

CRANFIELD UNIVERSITY

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ENERGY SCAVENGING PIEZOELECTRIC POWERED LED SYSTEM
FOR USE IN TRACER AMMUNITION

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This thesis is submitted in partial fulfilment of the requirements for the
degree of PhD

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ABSTRACT

Fuel-oxidizer tracer ammunition is the standard technology used to produce bright light for projectile observation. However, a modern electronic tracer system has the potential to eliminate the safety risks associated with combustible materials and open flame systems by replacing them with a safer, integrated energy harvester-powered electronic light-emitting system. The goal of this research is to investigate the technologies necessary to convert kinetic energy from the bullet propulsion into electrical power and to assess whether an integrated energy harvesting system, coupled with electrical storage and an LED with the accompanying circuitry, could feasibly replace the current technology in the future.

The study focuses on analysing existing mechanical-to-electrical transduction technologies, understanding their design and use limitations, and evaluating their suitability for implementation with small arms munitions that undergo high linear and rotational acceleration. Additionally, this research examines the complexity of manufacturing, construction, and adaptability of these technologies to smaller and larger of munitions. After reviewing and filtering previous system designs and technology prototypes, piezoelectric energy harvesting technology was selected due to its energy density, material and structural compatibility for withstanding large forces and lower mechanical system complexity for further development.

A prototype piezoelectric system was designed and simulated using commercial software to model both structural and electrical behaviour. Experimental validation tests were conducted with high compressive loads and rotational forces experienced in real-world conditions. The research developed three novel spring structures that significantly increase the power density of linear and rotational piezoelectric energy harvesters. These spring structures feature enhanced shearing capabilities with disc spring optimisation allowing 39% energy harvesting improvement and a prototype system tuned for the 7.62 mm tracer outputting 3 V. and can be manufactured with relatively low complexity compared to other energy harvesting technologies.

With the novel energy harvesting system in place, additional modelling was conducted to design the accompanying LED circuit and capacitive energy storage, thereby completing the development of the Electronic Tracer system.

Keywords:

Tracer, Small Arms Ammunition, Slug, Piezo, Piezoelectric, Energy Harvesting, Shear mode, Springs, Washers

“If you’re going through hell, keep going.” – Winston Churchill

“As I review the events of my past life, I realize how subtle are the influences that shape our destinies.” - Nikola Tesla

This PhD to me was a testament to my will, that I see my commitments through to the end, even if it gets tough.

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LIST OF ABBREVIATIONS

EH	Energy Harvester
HEH	Hybrid Energy Harvester
TEG	Thermoelectric Energy Harvester
PM	Permanent Magnet
DC	Direct Current
AC	Alternating Current
CNC	Computer Numerical Coding
PZT	Lead Zirconate Titanate
CFT	Contact Freestanding-layer Triboelectric
IC	Integrated Circuit
CS	(Vertical) Contact Separation mode
LS	In-plane sliding mode or Lateral Sliding mode
SE	Single Electrode mode
CFT	Contact Freestanding Triboelectric layer mode
SFT	Separated Freestanding Triboelectric layer mode
TENG	Triboelectric Nano Generator
SMA	Shape Memory Alloy
TEG	Thermoelectric Generator
EMF	Electromotive force
FOM	Figure of merit
PE	Piezoelectric

1 Introduction

1.1 Background & motivations

1.1.1 What are tracers?

Pyrotechnic tracers are a type of ammunition used by militaries globally. The characteristics of a pyrotechnic tracer are that they emit a bright light from an oxidation reaction that can be seen by the user after firing - even in daylight. The light emitted by the tracer round is used by the shooter to be able to visibly identify projectile trajectories, allowing the shooter to adjust aim and resulting in more accurate firing. Because of the intense light given off, the adjustments can normally be judged by eye and do not require using weapon sights. Other uses for tracers are for marking the direction of gunfire and identifying targets for other shooters to engage. Tracers also have had other specialist military uses; for example, the original tracer ammunition oxidation reaction burned intensely, it could be used by aircraft to attack fuel tanks and other aircraft (at the period of use - aircraft were wooden), creating explosions and fire. A common tactic still used is for the tracer rounds to be packed in with normal ammunition (sometimes in the last three rounds), this would notify the shooter for when they are nearing the end of their ammunition.

