Jaakko Palosaari

ENERGY HARVESTING FROM WALKING USING PIEZOELECTRIC CYMBAL AND DIAPHRAGM TYPE STRUCTURES
JAAKKO PALOSAARI

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Abstract

Many electrical devices already surround us in our everyday life. Some devices monitor car performance and traffic while others exist in handheld devices used by the general public. Electrical devices also control manufacturing processes and protect workers from exposure to hazardous working environment. All these devices require electricity to operate. This exponential growth of low power electronic devices in industry, healthcare, military, transportation and in portable personal devices has led to an urgent need for system integrated energy sources.

Many energy harvesting technologies have been developed to serve as a power source in close proximity to the electrical device itself. Solar and magnetic energy harvesters are the most common solutions when conditions are suitable. A more recent technique, called piezoelectric energy harvesting, has raised significant interest among scientists and in industry. Through piezoelectric (ceramic) material mechanical energy can be harvested and converted to electrical energy. This method requires accurate analysis of the kinetic energy experienced by the piezoelectric material so that the mechanics can be suitably designed. At the same time the mechanical design has to protect the piezoelectric material from intense forces that might cause cracks, while still transmitting the kinetic energy efficiently. These requirements usually mean a specific energy harvest design for each ambient energy source at hand.

This thesis is focused on energy harvesting from low frequency compressions using piezoelectric ceramic materials. The objective was to manufacture, measure and implement structures that could sustain the forces experienced under the heel of a foot and maximize the harvested energy amount and efficiency. Two different construction designs were developed and optimised with an iterative process. The kinetic energy impulse under the heel part of the foot was studied by measuring the electrical output of the harvester during walking and then analysed with modelling software. The results were used to create a walking profile for a computer controlled piston to study the input energy phase, speed and force influence on the amount of the harvested energy and the efficiency of the harvesting process. Finally, the functionality of the concept was tested in a real environment with an energy harvester inserted inside a running shoe. The developed harvester showed the highest energy density reported in this frequency region.

Keywords: bimorph, cymbal, energy harvest, piezoelectric, pre-stressed, unimorph
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Tiivistelmä


Asiasanat: bimorph, cymbal, energiankeräys, esijännitys, pietsosähköinen, unimorph
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Oulu, December 2017

Jaakko Palosaari
### List of abbreviations and symbols

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<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>AC</td>
<td>Alternating current</td>
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<tr>
<td>AFM</td>
<td>Atomic force microscope</td>
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<tr>
<td>DSSH</td>
<td>Double Synchronized Switch Harvesting</td>
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<tr>
<td>FEM</td>
<td>Finite element method</td>
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<tr>
<td>C</td>
<td>Capacitance</td>
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<tr>
<td>$d_{31}$</td>
<td>Piezoelectric coefficient</td>
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<tr>
<td>$d_{33}$</td>
<td>Piezoelectric coefficient</td>
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<tr>
<td>DC</td>
<td>Direct current</td>
</tr>
<tr>
<td>$E_{\text{eff}}$</td>
<td>Harvested energy efficiency</td>
</tr>
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<td>$E_{\text{in}}$</td>
<td>Compression energy</td>
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<tr>
<td>$E_{\text{out}}$</td>
<td>Harvested energy</td>
</tr>
<tr>
<td>$F_p$</td>
<td>Piston force</td>
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<tr>
<td>$F_s$</td>
<td>Pre-stress force</td>
</tr>
<tr>
<td>$k_{31}$</td>
<td>Coupling factor</td>
</tr>
<tr>
<td>$k_{33}$</td>
<td>Coupling factor</td>
</tr>
<tr>
<td>MEMS</td>
<td>Microelectromechanical system</td>
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<tr>
<td>P</td>
<td>Power</td>
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<tr>
<td>PC</td>
<td>Polycarbonate</td>
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<tr>
<td>POM</td>
<td>Polyoxymethylene</td>
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<tr>
<td>PSI-5A4E</td>
<td>Lead zirconate titanate type 5A</td>
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<tr>
<td>PVDF</td>
<td>Polyvinylidenefluoride</td>
</tr>
<tr>
<td>PZ-5A</td>
<td>Lead zirconate titanate type 5A</td>
</tr>
<tr>
<td>PZT-5H</td>
<td>Lead zirconate titanate type 5H</td>
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<tr>
<td>PZT</td>
<td>Lead zirconate titanate</td>
</tr>
<tr>
<td>Q</td>
<td>Mechanical quality factor</td>
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<tr>
<td>R</td>
<td>Electrical load resistance</td>
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<tr>
<td>$R_1$</td>
<td>Piezoelectric disc radius</td>
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<tr>
<td>$R_2$</td>
<td>Clamping inner radius</td>
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<tr>
<td>$R_3$</td>
<td>Clamping outer radius</td>
</tr>
<tr>
<td>$R_L$</td>
<td>Electrical load resistance</td>
</tr>
<tr>
<td>SECE</td>
<td>Synchronous Electric Charge Extraction</td>
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<tr>
<td>SSHI</td>
<td>Synchronized Switch Harvesting on Inductor</td>
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<tr>
<td>$t_p$</td>
<td>Piezoelectric disc thickness</td>
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<tr>
<td>$t_s$</td>
<td>Steel thickness</td>
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<td>Symbol</td>
<td>Description</td>
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<tr>
<td>$U$</td>
<td>Voltage</td>
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<tr>
<td>$x_1$</td>
<td>Compression starting point</td>
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<tr>
<td>$x_2$</td>
<td>Compression ending point</td>
</tr>
<tr>
<td>$x$</td>
<td>Compression distance</td>
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<tr>
<td>ZnO</td>
<td>Zinc oxide</td>
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List of original publications

This thesis is based on the following publications, which are referred to throughout the text by their Roman numerals:


In Paper I a cymbal type transducer structure was introduced and manufactured. The thickness of the metal end caps was optimized with an iterative process for energy harvesting and the piezoelectric energy harvester was measured with different compression frequencies and forces. Paper II showed the cymbal type energy harvester measured with sinusoidal compression cycles and compared to a developed compression profile imitating actual walking. Compression profiles were also analysed with a simulation model. In Paper III a diaphragm type energy harvester was designed and manufactured. The transducer was measured under different pre-stressing conditions to optimise the energy harvesting efficiency related to mechanical input energy versus harvested raw electrical output energy. In Paper IV a pre-stressed multilayer diaphragm structure was designed and manufactured. Harvester functionality and raw output power at different speeds were measured inside a shoe heel. The maximum output of the piezoelectric energy harvester was measured with the developed walking profile compressions.

In Paper I, the idea was developed together with co-authors. The design, manufacturing of the cymbal structures and measurements were done by the author. Also the main part of the writing was done by the author. The manufacturing and measurements for Paper II, and related writing in the range of context were done by the author. In Paper III, the manufacturing, measuring, the idea of the adjustable pre-stress and the main part of the writing were done by the author. In Paper IV the idea of the concept, design, manufacturing, measuring, and the main part of the writing were done by the author.
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Original publications
1 Introduction

Energy harvesting is a process where ambient energy in different forms is converted to another form of energy and potentially stored for future use. As there are many types of energy that can be harvested there are also many different harvesting techniques. The most common and well known are solar, biomass and magnetic energy harvesting. In solar energy harvested light is converted by photocells to electricity. From biomass such as trees and plants, energy can be directly converted through combustion to heat or, after being processed to biofuel, via a fuel cell to electricity, although this can be considered as energy production. Magnetic energy harvesters are used to convert mechanical energy directly to electrical energy. This method is also usually related to energy production but is also used in energy harvesting in many publications. Piezoelectric energy harvesting is not so familiar to the general public. As with the magnetic harvesters, piezoelectric materials can also convert mechanical energy to electricity and vice versa. Mechanical energy strain inside the piezoelectric material is released as an electrical charge, which can be harvested or used as a measurement signal. Due to this reversible electromechanical interaction, piezoelectric materials have been used for decades in many applications as actuators, sensors and ultrasonic motors.

Recently piezoelectric energy harvesting has raised a great deal of interest as the quantity of portable electronics has skyrocketed. Due to the developments of signal processing with low power consumption and the growing demand for a small scale energy source for self-sufficient sensor systems, piezoelectric energy harvesting has become a viable potential candidate. For example measuring, controlling and predicting possible maintenance during manufacturing with portable, self-sufficient and cost efficient solutions is now seen as a real possibility. Energy harvesting from human motion is very attractive as we carry many portable devices with us and a continuous source of power would open possibilities for further wearable electronics. For example the healthcare industry would be interested in self-supporting sensors that could monitor a patient’s heart rate, blood pressure, blood sugar levels or oxygen saturation. Fig. 1 shows the exponential growth in publications related to piezoelectric energy harvesters within the last 16 years.
As future sensor systems come to be designed smaller and smaller it would be convenient if the power source could also be scaled down. Piezoelectric energy harvesting provides this possibility with the most miniaturized size in the regime of microelectromechanical systems (MEMS). Another advantage is the long life span as the piezoelectric ceramics can be manufactured to operate over wide temperature ranges and designed to endure demanding dynamic conditions for several years. However, the piezoelectric energy harvester demands precise mechanical and electromechanical designs to match the ambient environment where the energy is being harvested, robust construction for a long life span and accurate designs to meet the energy requirements set by the application.

