',' ',' ',' ','5',' ',' ',' ',' ','10',' ',' ',' ',' ','15',' ',' ',' ',' ','20'})
title('Torque to bend the piezoelectric plate');
xlabel('Tip mass [g]');
ylabel('Bending energy [Nm] * 10^-3');

%How much energy does it take to bend the piezo-element?

Work_done = (Moment * 10^3) * Rated_Bending_Radians;                          %Newtonmeter * radians gives the energy in joule

subplot(1,2,2)

y = Work_done(x);
plot(x,y)
set(gca,'XTick',0:1:20)
set(gca,'XTickLabel',{' ','1',' ',' ',' ','5',' ',' ',' ',' ','10',' ',' ',' ',' ','15',' ',' ',' ',' ','20'})
title('Energy used when bending the PZT plate');
xlabel('Tip mass [g]');
ylabel('Bending energy [mJ]');

    %Eigenfrequencies for bend-oscillation in straight beam
    %Handbok och formelsamling i Hållfasthetslära, KTH, s. 156)

E_f_1 = 1.875^2 * sqrt((Ep*I/(Weight_beam*(Length_m^4))));      %1.875, see mechanics of materials - eigenfrequency for bend-oscillation in straight beam
E_f_2 = 4.694^2 * sqrt((Ep*I/(Weight_beam*(Length_m^4))));      %4.694, see mechanics of materials - eigenfrequency for bend-oscillation in straight beam

 CoM = (Weight_beam * Length_m + Weight_tip * (Length_m + Length_weight_tip/2)) / (Weight_beam + Weight_tip);    %Centre of mass for the piezo beam
system (tygndpunkt)
a1 = Length_m - CoM;                              %Distance from centre of mass for beam to total centre of mass
a2 = (Length_m + Length_weight_tip/2)- CoM;            %Distance from centre of mass for tip weight to total centre of mass
I1 = (Height_m * Length_m^3)/12 + a1^2*Weight_beam;
I2 = (Height_tip * Length_weight_tip^3)/12 + a2^2*Weight_tip;
I_tot = I1 + I2;

E_f_1_w = 1.875^2 * sqrt((Ep*I_tot/((Inner_mass + Weight_tip)*(Length_m^4))));               %First eigenfrequency with a mass at the tip
E_f_2_w = 4.694^2 * sqrt((Ep*I_tot/((Inner_mass + Weight_tip)*(Length_m^4))));               %Second eigenfrequency with a mass at the tip
disp(['First eigenfrequency without weight:   ' num2str(E_f_1) ' Hz'])
disp(['First eigenfrequency with weight:      ' num2str(E_f_1_w) ' Hz'])
disp(['Second eigenfrequency without weight:  ' num2str(E_f_2) ' Hz'])
disp(['Second eigenfrequency with weight:     ' num2str(E_f_2_w) ' Hz'])
disp(['These eigenfrequencies are with properties that assume a beam made of only PZT ceramic, thereby the high frequencies'])
disp([' '])

    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    % Electrical properties of the system                         %
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%How much current will the system need?

LED_time = (20 * 8 + 60) / 3600;                                %20 activations/day, 8 seconds each + half long time activation (120s)
System_current = 50;                                        %Current of system [mA]
mAh_needed = LED_time * System_current;
Piezo_charging_power_RF = 2.964/2 * 1.00;                        %Power output at rated frequency at Piezo Systems Inc, with a loss of charge due to efficiency
Time_2_charge = mAh_needed / Piezo_charging_power_RF;              %Time needed to charge to fulfill required light time
disp(['mAh needed to fulfill required light time: ' num2str(mAh_needed) ' mAh (@ rated frequency'])
disp(['Time_2_charge_by_specs:                   ' num2str(Time_2_charge) ' h'])
disp([' '])

    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    % Shu & Liens model for power output                           %
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Shu & Liens model for power output
Power_output_ShuLien = (((Inner_mass * Omega) / (Outer_force)^2 ) * (( Ke^2 * r) / (4 * Ro^2 * (r + pi/2)^2))) *10^3;
disp(['Power output by Shu & Liens model:                      ' num2str(Power_output_ShuLien) ' mW'])

    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    % Roundys model for power output                               %
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