Before the tracer, there was the “spotlight” round, this round created a light flash on impact but was banned in warfare under the Hague convention for exploding bullets. Smoke trail bullets were also created for tracing, but the burning of mass needed to create the smoke caused destabilisation and greatly affected the accuracy and the maximum travel distance. The current small arms tracers were developed by the United Kingdom in 1915 followed by the United States in 1917.

Incendiary tracers were used against hydrogen aircraft along with Incendiary rounds (dedicated burning rounds) to ignite the gas. The material inside the round is a pyrotechnic flare, this material is often phosphorus or magnesium or other chemicals and produces a bright light when burned (ignited by the bullet propellant).

Today tracers are used in warfare and have been researched to create different outputs for different situations, the chemical compounds are adjusted for a different brightness output; bright, subdued, dim and more recently infra-red. The lower light versions specifically for night vision and are purposefully designed not to give away the position of the shooter and not be blinding for operations using night vision. Tuning is possible by changing the combinations of the fuel and oxidiser, and the materials used is usually magnesium carbonate, calcium resinate, and barium and strontium peroxides. The fuel and oxidiser are capped by an igniter, ignited by the hot propellant of the gas during gunfire. [1]



Figure 1-1 M276 round example (red is the igniter shielding the fuel and oxidiser) [1]

In recent years, there has been movement away from certain fuels and oxidisers, specifically barium because of the environmental damage caused by this toxic material, and US Occupational Safety and Health Administration (OSHA) has regulated the material. Other core materials also have limiting factors such as the small numbers of suppliers, bad quality control standards and potentially dangerous self-igniting tendencies during excessive movement (calcium resinate). [1] Self-ignition, accidental ignition or accidental fires have been an issue with Pyrotechnic tracers and have caused serious incidents. The use of tracers in warm climates have caused wildfires destroying dry scrubland and causing danger to life.[2]. Replacing the current fuel-oxidiser and igniter combination with a less volatile material could be a safer alternative for all aspects of a tracer ammunition lifetime and remove the obstacles related with storage and the regulation of explosive materials. (MOD regulated tracers in the UK).

The attraction of a pyrolytic substance for creation of illumination (tracers in this case) is because of the energy density of the fuel and oxidiser and simplicity of fabrication. With a small work area and the exposure to high pressures and in some cases temperature swings, the choice of fuel (or simply -energy) is limited. Other such techniques to create a light source have been and are being explored, with materials with photoluminescence; a current technology of non-flammable phosphorus creating a very dim glow visible only to the shooter with a 30-degree view window, this type of light emission does not come with intense heat, burning and is safely storable.

Tracer fuel and oxidiser are in different quantities based on the type of weapon device used to propel the projectile. The basic sizes of NATO small calibre rounds are the 7.62 x 51 (L5A1) mm and the 5.56 x 45 mm round. Medium (20-40mm) and Large (105mm – 155mm) calibre munitions offer larger spaces at a reduced spin rate. All types of fuel or energy sources are needed to be confined to the interior of the slug (which is the bullet projectile). This slug is exposed to extreme pressure on ignition of the propellant, increasing velocity and high spin rates.

The basic energy of the projectile can be calculated using the equation:

Equation 1-1

$$Energy (J) = \frac{1}{2} mass (kg) \times velocity (m/s)^2$$

$$Energy = 1 J = 1 kg.m^2/s^2$$

$$1 \text{ grain (gr)} = 0.0065 \text{ grams (g)}$$

7.62 mm orange tip- 142 grains = 9.2 grams and muzzle velocity of 749 m/s [3]

$$E = \frac{1}{2}mv^2 = 0.5 \times 0.0092 \text{ kg} \times 749^2 \frac{\text{m}}{\text{s}} = 2580.6 \text{ Joules}$$