1.1 Piezoelectricity

Certain materials have the ability to generate an electric charge in response to applied mechanical stress, and the related phenomenon is called the piezoelectric effect. It was first discovered in crystals of topaz, tourmaline and quartz by the brothers Pierre and Jacques Curie in 1880. The word piezoelectric is derived from the Greek word piezein which means to press or squeeze. One unique feature of the piezoelectric effect is its reversibility. Subjecting piezoelectric material to an electric field generates expansion or shrinkage of dimensions of the material
meaning that it can both create stress and strain under an electric field and under stress it can generate electricity. [1]

After the discovery of piezoelectricity, the phenomenon remained just a laboratory experiment until World War I. The first practical application was sonar that was used to detect submarines via ultrasonic sounds. This application inspired a lot of interest in piezoelectric material properties and other possible applications. A vast amount of research lead to the finding of man-made materials called ferroelectrics which exhibited many times greater piezoelectric coefficients than natural piezoelectric materials. Ferroelectrics are a subgroup of piezoelectric materials, where so-called domains have a net polarization. These domains can be orientated with an electric field enhancing the piezoelectric properties. Additionally they offer the possibility of tailoring their performance to specific responses and applications by the introduction of intentional impurities or “dopants” into the material. After World War II material tailoring for specific applications and integration directly onto circuit board was made possible and resulted in a wide range of applications such as transducers, buzzers, igniters and signal filters for television and radio to respond to the demands of the growing communication industry. [2]

In the last three decades piezoelectric applications have spread into almost all industries. For example high frequency positioning of AFM (atomic force microscope) probes developed for research purpose and surgical instruments, imaging and dental cleaners for medical instruments, also ultrasonic applications for welding, level measurements, flow meters and for manufacturing and quality inspection. Specific structures have been made for inkjet printers, vibration damping, interferometers and optical instruments. Applications using piezoelectric energy harvesters are still few in commercial use. Some energy harvesting electronics and vibration based harvesters are commercially available but integration to the final application is left to the customer. Commercial energy harvesters usually work within a certain frequency range near to the resonance frequency. In this case the customer has to consider overall suitability to the environment, the electrical connections, the mounting to the ambient energy source and whether there are sufficient vibrations to power the system. [2–7]

1.2 Piezoelectric energy harvesting

Piezoelectric energy harvesters are based on the same principle as piezoelectric sensors which transform kinetic energy into electrical energy. In the sensor case a
strong and noiseless electrical signal is the design goal but in harvesters the maximal efficiency and the amount of harvested energy are usually prioritised. To facilitate the comparison between different energy harvesting devices, authors frequently report the average power or raw power of the energy harvester. This is calculated from the voltage measured across an electrical load. First publications on energy harvesting with piezoelectric materials are from the 1980’s. In Häsl er et al. (1984) an experiment with PVDF (polyvinylidenefluoride) film was implemented. PVDF is a ferroelectric polymer and can be polarized in the same way as ferroelectric ceramics using an electric field and, in some cases, applied tension. In the experiment a miniaturized prototype was attached to a dog’s ribs where spontaneous breathing expanded the PVDF film [8]. The goal was to prove a concept that enough energy could be harvested from the human respiratory system to power implants that require a permanent power source. Only 17 µW was achieved but the article stated that this could be vastly improved by material research and mechanical modifications. The human body has been used as a kinetic energy source for many energy harvesting studies. Kymisis et al. (1998) performed measurements on 8-layer stacks of 28 µm PVDF sheets and a PZT (lead zirconate titanate) “Thunder sensor/actuator” element embedded in a shoe insole. The PVDF multilayer sheet provided 1.1 mW and the pre-stressed PZT unimorph structure 1.8 mW. The prototype was able to power a RFID transmitter which sent a signal between every 3-6 steps [9]. Another source of wasted energy was exploited by Taylor et al. who designed strips made from PVDF to harvest energy from river or ocean currents [10]. The concept of the idea was to store the harvested energy in batteries so it could later to be used by sensors or robots. An energy harvesting “Eel” was tested inside a tank with different flow speeds. The publication investigated flow speed correlations to power output and dominant frequencies. Many studies have been made to exploit the mechanical resonance of a piezoelectric cantilever beam or diaphragm to harvest energy from vibrations [11–14]. For example in 2012 Wang et al. used an array of four piezoelectric circular diaphragms to harvest energy from mechanical vibrations. The diaphragms’ resonances were tuned close to 150 Hz with equal masses glued on top of them. Parallel electrical connection of the diaphragms resulted in a maximal raw power output of 28 mW at resonance [14]. Another source of energy that has been studied for piezoelectric energy harvesting is pressure fluctuations [15–17]. These experiments usually utilized the same type of piezoelectric circular diaphragm as utilized for vibration harvesting. The diaphragms were mounted from the circumference and deformed as a result of pressure fluctuations. These types of pressure harvester have been proposed to be used for example in the operation of biomedical implants, industrial manufacturing processes, sensors and in the wireless
communication devices carried by scuba divers. Piezoelectric energy harvesters can be quite easily scaled down even into microelectromechanical systems (MEMS). Liu et al. introduced a MEMS power generator that could harvest energy from low-level ambient vibration sources. The structure consisted of an array of piezoelectric cantilevers whose resonance frequencies were tuned by altering their dimensions and by adding different masses at the tip of the cantilevers. A total of 16 cantilevers were fabricated inside an area of 10 mm² which produced 3.98 µW with a 3.93 Vdc output at a frequency of 229 Hz [18].

Because so many portable electronics are now carried with us and because all of these devices require a battery to operate, energy harvesting from the human body has become an attractive topic. Many investigations have been made to transform human body heat into electricity [19–21]. Thermoelectric generator performance is strongly dependent on ambient temperature as the efficiency is determined by the temperature difference between thermocouples. Thermoelectric harvesters can generate power levels in the microwatts range from an area of 1 cm². The design challenge is to implement one side of the thermocouples to be in contact or close to the human skin at all times and still be open to outside temperatures on the other side while maintaining user comfort. Energy generation from clothing has been investigated by combining solar and thermal energy harvesting. Solar energy harvesters can generate around 3-130 µW/cm² from indoor solar light and from 1-100 mW/cm² from outdoor solar light. The solar energy harvesters are dependent on availability of the light but the incident angle and intensity of the light source are crucial [22, 23]. Implemented solar harvesters on clothes would rarely be at the desired optimal angle to the light source.

A lot of wasted energy is available when walking and some of this energy could be transformed into electrical energy without causing any additional burden or wearing any uncomfortable accessories. However, the level of harvested energy depends largely upon mechanics and placement on the human body. Without careful designing and knowledge of human physiology these devices could possibly cause injuries in the long run. [24]

Piezoelectric energy harvester studies have also used human motion to demonstrate the feasibility and functionality of the harvester. A very attractive position for the energy harvester is inside the shoe because it absorbs most energy while walking. The article mentioned on the previous page was by Kymisis et al. (1998) who inserted the harvester inside a shoe insole. Shenck et al. (2001) continued this work and enhanced the power output to 8.4 mW by implementing a double bimorph structure instead of the single unimorph structure. Measured power from the “Thunder sensor/actuator” element corresponded to 4.4 mW/cm³ for the active material. [25] In
order to enable comparison between different energy harvester schemes a commonly used method is to calculate the generated power related to the volume of active material. In real applications, however, the total size of the component is also an important factor. Feenstra et al. implemented a harvester into a backpack strap buckle which had a piezoelectric stack compressed via a mechanical amplifier. This application delivered an average power of ~0.4 mW and was totally invisible to the wearer which is important when designing an energy harvester having human motion as an energy source. Another interesting demonstration has been made by Platt et al. (2005) inside a prosthetic knee implant where a piezoelectric stack was used to harvest enough energy to power sensors that could potentially provide \textit{in vivo} diagnostics for the whole 20 years lifetime of the implant. Such sensors could detect abnormal misalignments, loosening or premature detection of wear and so minimize harm to the patient. [9, 25–31].