P_max_output_Roundys = k31^2 * Inner_mass * Mechanical_Q^2 * a^2 / (4 * Resonance_frequency) *10^3;
disp(['Maximum power output by Roundys model (electromagnetic):  ' num2str(P_max_output_Roundys) ' mW *'])

    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    % William & Yates simplified model for maximum power output    %
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%P_max_output_WilliamYates = Inner_mass * Y_0^2 * sqrt(Omega_n_square)^3 / (4 * Damping_ratio)
```

```
disp(['Maximum power output by William & Yates simplified model:' ' Vibration spectrum needs to be known for calculations'])

    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    % William & Yates model for power output                     %
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%Power_output_WilliamYates = (Inner_mass * Damping_ratio * Y_0^2 (Omega/sqrt(Omega_n_square))^3*Omega^3 / ( (1- (Omega/sqrt(Omega_n_square))^2
+ (2* Damping_ratio * (Omega/(sqrt(Omega_n_square)))^2))));
disp(['Power output by William & Yates model:                 ' ' Housing vibration unknown'])

    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    % Erturk & Inman model for power output                      %
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Bmct_r;                                       %Backward modal coupling term
% Fmct_r;                                       %Forward modal coupling term
% Unf_r;                                        %Undamped natural frequency
% Mdr_r;                                        %Mechanical damping ratio of the r´th mode
% iCp;                                          %Internal Capacitance of the piezoceramic layer (Cp = epsilon (upper s, lower 33) *b*L/hp)
% R1;                                           %Load resistance
% Fr;                                           %Modal mechanical damping ratio
% %Omega is the same as in Shu & Liens model
%
% % Erturk - Inman model for power output
% Peak_power_output_Erturk_Inman = (R1 * (Omega * Fmct_r * Fr)^2) / (((Unf_r^2 - Omega^2 *(1 + 2 * Mdr_r * Unf_r * R1 * Cp))^2) + ((2 * Mdr_r * Unf_r
* Omega + Omega * R1 * (Cp * (Unf_r^2 - Omega^2) + Fmct_r * Bmct_r))^2));