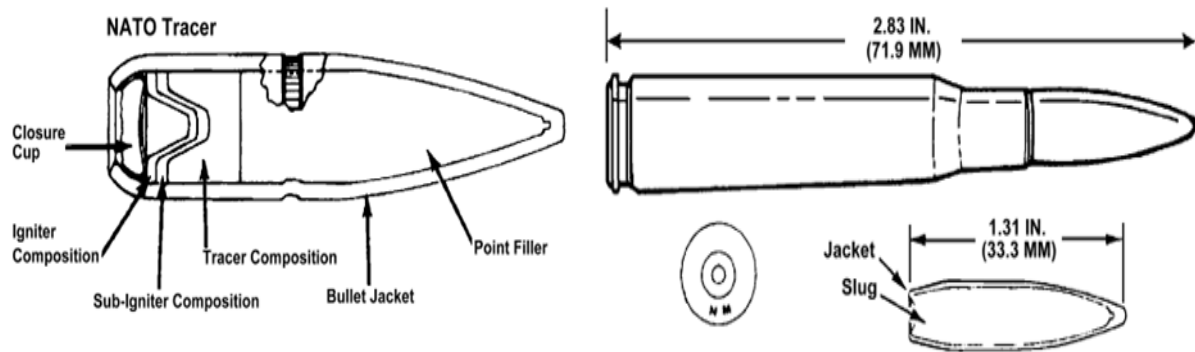


Figure 1-2 - 7.62 x 51 Tracer Schematic [4]

5.56 mm red tip - 55 grains (3.56 grams) and muzzle velocity of 975 m/s [4]

$$E = \frac{1}{2}mv^2 = 0.5 \times 0.00356 \text{ kg} \times 975^2 \frac{\text{m}}{\text{s}} = 1692.1 \text{ Joules}$$

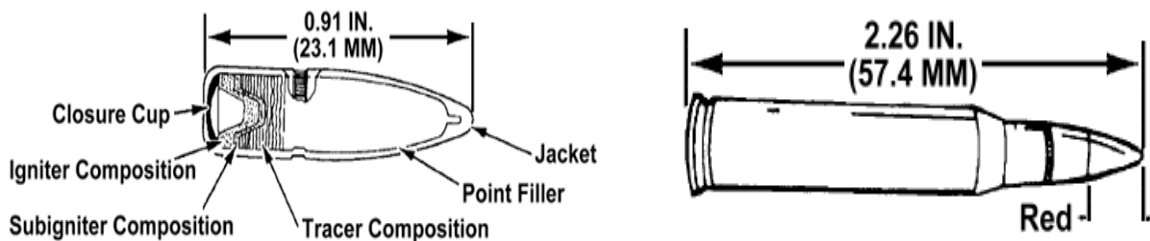


Figure 1-3 - 5.56 Tracer Schematic [4]

The velocities are dependent on time and type of munition, meaning there are variations in energy of each munition type and small variations in each individual munition. Another factor that affects energy is grain size (weight) of the slug and mass of propellant used in body, in non-military use – different energy is required for hunting (depending on animal size) and high velocity & pressure tests (NASA hypervelocity - 6000m/s light-gas gun used for high pressure experiments e.g., metallic state Hydrogen experiment).

Larger medium-calibre cannon munition such as the 40 mm M81A1 anti-armour ammunition has a muzzle velocity of 872 m/s. The ammo has larger amounts of explosive tracer in the shell, which makes them more of a hazard to store. For conversion to non-combusting tracer configurations, the pocket for the chemicals takes up a size of 15 mm diameter at approximately 30 mm length.[5]