Regardless of the source of harvested energy, from wind, ocean, ambient vibrations, pressure deviations or kinetic energy, all piezoelectric energy harvesters rely on compressing and/or tensioning of the piezoelectric material. Harvesters that focus on applying stress to the material along the polarization axis generate the electric field or charge through the piezoelectric coefficient $d_{33}$ which is based on material properties. A good example of a harvester that utilizes compression of piezoelectric material is by Feenstra et al. where a mechanical amplifier was used to amplify the applied forces and generate electrical energy from a piezoelectric stack [32]. Piezoelectric coefficient $d_{33}$, through which the electric field is obtained when strain is orthogonal to the polarization axis, is known to be higher than the $d_{31}$ coefficient. Most energy harvester designs rely on kinetic energy straining the material in such way that the mechanical energy is converted through coefficient $d_{31}$. Examples are the stack, cantilever and diaphragm type harvesters mentioned earlier. Good examples of energy harvesters stretching the piezoelectric material in the $d_{31}$ direction are cymbal type piezoelectric transducers.

This thesis investigates both diaphragm or membrane type transducers and cymbal type transducers as energy harvesters (Fig. 2). A unimorph diaphragm consist of a passive layer and a piezoelectric layer. The passive layer is clamped around the outer region and the piezoelectric layer is bonded onto it. As pressure is applied on the diaphragm it bends both the passive and active piezoelectric layers ideally in a uniform fashion. Possibly harmful sharp stress points to the piezoelectric material are restricted to the boundary of the passive layer and the clamping region while the piezoelectric layer in the center experiences more uniform stress. A bimorph type diaphragm consists of a passive layer and a piezoelectric layer on both sides. [14–18, 33, 34]
Fig. 2. Schematics of the cymbal and a typical diaphragm type transducers.

A cymbal type transducer consists of a piezoelectric plate sandwiched between two convex metal end caps forming a cavity between the piezoelectric disc and the end cap. Applied pressure on the end caps amplifies and directs the force to the piezoelectric material so that it stretches. Cymbal type transducers can be tuned to withstand high levels of stress or to work as very sensitive sensors by using different dimensions for the cavity length, bonding area, end cap flat area and piezoelectric disc or by altering the profile of the end design. [35–38]

1.3 Scope and outline of the thesis

The outline of the work was to design and manufacture piezoelectric energy harvesters capable of harvesting ambient kinetic energy and transform it to electrical energy. The structures were designed to harvest energy from compressive forces by exploiting human walking and running thus being capable of exploiting millimetre range fluctuations. They should also be robust enough to work in the conditions existing under the heel of a foot without noticeable interference to the human actions. The goal was to harvest enough energy to meet the power consumption requirements of low power sensors or to extend the battery life of a portable device.
In Chapter 2 the cymbal type harvesters’ design parameters were explored and four samples were made to investigate the optimum steel thickness of the end cap to produce the maximum energy output. Cymbal harvesters were compressed with varying force amplitudes and frequencies to study the effects on harvested energy gain. A computer controlled piston was used to simulate the actual pressure occurring under the heel when a person is walking. A developed pressure profile imitating the compression cycle of actual walking was used to measure the harvested energy output of a cymbal and this was compared to that from sinusoidal wave type compression cycles. A FEM model was created to analyse compression cycles, electromechanical and mechanical performance of the cymbal type harvester.

Chapter 3 presents the unimorph and bimorph type diaphragm energy harvesters and shows the undisputed benefits that can be achieved with mechanical pre-stress. The unimorph type harvester was used to demonstrate the harvested energy gain without pre-stress and the enhancement with different states of pre-stressing. The chapter reports the improvements in the efficiency related to mechanical input energy versus harvested output energy due to pre-stressing. A bimorph type energy harvester was designed as a stacked four layer diaphragm structure. The harvester worked as a unit where all the layers were bent in the same phase directing the force from the previous layer to the next while all layers were also mechanically pre-stressed. The harvester unit was fitted inside a running shoe to test its functionality and energy harvesting capability on a treadmill. Finally the computer controlled piston was used to measure the maximum potential of the harvester with the walking profile compression cycles developed earlier.
2 Cymbal type energy harvester

2.1 Cymbal type piezoelectric transducers

Cymbal (Fig. 2) type piezoelectric transducers consist of a circular piezoelectric disc with convex end caps bonded at the circumference on both sides of the disc, thus creating a cavity inside. This creates a displacement profile where the cymbal primarily moves with a flexural motion but also has some rotational motion. [39] While operating as an actuator the end cap works as a mechanical amplifier by converting the small change in radial dimension of the piezoelectric disc into a much larger axial displacement. These types of transducers have been widely studied, for example in sonar, positioning actuators and biomedical applications due to their versatile properties and easy tailoring. The overall size, end cap stiffness and cavity design have the strongest effects on resonance frequency, displacement or sensitivity of the actuator or sensor. Piezoelectric material thickness can also be adjusted to meet the required performance. [39–43]

2.2 Cymbal energy harvester design

Due to their versatile tailoring options, high reliability and small deviation during long term operation, the cymbal type piezoelectric transducer has also been studied as an energy harvester [35–38, 44]. These reports focus on harvesting energy from vibration based sources and are modelled for such an environment or tested with a mechanical shaker at around the 100 Hz to 500 Hz region. As a harvester, a cymbal transducer converts mechanical input energy to electrical energy. The force experienced by the metal end caps is amplified and causes radial stress in the piezoelectric material. This stress in turn creates an electrical charge which can be harvested. In this work a cymbal type energy harvester was designed and optimised with respect to the steel end cap thickness for maximum energy harvesting gain at frequencies close to those of walking and running. The effect of mechanical input energy frequency and speed profile related to the amount of energy being harvested was investigated. Furthermore, the harvester was used to characterize the force profile occurring under the heel of the foot at walking speed and to investigate the feasibility of the harvester being mounted inside a shoe. Human feet are convenient places for energy harvesters as the compressing force of the heel can momentarily be more than three times the body weight when walking or running [45].
Piezoelectric cymbal type energy harvester parts and a schematic of the assembly are shown in Fig. 3. Brass rings (150 µm thick, 1.5 mm wide) for electrical connection and steel end caps were laser machined to the same diameter (35 mm) as that of the piezoelectric bulk (PZT-5H) with a thickness of 500 µm. Next the end caps were compressed with a hydraulic press and mould to form a dome shape. Brass rings were then glued on to the piezoelectric disc using cyanoacrylate adhesive, also known as fast glue or super glue. The brass rings presented a convenient place for a good electrical contact and a precise bonding area between samples. A small drop of electrically conducting silver paint was used to ensure electrical contact between the brass rings and the silver electrodes on the ceramic discs. Finally the end caps were bonded on top of the brass rings using the same adhesive and applying a small pressure to the outer edge of the steel discs creating a cavity between the end caps and piezoelectric disc. As the force was applied to the middle points of the end caps, the strain in the piezoelectric material was amplified by a factor determined by the cavity depth and radius. Compressing the steel end caps stretched the piezoelectric material between them in the d_{31} direction, thus creating an electrical charge which could be harvested. A total of four cymbal transducers were made with different thicknesses of the steel end caps: (150, 200, 250 and 300) µm. These samples were made to test the optimum steel thickness relation to the harvested energy and to investigate the compression frequency effect on the amount of energy being harvested.

Another cymbal structure with a steel thickness of 250 µm was manufactured to test the effect of compression acceleration and speed on the voltage output and the amount of energy being harvested. This test compared mechanical sinusoidal compression cycles to more impulse type compression cycles with the same peak force amplitude and frequency. Sinusoidal cycles were smooth repetitive oscillations whereas the impulse type compressions cycles more closely simulated the accelerations occurring during actual walking.
2.3 Kinetic energy harvester measurement setup

The measurement setup consisted of a robust computer controlled positioning system attached to a dynamic load cell recording the force transmitted to the energy harvester. The piston movement range, speed and acceleration were precisely controlled. Forces up to 800 N could be applied to the energy harvester and measured through ball bearing guidance with the force gauge while simultaneously recording the voltage output of the harvester. A schematic and a photo of the measurement system are shown in Fig. 4.