disp(['Power output by Erturk & Inmans model:                 ' ' Unknown, testing required to obtain circuitry and mechanical dependencies'])
 disp([' '])
disp(['* Roundys model is for an electromagnetic system, and the answer given is an extremely seldom achieved peak,'])
disp(['since it is only achieved when the system is resonant (our frequency varies the whole time'])
```

## *Capacitor discharge analysis*




The figure shows the discharge rate during a period of 21&½ hours

**Data used in capacitor discharge plot.**

| A | B | C | A | B | C | A | B | C |
|---|---|---|---|---|---|---|---|---|
| 0 | 1,505 | 0 | 19 | 1,001 | 0 | 18 | 1,001 | |
| 1 | 1,354 | 0,604 | 20 | 0,989 | 0,048 | 20 | 0,971 | |
| 2 | 1,292 | 0,248 | 21 | 0,978 | 0,044 | 22 | 0,948 | |
| 3 | 1,251 | 0,164 | | | | 24 | 0,926 | |
| 4 | 1,22 | 0,124 | 18 | 1,01 | 0 | 26 | 0,905 | |
| 5 | 1,194 | 0,104 | 19 | 0,997 | 0,052 | 28 | 0,885 | |
| 6 | 1,172 | 0,088 | 20 | 0,985 | 0,048 | 30 | 0,866 | |
| 7 | 1,153 | 0,076 | | | | 32 | 0,848 | |
| 8 | 1,135 | 0,072 | 11 | 1,101 | 0 | 34 | 0,832 | |
| 9 | 1,119 | 0,064 | 12 | 1,079 | 0,088 | 36 | 0,814 | |
| 10 | 1,109 | 0,04 | 13 | 1,065 | 0,056 | 38 | 0,797 | |
| 11 | 1,089 | 0,08 | 14 | 1,051 | 0,056 | 40 | 0,781 | |
| 12 | 1,076 | 0,052 | | | | 42 | 0,766 | |
| 13 | 1,062 | 0,056 | 14 | 1,052 | 0 | 44 | 0,751 | |
| 14 | 1,05 | 0,048 | 15 | 1,039 | 0,052 | 102 | 0,553 | |
| 15 | 1,038 | 0,048 | 16 | 1,027 | 0,048 | 104 | 0,544 | |
| 16 | 1,026 | 0,048 | 17 | 1,015 | 0,048 | | | |
| 17 | 1,015 | 0,044 | | | | | | |
| 18 | 1,004 | 0,044 | | | | | | |
| 19 | 0,993 | 0,044 | | | | | | |
| 20 | 0,983 | 0,04 | | | | | | |

**Column A** is the time-scale in the measurements, where each jump between two integers represents 15 minutes in time (e.g. 1 to 2 = 15min, 38 to 40 = 30 min).
**Column B** is the measured charge in the capacitors at the given time.
**Column C** represents the discharge rate per hour at between the given charge rate and the previous charge (15 minutes earlier).

Discharge rates were measured day before test-drive, same day (middle ABC columns) and two days after (last ABC columns).

**Code used to generate capacitor discharge plot**

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%
% Piezo power circuit leakage                              %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%
clc
clear all

A1=xlsread('C:\Users\Vi\Documents\MATLAB\Kondesator_lacka.xlsx','A1:A21');
B1=xlsread('C:\Users\Vi\Documents\MATLAB\Kondesator_lacka.xlsx','B1:B21');
C=xlsread('C:\Users\Vi\Documents\MATLAB\Kondesator_lacka.xlsx','C1:C21');

disp('  ')

plot(A1,B1,'r')
hold all

A2=xlsread('C:\Users\Vi\Documents\MATLAB\Kondesator_lacka.xlsx','A19:A21');
B2=xlsread('C:\Users\Vi\Documents\MATLAB\Kondesator_lacka.xlsx','B23:B25');
plot(A2,B2,'b')
hold all

A3=xlsread('C:\Users\Vi\Documents\MATLAB\Kondesator_lacka.xlsx','A18:A20');
B3=xlsread('C:\Users\Vi\Documents\MATLAB\Kondesator_lacka.xlsx','B27:B29');
plot(A3,B3,'g')
hold all

A4=xlsread('C:\Users\Vi\Documents\MATLAB\Kondesator_lacka.xlsx','A11:A14');
B4=xlsread('C:\Users\Vi\Documents\MATLAB\Kondesator_lacka.xlsx','B31:B34');
plot(A4,B4,'g')
hold all

A5=xlsread('C:\Users\Vi\Documents\MATLAB\Kondesator_lacka.xlsx','A14:A17');
B5=xlsread('C:\Users\Vi\Documents\MATLAB\Kondesator_lacka.xlsx','B36:B39');
plot(A5,B5,'b')
hold all

A6=xlsread('C:\Users\Vi\Documents\MATLAB\Kondesator_lacka.xlsx','A50:A65');
B6=xlsread('C:\Users\Vi\Documents\MATLAB\Kondesator_lacka.xlsx','B50:B65');
plot(A6,B6,'c')
hold all

set(gca,'XLim',[0 68]);
set(gca,'XTick',[0:68])
set(gca,'XTickLabel',{' ',' ',' ',' ','1',' ',' ',' ','2',' ',' ',' ','3',' ',' ',' ','4',' ',' ',' ',' 5',' ',' ',' ',' 6',' ',' ',' ',' 7',' ',' ',' ',' 8',' ',' ',' ',' 9','
',' ',' ','10',' ',' ',' ','11',' ',' ',' ','12',' ',' ',' ','13',' ',' ',' ','14',' ',' ',' ','15',' ',' ',' ','16',' ',' ',' ','17'})
title('Capacitor discharge rate');
xlabel('Time [ h ]');
ylabel('Capacitor charge [ V ]');
```

## Appendix III: Energy Harvesting Kit specification sheet

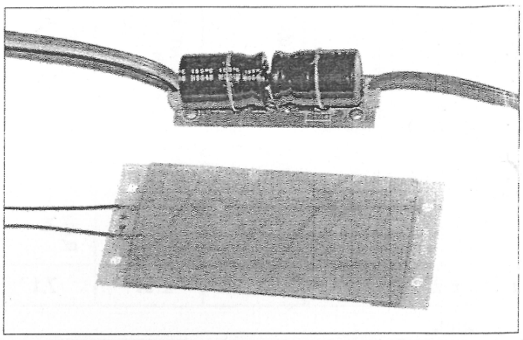
PIEZO ENERGY HARVESTER

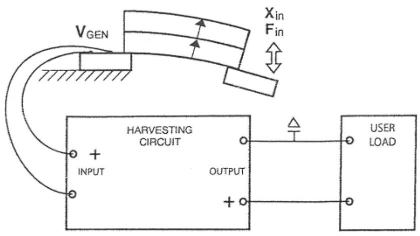
PIEZO SYSTEMS, INC.