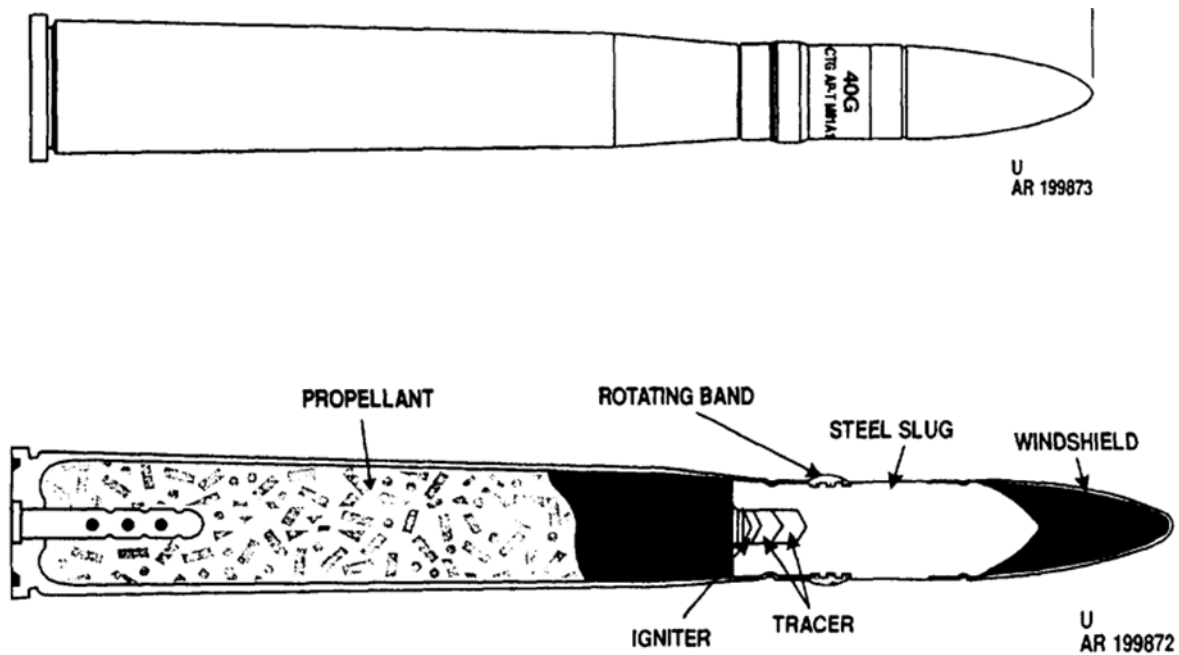


Figure 1-4 M81A1 Tracer Schematic [3]

Replacing the metal oxidation as a fuel and light source can be done using LED light and an electrical generation system that can be designed to fit the small work package. The introduction of an electrical system also comes with benefits of not changing the weight of the round during flight, no dangerous oxidation reactions from accidental ignition, and complete customisation of the electrical components and light emissions. The electrical energy required to power an LED could be extracted from the system via an energy harvesting method; piezo electrical, thermoelectric, or electromagnetic.

The amount of energy extracted from the propellant explosion energy and transferred into the slug is dependent on the efficiency of the energy harvester mechanism fitted into the available space, which is shown below for a 7.62mm bullet. Energy requirements to turn on an LED for 1 second or 749 m, can be as little as 32 millijoules (assuming a low power LED of 1.6 V and 20 mA – 32 mW is used).

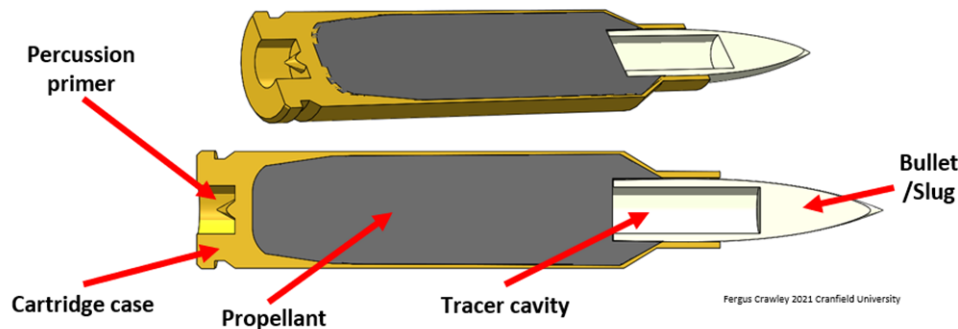


Figure 1-5 - 7.62 Tracer Cut Away

There exists a significant research gap concerning the feasibility of developing an electronic tracer with an integrated energy harvesting system that matches the functionality of the currently utilized pyrotechnic tracers. An electronic system could potentially address numerous challenges encountered within the industry. Although there are numerous instances of energy harvesting technologies designed for larger systems that generate electrical power for electrical sensors and timers in specialist munitions, as cited in references [6], [7], [8], and [9], there is limited research on their applicability to smaller systems. The scalability of such systems for small arms ammunition, which must endure substantial linear and rotational forces, remains unclear. Furthermore, there is insufficient investigation into the types of energy harvesting technologies that would be suitable for small arms munitions, as well as the necessary electronic components required to develop a functional LED driver circuit combined with the energy harvester.

Given these considerations, there is a compelling industrial incentive to explore whether an electronic alternative is feasible in terms of manufacturability, cost, and complexity. The prospect of self-powered electronic tracer ammunition holds substantial commercial appeal for both military and civilian customers and could potentially mitigate environmental impacts.

1.2 Aim & Objective

The aim of this research is to create and test an energy harvesting system capable of powering an Electronic Tracer sufficiently, with the goal of electronic tracers replacing conventional fuel-oxidiser tracers currently used. The focus is on the main mechanical to electrical technology, the structural mechanics and behaviour of the device and the electrical energy storage and use.

Objective 1:

Review the current technologies used in small scale energy harvesting. Evaluate the technology in terms of scaling, power generation, system complexity and power density.