All the force levels in Paper I were measured correctly but the electronics for the force gauge were faulty. Consequently the correct force levels were ~37% higher than reported in Paper I. The corrected values are reported below. In Paper II the same cymbal structure was measured and reported with correct force values.
2.4 Structural optimisation of cymbal type energy harvester

Next paragraphs describe structural optimisation of the harvester for customised force profile and tailored input force effects to harvested output energy. Many mechanical and electrical factors influence the efficiency and the amount of energy that can be harvested from a cymbal type energy harvester. To determine the optimum steel thickness the shape of the steel end caps and the cavity beneath were designed to be similar for all samples. This was because the profile of the end caps and the cavity height strongly effect the strain experienced by the piezoelectric ceramic and consequently the energy harvesting gain. Secondly, the attachment area between the piezoelectric disc and the end caps has a major effect on the transducer functionality. To minimize this variable laser machined brass contacts offered a precise and equal bonding area for each sample. Also small plastic cushions (Ø2.50 mm) were glued on the middle point of each end cap to direct the force cycles in a repeatable manner. The harvester output was measured with sinusoidal compression cycles at 1.19 Hz. The voltage from the harvester was then directed through a rectifier circuit (Fig 5.) and the average raw power was calculated as a function of electrical load. The harvester electronics in Fig. 5
consisted of a rectification circuit using Schottky diodes, a 1 µF capacitor and an electrical load \( R_L \) across which the voltage was measured.

![Harvester electronics diagram](image)

**Fig. 5. Harvester electronics.**

Fig. 6 shows the results of each sample with different end cap thickness. A cymbal harvester with 250 µm steel end caps was found to produce the highest power (0.27 mW) with 34.0 N of compression force as measured with the harvester electronics. End caps with 300 µm, 200 µm and 150 µm thickness resulted in a harvested power of 0.18 mW, 0.16 mW and 0.062 mW respectively and the associated force amplitudes were 37.1 N, 23.1 N and 13.6 N. Although the spring constants of the cymbal structures and the exact input energy were not determined, it is still safe to assume on the basis of the measured output average power and force levels that the sample with 250 µm end caps was also the one with the highest efficiency. Fig. 7 shows the voltage and power from the 250 µm cymbal harvester measured directly across an electrical load (2.6 MΩ) under applied cycles of compression. The calculated average raw power (dashed line in Fig. 7) in this setup was over two times higher at 0.66 mW compared to the 0.27 mW power measured with the harvester electronics. This can be explained by the efficiency of the electronics. The measured power of 0.66 mW corresponded to a power density of 1.37 mW/cm³ for the piezoceramic element.

In the past decade a great deal of research has been conducted on electronic circuits for energy harvesting as they are an essential part of the final application. Piezoelectric energy harvester output current and voltage depend on excitation and therefore they are irregular as a function of time. Because of this irregular voltage an AC-DC rectifier interface circuit is required to produce a DC power supply. With different harvester mechanics and ambient energy sources a harvester output amplitude, frequency and predictability can be anything from pulsed random bursts
of bipolar voltage to a precisely known sinusoidal voltage with a constant amplitude and frequency. For these reasons it is essential to design the electronics to match the voltage output and the impedance of the harvester and also to match the specifications of the final application.

Many of the current research investigations utilize an SSHI (Synchronized Switch Harvesting on Inductor) rectifier to harvest energy very efficiently. It is one of the most energy-efficient circuits with ideally no charge wastage. SSHI was first introduced by Guyomar in [46]. Later it was developed to be self-sufficient with a very low power demand in the micro watt range and the capability to start up independently by detecting zero crossing of the input current [47–49]. Other promising energy harvesting circuits are SECE (Synchronous Electric Charge Extraction) and DSSH (Double Synchronized Switch Harvesting). They are not sensitive to the electrical load and improve the harvested power gain by around 400% and 600% respectively compared to the standard DC mode technique (STD DC) where a regulated output voltage is delivered through a full-wave diode bridge, a capacitor is used filter the output voltage and the power is related to the load impedance. [50–52]

The majority of publications on energy harvesting usually report the average power or raw power gained without any harvesting electronics as it makes comparison between similar techniques or components much easier. In this thesis from now onward the average power and its comparisons refers to this raw power calculated from the voltage across an optimal load.
Compressing the cymbal structure at a higher frequency while applying the same force had a significant effect on harvested power and matching impedance as can be seen in Fig. 8. A harvester with 150 µm thick steel end caps was compressed at 0.35 Hz, 1.19 Hz and 1.65 Hz frequencies using the same 8.1 N force excitation. The 1.65 Hz compression cycles resulted in 39.1 µW and the 0.35 Hz cycles resulted in 8.3 µW, almost five times less.
The next investigation in Paper II focused on how a more impulse type compression profile (walking profile) affected the harvested energy output compared to sinusoidal compression cycles with smooth repetitive oscillations when both cycle
profiles were executed with the same frequency and force amplitude. A casing was made for the cymbal structure and fitted inside a shoe heel (Fig. 9). The piezoelectric element with silver electrodes (PZT-5H), diameter of 35 mm and 0.5 mm thick, was the same as in Paper I. Casing lids and small plastic cushions between the lids and the steel end caps (250 µm thick) directed the force from the heel of the foot to the middle point of the cymbal harvester. By this means the force was directed into the harvester component in the same way as in the computer controlled piston cycles.

![Fig. 9. Harvester inside the casing and fitted inside a shoe heel. (Paper II, published by the permission of Institute of Physics - Journals.)](image)

The voltage output from the harvester inside the shoe heel was measured when walking at a constant pace close to 1 Hz frequency. The harvester was then compressed with the piston by adjusting the acceleration, deceleration and frequency to match the output voltage measured from actual walking. Fig. 10 shows the piston movement adjusted to match the actual accelerations during walking. The cycle starts with a fast compression that reflects the shoe heel hitting the ground.
A small pause occurs before the piston releases the pressure at a slower deceleration reflecting the heel being lifted off the ground. A longer pause takes place before the heel hits the ground again and the cycle starts again from the beginning. The average frequency of a brisk walk was found to be close to 1 Hz, which has also been reported by other publications [9, 25]. The harvester voltage generated by the piston using the walking profile cycles and the actual voltage output from walking can be seen in Fig. 11. The voltage output of the harvester from walking matched very closely to that made with the piston. The voltage peaks were close to two times higher when the heel of the foot hit the ground compared to the foot lifting from the ground. The major part of average power generation was produced at this moment as the power is related to voltage as $P = U^2/R$, where $P$ is power, $U$ is voltage and $R$ is the electrical load.

![Diagram](image.png)

**Fig. 10.** Piston velocity and movement with the walking profile as a function of time. (Paper II, published by the permission of Institute of Physics - Journals.)
The recorded force profile in the creation of the walking profile cycles was then used to analyse the cymbal harvester with a Finite Element Method (FEM) model using different displacements in compression. Cymbal type harvesters have been previously modelled with FEM using sinusoidal input energy and different mechanical configurations [36, 44]. However, simulations comparing an actual walking profile and sinusoidal force input have not previously been investigated in terms of energy harvesting. Fig. 12 shows the measured (with the piston) and simulated power across a load resistance of 2.63 Ω that was found to be the optimal load in Paper II. The maximum average power of 780 µW was measured with 1.5 mm walk profile compressions at 1.0 Hz cycles corresponding to 1.62 mW/cm³ energy density in the piezoelectric element.

Previously (Paper I) with a sinusoidal compression profile at 1.19 Hz frequency and 1.1 mm compression the maximum of 660 µW average power was calculated for the same type of harvester. This power corresponds to an energy of 555 µJ per cycle. With the walking profile and the same 1.1 mm compressions 650 µJ was recorded from a single cycle, which is over 17% greater energy.
Kim et al. showed that with an optimal matching load the generated electrical power is linearly proportional to the frequency as long as the vibration remains at a high frequency with constant force and with negligible damping. This means that the same amount of energy per cycle is obtained regardless of frequency. However, it should be noted that in this case the cymbal type energy harvester was operated below resonance (~13.5 kHz). [36] Results from Paper II may be compared to similar research in the field of cymbal type energy harvesters although the robustness of the structures and the AC to DC conversion efficiency of the harvesting electronics must also be considered. Kim et al. measured a cymbal structure (Ø 29 mm) with different end cap thicknesses and 1 mm thick piezoelectric materials using a mechanical shaker. Approximately 100 mW power was measured from the cymbal structure under high pre-stress and at a much higher frequency of 200 Hz. This corresponds to 760 µJ/cm³ per cycle which is less than half that reported in Paper II (1630 µJ/cm³). Also Ren et al. measured a cymbal structure (Ø 26.6 mm) with a mechanical shaker using 0.7 mm thick single crystal piezoelectric material. A proof mass of 17.0 g was glued on top of the cymbal and 14 mW of power was generated at the resonance frequency of 500 Hz. This corresponds to only 72 µJ/cm³ of power density per stress cycle due to the high frequency. Yan et al. stated that some of the mechanical energy expended in the metal end caps could be directed more efficiently.
to the piezoelectric material by fabricating radial slots in the end caps. The slotted cymbal was manufactured from PZT 5H disc (35 mm in diameter, 2 mm thick). Same diameter 0.5 mm thick brass end caps were slotted and bonded on the piezoceramic disc. The energy harvester was measured at 120 Hz with a mechanical shaker under 30 N bias. Maximum output power was measured at 16 mW which corresponds to 69 μJ/cm³ of power density per stress cycle. The article states that the slotted cymbal average power was about ~67% more than that of the original cymbal transducer. In Paper I almost the same power gain difference (~68%) was measured for a cymbal with 250 μm and 200 μm end caps. From these results it can be concluded that at least some of the same benefits of the slotted cymbal could be also achieved by optimising the end cap thickness. [35, 37, 38, 44]