65 Tower Office Park, Woburn MA 01801 • Phone: (781) 933-4850 • Fax: (781) 933-4743 • Web: www.piezo.com • E-mail: sales@piezo.com

# PIEZOELECTRIC ENERGY HARVESTING KIT

INSTRUCTIONS






### DESCRIPTION

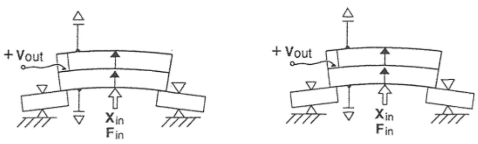
When a piezoceramic trandsucer is stressed mechanically by a force, its electrodes receive a charge that tends to counteract the imposed strain. This charge may be collected, stored and delivered to power electrical circuits, sensors or microprocessors.

The Energy Harvesting Kit (EHK) consists of one Double Quick-Mount Harvesting Bender, one Energy Harvesting Circuit, and two cables.

### THE PIEZO BENDING GENERATOR

When the Piezo Harvesting Bender is flexed, one piezo layer is compressed while the other is streched. This work strains the atomic crystals, producing an electric field within the bulk of the piezoceramic, causing charges of opposite sign to collect on the electrodes of the transducer. Strains may be induced by forces which are intermittent or continuously changing, from low frequency to resonant frequency (where rated displacement is achieved at the lowest force level) and beyond.

The Piezo Harvesting Bender is a pre-mounted and prewired Double Quick-Mount Bending Generator designed to attach easily to sources of mechanical bending strain. Its double ended design lends itself to being mounted either as a cantilever or a simple beam.




Cantelever Mount Simple Beam Mount

NOTE: Although the EHK utilizes a transducer designed to be sensitive to bending, other transducers sensitive to stretching (extension elements) or compression (stacks) can be used as input devices to the harvesting circuit.

### PIEZO ENERGY HARVESTING CIRCUIT

The self powered Piezo Energy Harvesting Circuit collects intermittent or continuous energy input from the piezo generator at Pins 1 & 2, and efficiently stores their associated energy in an on-board capacitor bank.

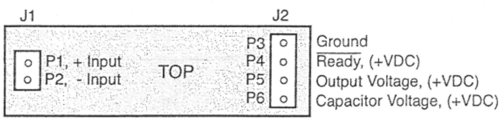
During the charging process, the capacitor bank voltage may be monitored at Pin 6. When the charging voltage reaches 5.2V the output voltage Pin 5 is enabled to supply power to an external (user) load. 55 mJ of electrical energy are available. When input energy from the piezo generator exceeds load demand, the circuit output voltage remains ON continuously. Capacitor or output voltage is clamped at 7V. If the load demands more power than the piezo can generate, output voltage decreases. When the capacitor bank voltage drops to 3.1V, power to the load is switched OFF and is not turned on again until the capacitor bank has been recharged to 5.2V.

A $\overline{\text{READY}}$ logical control output signal is available at Pin 4 preceeding output voltage switching.

The circuit accepts input voltages from 0V to ±500V AC or DC and input currents to 400 mA.

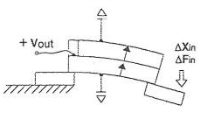
Connection to an additional external capacitor bank is available at the capacitor Pin 6.

No user setup required.