Objective 2:

Evaluate the current Tracer technology, energy available from the system and space available to insert an energy harvester. Understand the mechanical forces involved and identify the technology that is well suited to the scale and environment.

Objective 3:

Develop an efficient energy harvester system capable of operating under high-force loads. Using advanced CAD and Multiphysics simulation tools, design and model a system incorporating the energy harvester. Detailed simulations optimizing parameters such as structural dimensions for shear mode actuation for enhanced energy generation in piezoelectric material. Fabricate prototypes using precision manufacturing techniques for complex geometries, such as 3D printing and machining. Measure energy outputs and validate the design. Evaluation of performance, energy density, structural integrity, and manufacturability to ensure the system meets its intended application requirements.

Objective 4:

Formulate the electronic storage and light emitting circuit configuration to condition the electrical power output of the energy harvester and maximise the light produced. Understand and compare the electronic tracer strengths and limitations to the existing fuel-oxidiser technology.

1.3 Novelty and Project Outputs

This research of energy harvesting for electronic tracer ammunition has contributed one published publication with more papers yet to be published. Three patents have been filed regarding novel spring structures designed and explored in this research. Due to time constraints and the broadness of tracer ammunition sizes and available information, certain sized systems were focused on to complete the objectives.

A literature review was undertaken to make sure that concentrated analytical studies seen in the chapters 2-7 had not been explored in depth. Understanding other literature allowed for comparing other prototype energy harvesting systems and identifying their strengths, weaknesses, and working volumes. This information also highlighted which technologies could be scaled down effectively and the complexity of the mechanism transducing the forces from slug body to the energy harvester system. Without this section, filtering to the appropriate technology, progressing to the next objectives would be more difficult.

The crinkle and disc spring washer structures were analysed through simulation and experiments to compare their deformation behaviour under load when in combination with a piezoelectric disc. The investigation of these structures identified the potential benefits of the alternative designs. The research demonstrated each washers shearing capacity, deformation under load and identified the structures limiting characteristics such as stress concentration which were shown to negatively affect electrical energy production.

New design considerations were explored which led to a novel shaped disc washer with a tapered, curved and topology optimised cross-sectional area designed to be paired with piezoelectric discs to maximise shearing outputs from a linear compression force and thus improve electrical energy generation.

Later research combined the previous findings to create a novel design of crinkle shear washer, called the hyperbolic paraboloid washer, capable of being loaded on 2 faces to maximise space saving while remaining a single component. The structure also took advantage of topology optimisation and simulation to decrease internal stresses and aid in the deformation characteristics that improve shearing. This washer was then simulated in the 7.62mm tracer user case scenario under the acceleration and load characteristics to demonstrate its capabilities yielding

optimistic results for small calibre piezoelectric energy harvesting electronic tracer munition.

Another novel solution to the energy harvesting in tracer ammunition was the use of a flat torsional spring combined into a rotational mass-spring dampener system that would absorb the torque from the rotational acceleration and exert shear stress onto a bonded piezo disc surface. This was created using additive manufacturing and demonstrated the concept of spiral - compressive and expanding torsional disks for the lesser explored rotational piezoelectric energy harvester.

1.4 Electronic Tracer application summary

This research aims to design an energy harvester system capable of powering a light emitting system that must all be located inside the projectile component (slug) of a tracer bullet.

The space available for this harvester and electronic light-emitting circuit is:

- $\text{Ø}6\text{mm} \times 10\text{mm} = 282.74 \text{ mm}^3$

The energy harvested must power on an LED:

- Voltage range = 1.6 V – 3V
- Current = 20 mA
- Power = 32 mW
- Time = 1 second
- Energy = 32 – 60 mJ

This energy requirement can be adjusted and reduced using various methods of power conditioning and including a pulsation architecture to the circuit.

The weight of the volume removed for the energy harvester and electronics:

- Steel volume removed: $282.74 \text{ mm}^3 = 2.233 \text{ grams}$
- Total weight of 7.62 mm (no tracer component): 9.2 grams

Velocity of 7.62 mm Ammunition:

- Peak velocity is 749 m/s

Energy of a standard 7.62 mm slug = 2580.6 Joules

1.5 Thesis Outline

Chapter 1 defines the work, introduces the challenge and the importance of the research.

Chapter 2 is the review of energy harvesting technologies, specifically on the mechanisms needed to convert mechanical energy into electrical energy and the size and power constraints.