In Fig. 13 the power outputs of the sinusoidal compression and walking profile compression cycles are presented. The walking profile produced an average of 25.9% greater power compared to that of the sinusoidal profile with the same compression distance and frequency. The walking profile compressed the cymbal structure with a rapid acceleration at the beginning of each cycle. This generated a high voltage level response from the piezoelectric element as can be seen from Fig. 11. The same effect has been reported by Okayasu et al. who studied the electric power generation of a piezoelectric plate under various cyclic loading conditions. Their results showed that at low frequencies, from 0.1 to 10 Hz, square wave compression cycles having a higher acceleration generated much higher voltage levels than triangular and sinusoidal wave modes. This behaviour could be related to the internal resonance of the piezoelectric material as a walking profile or square wave applied to the material might have a higher mechanical to electrical coupling coefficient than slower sinusoidal excitations. [53, 54]
Fig. 13. Power outputs of the harvester with sinusoidal and walking profile excitations as a function of compression distance.
3 Diaphragm type energy harvester

3.1 Diaphragm type transducers

A wide range of membrane or diaphragm type actuators has been developed for numerous applications during the last hundred years. Diaphragm type transducers consist of a piezoelectric thick or thin film which is embedded in an oscillating membrane (Fig. 2). The first underwater sound detection devices (hydrophones) were developed for submarine detection during the First World War in 1917. A piezoelectric membrane turned mechanical vibrations into electrical signals and converted them to soundwaves in earphones. After the War, membrane type piezoelectric transducers were widely studied in the early 1930’s for use in microphones, loudspeakers, recorders etc. [55, 56]. More recently research has concentrated more on (MEMS) based devices where diaphragm type transducers are useful in, for example, microfluidic control systems such as micropumps, valves and inkjet printers [57–60]. There are also many optical applications that utilize diaphragm type actuators, such as devices for deforming mirror surfaces [61, 62].

Within the last decade piezoelectric diaphragm type energy harvester designs and models have been presented. Publications have investigated their feasibility for energy harvesting from ambient energy sources of alternating pressure such as fluctuations of blood pressure, tyre pressure variations, in micro combustion chambers, and in other industrial devices [15–17, 63–72]. Also, alternating mechanical forces or vibrations can be utilised by piezoelectric diaphragm energy harvesters, as described in various publications [14, 73]. Many aspects in the design, manufacture and electrical realization need to be considered to fully exploit the potential of the diaphragm type energy harvester. Electrical, mechanical, material choice and design parameters all determine the efficiency of transformation of mechanical energy into electrical energy. These consists at least of boundary conditions, choice of bonding layer, temperature variations, ratio of passive and active layers both in diameter and in thickness, pressure or compression profile, poling profile and direction, level and type of pre-stress and lastly the efficiency of the associated electrical circuitry. [64, 65, 67–70, 74–80]

In this work the effect of pre-stress on efficiency and the amount of the maximum harvested energy was investigated with a unimorph type diaphragm. A pre-stressed bimorph type energy harvester was used to investigate power density maximization related to piezoelectric material volume, functionality of a stacked
structure and the benefits of pre-stressing with a stacked structure. A unimorph type transducer consists of a piezoelectric layer and a passive layer beneath it while bimorph transducers have a passive layer in the middle and piezoelectric layers on both sides. Pre-stressing was originally developed to enhance piezoelectric coefficients for actuators or to enhance mechanical robustness and electromechanical efficiency, for example in stack type actuators. In unimorph type actuators the pre-stress can be generated by utilizing layers with different thermal coefficients and/or sintering shrinkages. In the cooling process the variances in thermal expansion or shrinking between the passive and active material inflict anisotropic internal stresses that differ across the thickness of the transducer. As a result of these stresses the piezoelectric coefficients are enhanced [81–83]. Pre-stressing has been proven to enhance piezoelectric coefficients not only in actuators but also in energy harvesters. Energy harvesters that exploit mechanical vibrations have been widely studied and in some publications a pre-stressing mass or mechanical axial pre-stress has been noticed to improve power output [13, 14, 35, 71, 72, 76, 84]. In this thesis pre-stressing effects were investigated when an energy harvester was submitted to compression cycles at 1 Hz. Electro mechanical effects related to power generation and efficiency were observed as an adjustable mechanical spring setup acted on the diaphragm type piezoelectric energy harvester. This setup provided a possibility to control precisely the pre-stressing state and to investigate its impact on the energy harvesting performance.

### 3.2 Unimorph diaphragm energy harvester design

The unimorph type piezoelectric diaphragm energy harvester was designed with a mechanical pre-stressing mechanism as shown in Fig 14. Dimensions and parameters of the piezoceramic can be seen in Table 1. A piezoelectric disc (PSI-5A4E, Piezo Systems, INC.) with a thickness of 191 µm, 250 µm thick steel, 560 µm thick polycarbonate clamping rings and 100 µm thick steel plate were all laser machined from bulk materials. The piezoelectric disc (Ø 34.5 mm, radius R1) was first glued on the 100 µm thick steel plate (Ø 45.5 mm) with a thin adhesive layer of ~10 µm. A thin adhesive layer was pointed out to be essential by Mo et al. in diaphragm type energy harvester designs, thus keeping the bonding layer effect to a minimum and ensuring a higher energy harvesting efficiency [70]. A small drop of conductive silver paint was mixed into the glue to confirm a good electrical contact between the piezoelectric disc and the steel plate on the bottom and the 50 µm brass foil on top. These two formed the top and bottom electrodes for the
factory polarized piezoelectric disc. Steel and polycarbonate clamping rings together with 16 screws (Ø 1.5 mm) were used to guarantee a robust and precise clamping region from Ø 45.5 mm (radius R3) to Ø 39.0 mm (radius R2, Fig. 14) for the steel plate. Boundary conditions were related to the clamping conditions on the edge of the passive layer. This edge condition had a significant impact on the overall electromechanical coupling coefficient and generated voltage. In general, a simply supported boundary condition can deliver higher electromechanical coupling and therefore lead to higher efficiency. In practice, ideal boundary conditions are difficult to achieve and also at higher stresses there is only a small difference between the clamped and simply supported cases [67, 77].

![Fig. 14. Piezoelectric diaphragm harvester. a) Construction and adjustable rings for clamping, b) schematic view of the harvester and c) harvester attached to pre-stressing mechanism. (Paper III, published by the permission of Institute of Physics - Journals.)](image)

<table>
<thead>
<tr>
<th>PSI-SA4E</th>
<th>$d_{33}$</th>
<th>$d_{31}$</th>
<th>$k_{33}$</th>
<th>$k_{31}$</th>
<th>Q</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>390 pm/V</td>
<td>-190 pm/V</td>
<td>0.72</td>
<td>0.35</td>
<td>80</td>
<td>~72.5</td>
</tr>
</tbody>
</table>

Table 1. Piezoelectric material properties and energy harvester diaphragm dimensions. (Paper III, published by the permission of Institute of Physics - Journals.)
A pre-stressing mechanism was assembled on the underside of the steel plate (Fig 15). This consisted of a spring inside an aluminium tube with four slots for a metal plate that held the spring aligned. The positions of the metal plate together with an adjustable jig length were used to adjust the pre-stressing state (bias force) by regulating the gap of the spring cavity. Small Ø3 mm polycarbonate cushions were glued on both sides of the diaphragm to align the piston ($F_p$) and pre-stressing spring ($F_s$) forces. Fig. 15 shows a simplified schematic of the experimental setup which was the same as that used in the cymbal type harvester measurements (Fig. 4) with the exception of the pre-stressing mechanism. The harvester was compressed with computer controlled cycles and with the same walking profile as that described earlier in the cymbal type harvester measurements. The walking profile imitated the force occurring under the heel of a foot during actual walking.

![Fig. 15. Schematic of the measurement setup. (Paper III, published by the permission of Institute of Physics - Journals.)](image)

The harvester voltage output was obtained through the $d_{31}$ coefficient as the strain was orthogonal to the polarization axis. The optimum electrical load was determined from the output voltage by calculating the power generated. Measurements were made to determine the maximum efficiency of the harvester while altering the pre-stressing state and comparing mechanical input energy to electrical output energy. Also the maximum power output in relation to the volume
of active material was measured and compared to other similar type energy harvesters or harvesters working in the same frequency region.