## SPECIFICATIONS

### PIEZO BENDING GENERATOR




| **Part Numbers** Double Quick-Mount Bending Generators — Y-poled for parallel bending operation (3 wire). | Piezo Material | Weight (grams) | Stiffness (N/m) | Capacitance (nF) (Parallel Operation) | Rated Tip Deflection ① ($mm_{peak}$) | Max. Rated Frequency (Resonant Frequency) ① (Hz) | Open Circuit Voltage ① At rated deflection (Vpeak) | Closed Circuit Current ① At rated deflection / cycle (µApeak / Hz) | Rated Output Power ① At rated deflection and frequency ($mW_{rms}$) |
|---|---|---|---|---|---|---|---|---|---|
| EH220-A4-503YB | 5A4E | 10.4 | $1.9 \times 10^2$ | 232 | ± 2.6 | 52 | ± 20.9 | ± 57 | 7.1 |

① Cantilever mount. Force applied at the outermost tip of the mount.

**MECHANICAL**

| | |
|---|---|
| Overall Dimensions | 3.00" Long x 1.25" Wide x 0.9" High |
| Weight | 10.4 grams |

**ENVIRONMENTAL**

| | |
|---|---|
| Operating Temperature Range | 0 to 90° C |
| ROHS | Piezo exempt, product compliant |

### ENERGY HARVESTING CIRCUIT

**ELECTRICAL**

| | |
|---|---|
| Maximum Instantaneous Input Voltage | ± 500 V |
| Maximum Instantaneous Input Current | 400 mA |
| Maximum Input Power | 500 mW |
| Minimum Charging Input (Power Dissipation) | 6.0 V @ 500 nA (3 µW) |
| Internal Voltage Clamp | 7.0 V @ 10 mA |
| Maximum Output Current | 1 amp |
| Operating Life Cycles | Virtually unlimited |
| Logic Compatibility | CMOS |
| Supply Voltage Thresholds | VL = 3.1V VH = 5.2 V |
| Useful Average Energy Output | 55 mJ |
| Output On-Time Rating | 88 msec @ 150 mA |

**MECHANICAL**

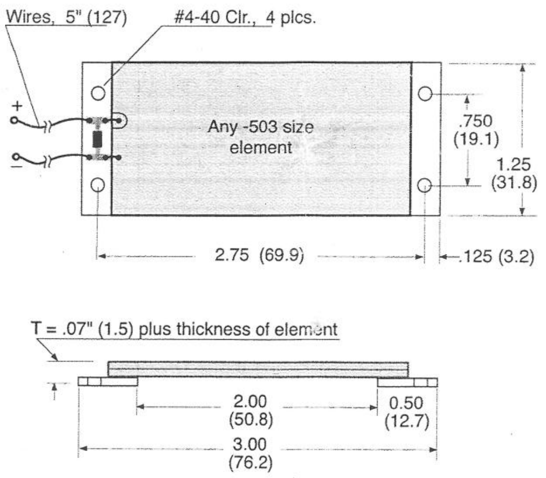
| | |
|---|---|
| Outline Dimensions | 2.00" Long x 0.55" Wide x 0.7" High |
| Mounting Holes | .085" Diameter, 4 places |
| Weight | 14 g (0.5 ounce) |
| Input / Output Cable | 6" J1 connector / 6" J2 connector |

**ENVIRONMENTAL**

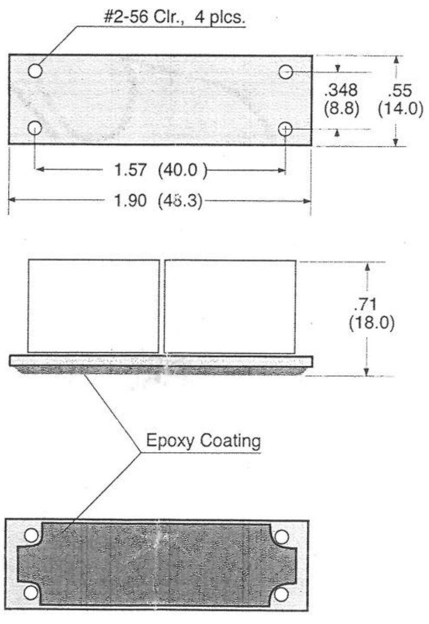
| | |
|---|---|
| Operating Temperature Range | 0 to 70° C |
| Max. Average Operating Temperature | 50° C |
| Storage Temperature | -40 to 85° C |
| Humidity | To 90% (no condensation) |
| Protection | Conformal and epoxy coated |
| ROHS | ROHS Compliant |