Chapter 3 is focused on a section of the available system energy: linear force. It is comprised of testing two types of structural washers that have beneficial shearing characteristics when combined with piezo electric systems.

Chapter 4 explores optimisation of the shear structure: Disc Spring used to improve the electrical energy output of a piezoelectric element. The research applies Multiphysics with shape and topology optimisation to further enhance the transduction of linear force to shear force and improve electrical generation.

Chapter 5 presents a design iteration and optimisation of less understood structure: wave/crinkle washer, to create a novel design of a compact two side shear structure.

Chapter 6 is focused on the second part of the system energy which is the rotational force. Using experiments and simulations to create novel Piezoelectric activation structures that can absorb rotational energy in a spring-mass system.

Chapter 7 consists of the combination of work undertaken in the previous chapters. It brings together the research to design and build a fully working system and test the effectiveness in lab conditions.

Chapter 8 gives a general discussion of the work undertaken and the results linking all work back to the main aim and objectives.

Chapter 9 concludes the work and provides future recommendations.

2 A review of Current Technologies used for Small-Scale Energy Harvesting Systems

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Abstract

Electronic components are becoming much smaller, lighter, and with higher functionality than ever before. The growing need for more energy dense battery storage, rapid charging and/or the ability to harness ambient energy has driven the need for more integrated, compact, and effective energy harvesting systems. With decreasing size of electronic devices and improved wireless communication, electronic devices are used more frequently in larger quantities and in more remote locations. An issue that arises from the usage of the electronic devices is the power consumption and the duration of the electronics' battery life. Lower power consumption electronics has extended the duration of use, but it has not completely solved the issue.

For smaller volume electronic systems that experience harsher environments such as large compressive force and high accelerations be it linear or rotational, the available harvesting technology that can be scaled down without adding high levels of complexity is somewhat limited to those with transduction mechanisms that can convert deformation, rotational or vibration energy into electrical energy. Piezoelectric and electromagnetic energy harvesting systems have demonstrated through a variety of different mechanical systems the capability to be scaled and compacted which this review aims to further summarize.

2.1 Introduction

Energy harvesting has garnered significant attention due to the rapid evolution of technology developed annually. The increasing complexity and functionality of electronic devices, coupled with their widespread daily use, have underscored the importance of advancements in this field. These technological improvements, particularly in the miniaturization of components such as computing processors, have been enabled by the development of battery technologies with enhanced energy density, facilitating greater efficiency and portability. [6].

Current battery technologies are capable of powering electronic devices, such as mobile phones, for daily use, typically requiring recharging daily. While this arrangement is convenient for most users of consumer electronics, it presents challenges for devices that are used intermittently or are situated in remote locations where access to mains power for regular recharging is not feasible. Although batteries are useful in most cases, there are issues which are highlighted by Hannan [6] including the high cost of the batteries if there are large volumes needing to be replaced monthly or annually, and the contribution to environmental waste from batteries that are unrecyclable. Other factors that are also detrimental to batteries include charge cycling and weather fluctuations such as heat or cold that can cause an increase in the rates of self-discharge or can decrease the storage capacity.

An example of improving remote device power systems used by S. W. Arms, involves the use of remote devices such as sensors or low power communications as used in agriculture or industrial automation. These function on the requirements of under 2mW [7]. Methods of periodical battery replacement has been an option for remote device energy storage, but larger batteries lead to bulkier devices and not all consumer products would be able to accommodate bulky and expensive battery packs.

A solution to this issue of energy storage in an electrical device has been identified as adding an energy harvesting system that can draw power from the surrounding environment such as sunlight, wind, or vibrations [8]. An energy harvesting system is a system which composes of a technology that can convert solar energy (or Electromagnetic Spectrum) or kinetic energy into electrical energy, combined with an electrical system that regulates the electricity produced so that it can charge a storage device (battery). The complexity of an energy harvester system is based on the application, with the possibility of additional levels of controls included to prevent damage, caused by power surging, overcharging, or overheating, to the main electronics in the devices components. Figure 2-1 is a schematic of the components of a simplified energy harvesting system.