### 3.3 Results of the unimorph type energy harvester

The optimum electrical load was determined by compressing the harvester with walking profile cycles. The voltage output from the harvester was measured as a function of electrical resistive load and the power output was calculated (Paper III). An optimum load resistance of 1.25 MΩ was selected to be used for the power output measurements with different pre-stressing states. Before energy harvester measurements the spring constant of the pre-stressing spring and the diaphragm was measured. The pre-stressing spring was initially measured with weights and later by compressing with the computer controlled piston and the diaphragm. Fig 16 shows the nonlinear spring constant of the diaphragm as measured from -0.8 mm to 1.1 mm by bending in both directions from the flat state together with the behaviour of the pre-stressing spring as measured from 1 mm to 20 mm. The figure also shows trend line equations for both spring constants calculated with Excel software. These results showed linear behaviour of the pre-stressing spring constant and good comparison between weight and piston measurements.
Fig. 16. Spring constant measurements of the pre-stressing spring and the diaphragm and trend line (black lines) equations for both.

The energy harvesting potential was first measured without bias force and then with pre-stressing forces of 8.3 N, 13.3 N, 17.6 N and 22.5 N opposite to the compression direction. Compression cycles were performed at 0.96 Hz starting from a 0.3 mm cycle and increasing the compression length by 0.1 mm increments. A small initial force of ~2.0 N was applied via the piston to eliminate any slack in the structure. Due to this initial pressure, the compression cycles started from 0.05 mm and reached a maximum bending of 1.05 mm where the power started to saturate strongly as a function of force.

Fig. 17 illustrates the basic principle of the compression cycles with and without a pre-stress. Compression cycles of 1.00 mm for 0 N and for 17.6 N bias forces (pre-stress) are illustrated with the black arrows. Red arrows indicate the 0 N and 17.6 N bias forces. Due to the non-linear spring constant (Fig. 16) of the diaphragm 52.8 N of force was required to bend the diaphragm from 0.05 mm to 1.05 mm. With the 17.6 N bias the starting point of the cycles was -0.52 mm towards pre-stress and the 1.00 mm deflection only required 24.2 N of force which was less than half that compared to the case without pre-stress.
Fig. 17. Illustration of the 1.00 mm compression cycle with a) 0 N and b) 17.6 N pre-stressing force bias.

Fig. 18 shows the great enhancement in voltage generation due to pre-stressing. The curves compare the energy harvester at zero pre-stress and at 17.6 N pre-stressing states, both bent with 1.00 mm compression cycles. The voltage was measured across the optimal load of resistance $1.25 \, \text{M} \Omega$. The generated peak voltage was $\sim 38\%$ higher in the pre-stressed case and the peak force needed to achieve this was only $\sim 46\%$ of that for the non-pre-stressed state. Non-linear behaviour was observed in the force curves where the compression cycle distance was longer than the curvature depth of the diaphragm created by the pre-stress (Fig. 17). For example, in Fig. 18 with the 17.6 N pre-stress, the non-linear point of the force curve was at the halfway point of 1.00 mm compression cycle ($\sim 0.65 \, \text{s}$), although the piston retraction speed was constant at 3 m/s. This occurs when the compression cycle goes over the flat state of the diaphragm.
Fig. 18. Voltage and force outputs of non-pre-stressed case and with 17.6 N bias from 1 mm compression cycle. (Paper III, published by the permission of Institute of Physics - Journals.)

Fig. 19 presents the harvested power as a function of compression distance and Fig. 20 shows harvested energy as a function of compression energy for each pre-stress state. The harvested power in watts was calculated from the measured voltage across the matching electrical load resistor and the energy output from the integrated power in watts within a known time period. The input energy \( E_{in} \) at compression, equation 1, was calculated for all force biases by integrating over the nonlinear spring constant of the diaphragm and adding the pre-stressing linear spring energy from the compression distance \( x \) in each case where \( x = x_2 - x_1 \) meaning the ending and starting points respectively.

\[
E_{in} = \frac{1}{2} k x^2 + \int_{x_1}^{x_2} f(x) \, dx
\]  

(1)

With 17.6 N pre-stress and with 1.5 mm compression distance the energy harvester generated a maximum average power of 1079 µW or an energy of 1.12 mJ/cycle. The same pre-stressing bias was also the best in measurements of power versus compression distance, with 771 µW/mm achieved at 1.1 mm cycles (Fig. 19). When
comparing the cases without pre-stress (0 N bias) and with 17.6 N force bias the energy harvesting enhancement can be clearly seen. The maximum compression distance of 1.0 mm with 0 N and 17.6 N bias generated 438 µW and 752 µW, respectively with the same cycle. This is a ~72% increase in power generation due to pre-stressing. In addition, only one third of the energy input to the system was needed with the 17.6 N compared to 0 N bias, consuming only 6.2 mJ instead of 18.9 mJ. This is due to the non-linear spring constant of the diaphragm and the fact that the pre-stressing cycle was performed over the flat region of the diaphragm from -0.52 mm to 0.48 mm, reaching the diaphragm flat state in the middle of the compression cycle. As the zero bias cycle started from the flat state of the diaphragm and the energy demand to bend the diaphragm grows exponentially, hence the profound difference between 0 n and 17.6 N pre-stressing states is explained. In addition, pre-stressing affects the piezoelectric coefficients of the piezoelectric material and improves the harvested energy radically. [85–87]

Fig. 19. Harvested power as a function of compression cycle distance with different force biases. (Paper III, published by the permission of Institute of Physics - Journals.)
In Fig. 21 the efficiency curves for each pre-stress state as a function of harvested energy are shown. Efficiency was calculated by dividing the output energy by the input energy as seen in equation 2. These calculations clearly show the benefits of the pre-stressing effects.

$$Eff. = \frac{E_{out}}{E_{in}} \times 100\%$$

Without pre-stress the energy harvesting efficiency from 0.3 mm to 1.0 mm compression started from 10.1% and continuously decreased to 2.4%. This was due to the non-linear spring constant of the diaphragm (Fig. 16) as the input energy required to bend the diaphragm increased exponentially as a function of distance. In the pre-stressed cases all the efficiencies first increased after the 0.3 mm compression cycle. The input energy required to bend the structure was mostly determined by the pre-stressing linear spring up to the point where the compression distance equaled the pre-stressing distance. A major difference from the non-pre-stressed case was that the saturation of the efficiency started after 0.7 mm (8.3 N bias) and at 1.1 mm (22.5 N bias) compression, whereas in the non-pre-stressed

Fig. 20. Harvested electrical energy as a function of compression energy per cycle. (Paper III, published by the permission of Institute of Physics - Journals.)
case the saturation had already started before 0.3 mm. The 13.3 N pre-stress produced the highest efficiency and, in contrast to the case without pre-stress, after the 0.3 mm compression efficiency (5.1%) it still increased. With 0.8 mm compression the efficiency was 14.7% and was still 5.8% with a 1.4 mm compression cycle. The highest 14.7% efficiency was achieved with a compression energy of 3.776 mJ which resulted in 0.556 mJ of harvested energy.

Fig. 21. Efficiency as a function of harvested energy per compression cycle. (Paper III, published by the permission of Institute of Physics - Journals.)

It is essential to harvest wasted energy as efficiently as possible so it is sensible to design and optimise the diaphragm type harvester to work in the most efficient region of its characteristics. Based on these results this can be only done when the failure limit and the input energy available to the system are known. Although more energy could be harvested with the maximum applied pre-stress and with the maximum bending used in the measurements this might lead to serious discomfort in the case of shoe implementation. In addition, the lifetime of the harvester would be more likely to be shortened as higher stresses would wear out parts more rapidly. To reach the amount of energy needed from the harvester to support that required by the electronics the unimorph design could be realized as a multilayer structure.
in contrast to the extreme bending of the structure from maximum pre-stress to maximum compression distance. To enhance the energy density and efficiency even further the layers could be designed with bimorph layers as described in the next section and in Paper IV. Also, adjustment of the thickness ratio of passive and active material to the optimum could further improve the stress distribution to the piezoelectric ceramic and hence the gain of harvested energy. This is because too thin a passive layer could collapse under stress and too thick a layer would decrease the total deflection [16, 70]. The thickness of the active piezoelectric layer can be also adjusted with a nonlinear approach according to El-Sabbagh et al. [80].