## DIMENSIONS

### PIEZO BENDING GENERATOR

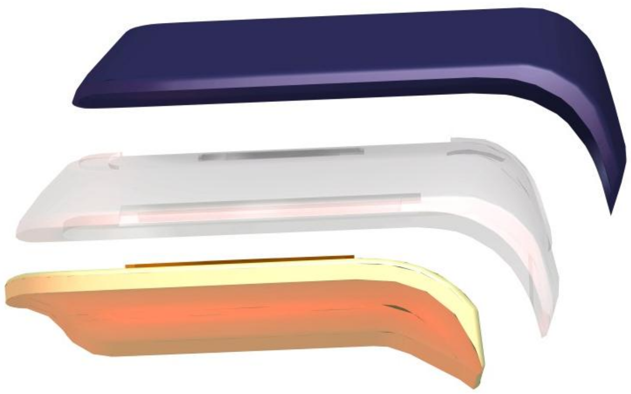


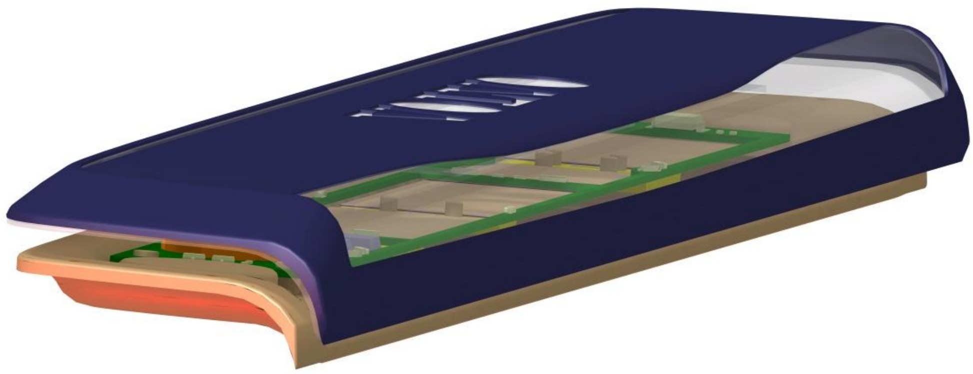

### ENERGY HARVESTING CIRCUIT



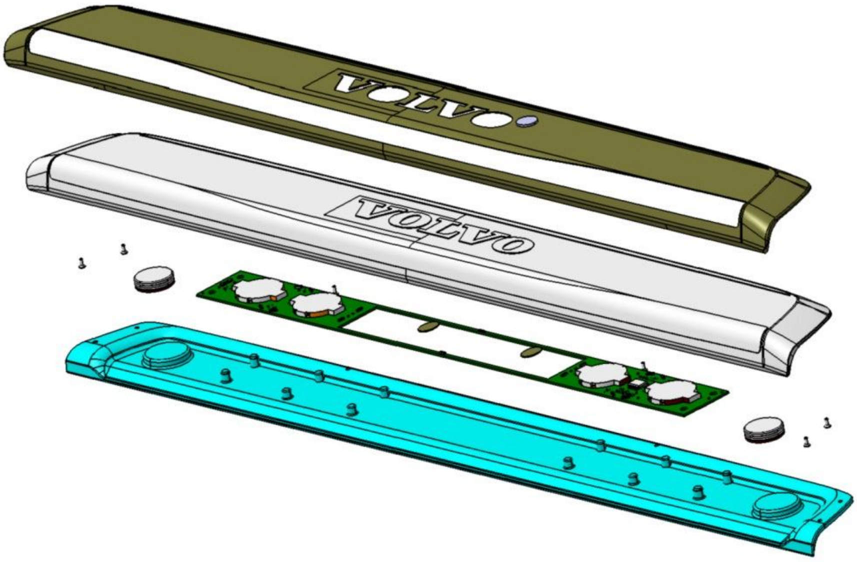
## Appendix IV: Renders and pictures

### *Renders of a step-in-spline with 4 piezoelectric plates inside*



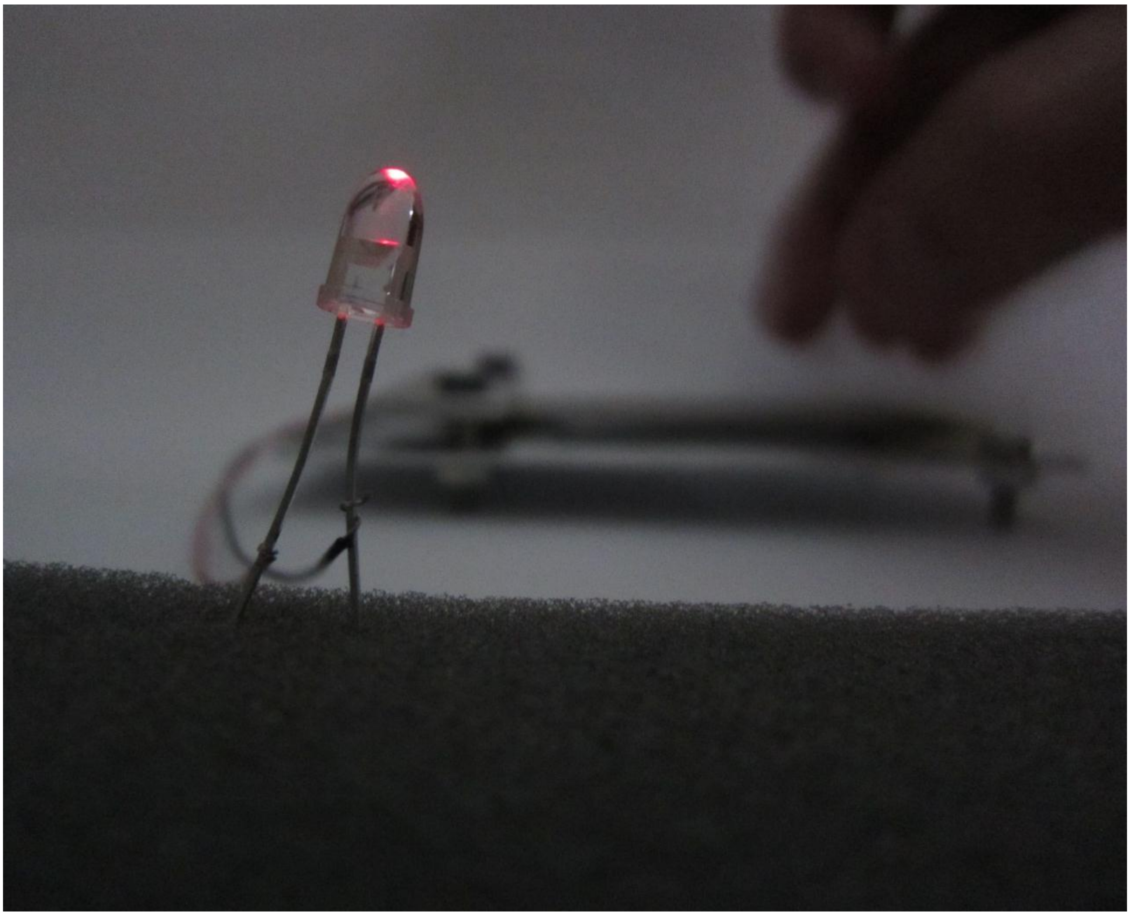


## *Render of the step-in-spline with a battery solution*




## *Energy conversion caught on picture*

A picture illustrating the energy conversion when dropping the mounting system from a height of 2-3 centimeters.



# An alternative energy source for interior accessories

## - Using vibration energy harvesting to power step-in-spline lights

*Master of Science*

Matti Halonen

The purpose of the project is to analyze the possibility of having a piezoelectric energy harvester within the step-in-spline in order to make the system a closed plug-and-play product. What became evident during the literature studies is that the current state of piezoelectric development is in a stage where almost every new application requires a custom-tailored solution in order to work within the intended environment.

The project resulted in a proof-of-principle prototype that shows the potential in having a piezoelectric energy harvesting system implemented within a step-in-spline. The result provides an approximation of how much energy a piezoelectric solution could scavenge from the ambient vibrations that originates from different road conditions when driving a Volvo V60. These ending test-results shows that piezoelectricity is a viable option when designing the power supply of not so power demanding electronic components that otherwise proves difficult to power in traditional ways.

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