### 3.4 Multilayer bimorph energy harvester design

As in the unimorph design (sections 3.2 & 3.3) all parts were laser machined except for the pre-stressing spring (Fig. 22). The bimorph harvester design had the same outer diameter of 45.5 mm as did the unimorph harvester. The multilayer bimorphs consisted of four 50 µm thick steel plates with 191 µm thick PSI-5A4E (PZ-5A, Piezo Systems Inc.) piezoelectric ceramics (Ø 34.5 mm) attached on both sides with conductive epoxy. Small polycarbonate (PC) cushions 500 µm thick (Ø 3.5 mm) between each layer directed the applied force from the piston to the middle point and also isolated the layers from each other. Copper tape was used to make electrical contacts to each of the piezoelectric discs. Clamping rings made from 300 µm thick steel and 560 µm thick PC rings were used to create a precise and robust construction. The overall thickness of four bimorph diaphragms with cushions and clamping rings was ~4.0 mm. A casing housing the pre-stressing mechanism was made from polyoxymethylene (POM) and the structure was sealed with 1.5 mm polycarbonate (PC) covers. The cavity depth of casing for the pre-stressing spring from the bottom cover to the bimorph layers was designed to direct a ~58 N pre-stress. The whole closed harvester assembly was 15 mm thick and was clamped together with 16 screws.
Electrical contacts were guided out from the casing with wires. These can be seen in Fig. 23 where the energy harvester is embedded into a running shoe. A round hole was carved into the shoe where the harvester was placed and locked in place with silicone rubber. The voltage output was first measured when running and walking on a treadmill at different speeds. Next the multilayer bimorph harvester was removed from the shoe and tested with the computer controlled piston setup described earlier in the cymbal and Unimorph harvester measurements (Papers II & III). A simplified cross-section of the bimorph harvester during the measurement procedure can be seen in Fig. 24. This illustrates how the bimorph layers stacked up inside the holster and were connected with each other through the PC cushions. It can be also seen how the layers bent towards the holster top cover due to the pre-stress and how the layers bent in the opposite direction as a result of the force input.
3.5 Measurement results of the multilayer bimorph type harvester

First the energy harvester was fitted inside a running shoe and the voltage output was measured over the optimum 147 kΩ load. The weight of the harvester was ~44 g, being hardly noticeable during the treadmill tests as it was inside the silicone rubber and under the shoe insole. Fig. 25 shows the voltage output when walking with speeds of 4, 6 and 8 km/h and running with speeds of 10, 12 and 14 km/h on a treadmill. The step frequency increased as the treadmill travel speed was increased.
Also the voltage output increased as the foot directed higher kinetic forces to the bimorph layers inside the shoe heel. Increasing the travel speed could be seen from the voltage curves as they became sharper at the impact moment and also when the foot rose and weight was lifted off the heel. The measured power increased significantly as a function of the walking speed. In the case of running, the power output improved between 10 km/h and 12 km/h but saturated slightly at 14 km/h. This could be a result of a change in running technique where the weight was moved from the heel towards the ball of the foot when running faster. Table 2 shows the average raw powers from a ~20 second period for each travel speed. The highest average power of 6.01 mW was measured when running at 12 km/h where the instantaneous power was as high as 83.82 mW.

Voltage curves measured at walking speed in Fig. 25 show a small voltage peak at the half point of the cycle. This represents the shock from the left foot hitting the ground and causing a small vibration in the harvester on the right foot heel. This small voltage peak is missing from the curves recorded at running speed as the right leg is up in the air when the left leg hits the ground. These tiny voltage peaks show the sensitivity of the harvester and a possibility that it could also be used to monitor a person’s walking to correct any harmful techniques. The treadmill test showed that the harvester module was very robust and a feasible implementation but was also very sensitive to even small fluctuations in pressure.
Fig. 25. Harvester voltages across 147 kΩ load during treadmill tests when a) walking at a speed of 4, 6, 8 km/h and b) running at a speed of 10, 12, 14 km/h. (Paper IV, published by the permission of John Wiley and Sons.)

Table 2. Average powers from walking and running at different speeds and the highest recorded power output from computer controlled piston measurements. (Paper IV, published by the permission of John Wiley and Sons.)

<table>
<thead>
<tr>
<th>Impulse</th>
<th>Power [mw]</th>
<th>Frequency [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walk 4 km/h</td>
<td>2.06</td>
<td>0.89</td>
</tr>
<tr>
<td>Walk 6 km/h</td>
<td>3.65</td>
<td>1.07</td>
</tr>
<tr>
<td>Walk 8 km/h</td>
<td>5.32</td>
<td>1.19</td>
</tr>
<tr>
<td>Run 10 km/h</td>
<td>4.29</td>
<td>1.43</td>
</tr>
<tr>
<td>Run 12 km/h</td>
<td>6.01</td>
<td>1.52</td>
</tr>
<tr>
<td>Run 14 km/h</td>
<td>5.46</td>
<td>1.58</td>
</tr>
<tr>
<td>Piston 1.8 mm</td>
<td>11.3</td>
<td>1.07</td>
</tr>
</tbody>
</table>
It was found out that the multilayer bimorph type energy harvester was capable of generating much more energy than that measured in the treadmill tests. A significant amount of the input energy was wasted in the top cover and into the shoe insole and the bimorph layers’ stiffness was not optimal for the weight of the test person. It was also found that different walking techniques with different weight distributions from person to person could significantly affect the amount of harvested energy. All these variables were considered in the next set of measurements. The harvester’s performance was measured with the computer controlled piston cycles using the walking profile. The top cover of the harvester holster was removed and the harvester voltage output was measured at 1.07 Hz. This frequency corresponded to the treadmill tests at 6 km/h and the voltage output from the treadmill was also in line with the voltage curves measured with piston cycles.

Fig. 26 shows the individual voltage gain of each bimorph layer across 634 kΩ (the optimum load for a single bimorph layer) measured with a 1.9 mm compression cycle. The voltage curves maintained the same level of amplitude due to the robust construction and the precision of the piston. Also the voltage outputs were maintained in the same phase between each bimorph layer. This is vital to keep charge cancellation to a minimum [14]. The mechanical pre-stress kept the bimorph layers in contact which each other at all times during the compression cycles. This was the key to the small phase difference. Pre-stress had also been proved earlier to enhance the physical compression distance and efficiency in unimorph type diaphragm harvesters (Paper III). Piezoelectric actuators had likewise been able to achieve larger displacements and piezoelectric coefficients due to pre-stress [81–83, 88].
To measure the maximum potential of the harvester all the layers were then connected in parallel and the voltage was measured across the optimum 147 kΩ load. The cycle compression distance was increased from 0.6 mm all the way to the cracking point at 2.0 mm in 0.1 mm steps. In the initial state the bimorph layers were bent ~0.85 mm with the 58 N pre-stress from the midpoint. With the maximum 2.0 mm piston cycle the layers bent ~1.15 mm in the opposite direction from the flat state. Fig. 27 presents the calculated average powers as functions of compression distance. The compression force was measured with the force gauge as described earlier and the compression energy was calculated by integrating the force curve over the compression distance. The maximum power output of 11.30 mW was measured with a 1.8 mm compression cycle at 1.07 Hz. This was achieved with 223.2 N of force which corresponded to 179 mJ of mechanical energy. The highest harvested energy output from a single cycle was 10.56 mJ and the calculated power density for the piezoelectric material was 10.55 mW/cm³. With higher forces and longer compression distances the power output started to saturate as the piezoelectric ceramic of one of the bimorph layers became cracked. The above reported power density of the piezoelectric multilayer bimorph energy harvester is the highest reported in this frequency range.
The efficiency for the harvester was calculated by dividing the harvested energy output by the compression input energy. The highest efficiency of 9.9% was calculated from a 1.2 mm compression cycle. This can be further enhanced with optimal pre-stress as proven in Paper III. Also the thickness ratio of the passive and active layer has a large effect as mentioned earlier. The amount of energy harvested can always be improved by adding more piezoelectric layers and by increasing the dimensions of the layers. In the case of the running shoe implementation the maximum piezoelectric disc diameter could be increased to ~Ø50.0 mm thus doubling the volume of the piezoelectric material.

Table 3 compares earlier reported cymbal and diaphragm type energy harvesters from different applications and from various working frequency ranges. The cymbal structure can sustain high force inputs even at high frequencies as demonstrated by Kim et al. where the harvester was under a vibration force of 70 N from 10 – 200 Hz with a power output up to 100 mW [36]. This corresponded to 500 µJ per cycle which is ~64% of the 784 µJ reported in this thesis from the cymbal type harvester. The diaphragm type harvesters investigated in this thesis produced ~10.5 mJ of energy for each cycle which is significantly higher than that reported in other publications. The only reported publication that comes close to these numbers refers to the double dimorph Thunder TH-6 transducer used by
Shenk et al. inside a shoe heel which produced 9.3 mJ. But the power density for the piezoelectric ceramic volume of the bimorph stack harvester was over two times higher at 10.55 mW/cm$^3$ compared to 4.41 mW/cm$^3$ of the dimorph Thunder harvester. Adjustable pre-stressing offers many design features and furthermore an advantage over the Thunder TH-6R transducers. These cannot be reverse bent without cracking of the piezoceramic as it is designed to work from a curved pre-stressed form to a flat form. [25]

### Table 3. Comparison of piezoelectric energy harvesters.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Application</th>
<th>Size: active material [mm]</th>
<th>Material</th>
<th>[Hz]$^a$</th>
<th>[µJ]$^b$</th>
<th>[mW/cm$^3$]$^c$</th>
<th>[mW]$^d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zhao [71]</td>
<td>Thermo-acoustic Diaphragm Ø 63.5, $t_p$: 2 x 0.1905</td>
<td>PZT-SA 180</td>
<td>1.2</td>
<td>0.17</td>
<td>0.21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wang [14]</td>
<td>Diaphragm array in resonance Diaphragm Ø50.0, $t_p$: 0.20</td>
<td>PZT 150</td>
<td>56.7</td>
<td>86.58</td>
<td>8.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mo [16]</td>
<td>Pressure loaded diaphragm Diaphragm Ø25.4, $t_p$: 0.127</td>
<td>PZT-SH 1</td>
<td>128.0</td>
<td>1.99</td>
<td>0.13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shenk [25]</td>
<td>Dimorph: TH-6R transducer (shoe heel) Area: 50x50, $t_p$: 2 x 0.381</td>
<td>PZT 0.9</td>
<td>9333.3</td>
<td>4.41</td>
<td>8.40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shenk [25]</td>
<td>Multilayer (2x8) Piezoelectric-foil (shoe insole) Hexagonal shape: 6500 mm$^2$, $t_p$: 16 x 0.028</td>
<td>PVDF 0.9</td>
<td>1444.4</td>
<td>0.45</td>
<td>1.30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Li [89]</td>
<td>Free edge bimorph (wind energy harvester) Cantilever: 16 x 72, $t_p$: 0.41</td>
<td>PVDF ~2.5</td>
<td>246.0</td>
<td>1.30</td>
<td>0.62</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zhu [90]</td>
<td>Cyclic stretching releasing agitation Nanowire arrays: 1 cm$^2$ working area, $t_p$: 200 nm</td>
<td>ZnO 3.0</td>
<td>63.4 pJ*</td>
<td>0.01*</td>
<td>0.19 nW*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kim [36]</td>
<td>Cymbal in a mechanical shaker Disc Ø 29, $T_p$: 1.00</td>
<td>PZT (D210) 200</td>
<td>500</td>
<td>151.36</td>
<td>100.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leinonen [Paper II]</td>
<td>Cymbal (shoe heel) Disc Ø 25.4, $t_p$: 0.50</td>
<td>PZT-SH 1</td>
<td>784</td>
<td>1.63</td>
<td>0.78</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Palosaari [Paper IV]</td>
<td>Pre-stressed Multilayer bimorph diaphragm Diaphragm Ø 34.5, $t_p$: 8 x 0.191</td>
<td>PZT-SA 1.07</td>
<td>10560.7</td>
<td>10.55</td>
<td>11.30</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^a$ Working frequency of the harvester
$^b$ Energy per cycle produced by the harvester
$^c$ Power density of the energy harvesting material
$^d$ The average power harvested

* Reported energy was 1.37 µJ from a 7200 second period with 3 Hz operation frequency

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4 Conclusions

The main focus of this thesis was to research and develop novel piezoelectric harvester designs for low frequency kinetic energy sources. The aim was to fabricate harvesters and characterise their behaviour in authentic conditions or conditions that simulated actual usage under the heel of the foot during walking. Four cymbal type energy harvesters were manufactured and measured to determine the optimal steel thickness and the cymbal structure with the highest potential for practical applications. This was investigated with the developed walking profile compression cycles and compared to sinusoidal compression cycles. In addition, a mechanically pre-stressed unimorph type diaphragm harvester was designed and measured with the walking profile compression cycles to determine the optimum pre-stressing level which delivered the highest efficiency in terms of compression input energy versus harvested output energy. The pre-stressing results and the diaphragm design were then utilized in a multilayer bimorph type energy harvester to investigate the amount of energy that could be harvested from the actual implementation and test its functionality when fitted inside a running shoe.

The presented cymbal type harvester deviates from a traditional cymbal transducer having uniformly curved convex steel plate end caps. Nevertheless, the same crucial design parameters of diameter, cavity depth and thickness of the steel end caps determined the functionality of the harvester. From the four different steel thicknesses examined in the cymbal structure, the 250 µm end cap steel thicknesses was found to be the closest to the optimal generating the highest amount of electrical energy. This cymbal harvester was fitted into a shoe heel. The generated voltage from actual walking was recorded, analysed and used to create walking profile compression cycles with a computer controlled piston. At 1.19 Hz compression frequency the harvested average power was 0.66 mW, which correlated with a power density of 1.37 mW/cm³ for the 500 µm thick and Ø35 mm piezoelectric element. The FEM analysis of the cymbal structure showed that the walking profile compression cycles generated close to 26% more energy at the same frequency and compression cycle distance than did the sinusoidal compression profile. With 1.5 mm compression cycle distance at 1.0 Hz a maximum average power of 780 µW was measured corresponding to a power density of 1.62 mW/cm³ for the piezoelectric ceramic.

The unimorph type diaphragm energy harvester was manufactured and measured first without any pre-stress and then with different force biases utilizing the developed walking profile compression cycles. With a mechanical pre-stress of
13.3 N the highest harvesting efficiency of 14.7% was achieved. Furthermore, the pre-stressed state compared to the non-pre-stressed case showed an increased energy gain of 141% with the same mechanical input energy. With the improved efficiency and longer compression distance with pre-stress the maximum power density for the piezoelectric material of 6.06 mW/cm³ was obtained with 0.96 Hz compression cycles.

The concept of a mechanically pre-stressed diaphragm type energy harvester was next utilised for a multilayer bimorph type diaphragm structure. The harvester consisted of four bimorph layers pre-stressed with a 58 N bias force. Functionality and the maximum amount of energy gain were tested. Functionality and robustness of the harvester was successfully proven in the treadmill measurements where the harvester was fitted inside a shoe heel. An average power of 6.01 mW and instantaneous peak powers as high as ~84 mW were measured when running at 12 km/h. Using the computer controlled piston and the walking profile cycle compressions a maximum of 11.30 mW was measured at 1.07 Hz, which corresponded to 10.55 mW/cm³ for the PZ-5A ceramic. This power density was found to be over two times higher than that reported for any application close to this frequency range.

Cymbal or diaphragm type harvesters designed and measured in this thesis would already meet the power consumption requirements of many developed low power sensors; the carbon dioxide sensor (COZIR LP) from GSS consumes 3.0 mW [91], the humidity sensor with integrated temperature sensor (HDC 1008) from Texas Instruments only consumes 6.0 µW [92], the operating power of the pressure sensor (MS5541) from Servoflo is ~12 µW [93], the Analog Devices 3-axis MEMS accelerometer sensor (ADXL354) consumes ~0.54mW in measurement mode and only ~76 µW in standby mode [94]. The pulse oximeter and heart rate sensor (MAX30100) from Maxim Integrated average power take is ~2.0 mW and maximum of 50 µW in sleep mode [95] and the carbon monoxide detector from Texas Instruments consumes ~1.7 mW in alarm state and only ~1.8 µW in stand by state [96, 97]. Some of these sensors could be operated from a suitable energy harvester, possibly together with some other power source, for example in a firefighter’s suit, in healthcare to monitor patients or in a warning system to protect workers or soldiers from exposure to hazardous working environment. However, harvesting electronics must always be designed to match the energy harvester output and input specifications of the final application.

The amount of energy harvested can still be improved by adding more piezoelectric material to the designs, increasing the dimensions and/or adding
layers. In the cymbal case the end cap is a critical component for transferring the kinetic input energy to the piezoelectric material and the design of this could further be enhanced with the aid of simulation software. For example, end caps could be designed with a nonlinear thickness to improve the mechanical energy transmission which would in turn lead to an enhanced gain in energy harvesting. Increasing the harvesting frequency could be a potential future experiment for the mechanically pre-stressed diaphragm structure. Future work should involve the development of harvesting electronics to investigate the total efficiency of the energy harvesting process. The power density of the pre-stressed multilayer bimorph type energy harvester measured at 10.55 mW/cm$^3$ for the PZ-5A ceramic is a strong argument for the high quality of the energy harvesting technique.
List of references


Original publications


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ENERGY HARVESTING FROM WALKING USING PIEZOELECTRIC CYMBAL AND DIAPHRAGM TYPE STRUCTURES