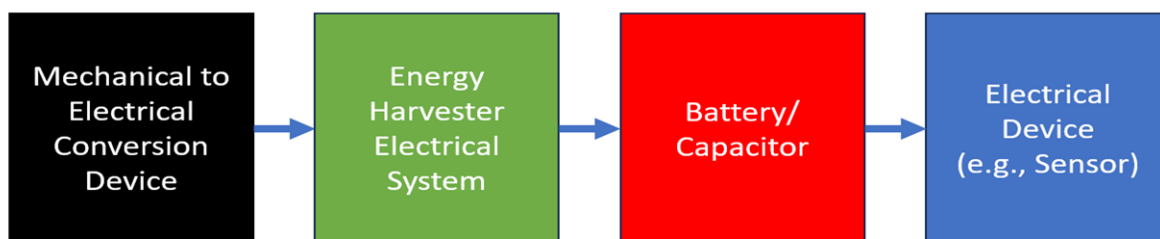


Figure 2-1 Simplified Energy Harvester Schematic

This review will:

- look further into the main technologies used in small volume energy harvesters
- attempt to understand the power constraints caused by scaling down to the mm-scale
- investigate the mechanism requirements and constraints for the mechanical to electrical transduction required to implement a smaller device.

The mm-scale is achievable using conventional machining and fabrication methods, such as CNC (Computer Numerical Coding) systems, and in other smaller systems the use of chemical etching (used in electronics and semiconductor industries) has been demonstrated to create accurate components.

2.2 Conventional Energy Harvesting (EH)

Energy harvesting (or energy scavenging) is when vibrations, mechanical loads, temperature gradients, surface static charges and light (photons) are scavenged and turned into usable electrical energy. Energy scavenging can be used for battery-less systems, (those systems where the option of recharging is not practical) and systems that an energy harvester can be added onto, to minimise energy losses and boost efficiency. Currently available and most conventional energy harvesting systems that can be scaled into most industries are piezoelectric, thermoelectric, electromagnetic, and electrostatic [9].

Energy harvesting systems come in many different shapes and sizes, with mm-scale energy harvesting systems manufactured by conventional machining methods being classed as a micro energy harvester or Micro-electrical-mechanical-system (MEMS). The class below the mm-scale is nano energy harvesters which are usually fabricated by chemical etching in the nano meter scale and integrated into micro or nano Integrated Circuit (IC) chips.

Table 2-1 below indicates typical achievable energy levels for micro energy harvesting applications.

Table 2-1 Energy Sources and Conventional Conversion Mechanisms

Type of Harvester	Energy Source	Conversion Mechanism	Power Density $\mu\text{W}/\text{cm}^3$
Micro energy harvesting	Vibration	Piezoelectric	100-330 $\mu\text{W}/\text{cm}^3$
		Electromagnetic	
		Electrostatic	
	Ambient radiation	Electromagnetic	1 $\mu\text{W}/\text{cm}^3$
	Ambient light	Photovoltaic	100 $\mu\text{W}/\text{cm}^3$ - 100 mW/cm^3
	Thermal	Thermoelectric	60 $\mu\text{W}/\text{cm}^3$
	Fluid Flow	Turbines	10000 - 50000 $\mu\text{W}/\text{cm}^3$

2.3 Piezoelectric energy harvesting

Piezo electricity is the result of the piezoelectric effect. The word “Piézo” (Πιέζω) comes from the Greek language and translates as “press down”. The effect was discovered in 1880 by Jacques and Pierre Curie using quartz crystals under pressure

to produce an electrical charge. They also found the inverse-piezo effect when applying an electrical field to the crystal, it produced structural deformation which is proportional to the inputted differentiating voltages and currents. The inverse piezo effect has been used to produce piezo speakers, piezo motors, and piezo actuators. The two types of materials which have piezo characteristics are crystals and ceramics, as they must not be electrically conductive [10] .

The piezoelectric effect relates heavily to the piezo material atomic structure. The organisation of the structure is either crystalline or amorphous, amorphous being long chained irregular structured materials, and crystalline having uniform defined and repeating atom chains. The atomic piezo structure required to generate a dipole (oppositely charged faces) must have no centre of symmetry, otherwise any deformation would result in the dipole remaining at an equilibrium charge. Another factor that affects the electrical dipole is the temperature. Piezo materials are subject to a Curie point, a critical temperature after which the material loses polarisation, and the internal dipole lowers to zero. The internal charge structure of a piezo electric material in the figure below represents Lead Zirconate Titanate (PZT) at a temperature below and above the Curie point. In Figure 2-2 which demonstrates the crystalline structure, the black dot indicates that the charge symmetry is off centre (left, polarised) until the critical temperature, resulting in charge equilibrium (right, equilibrium) [11].

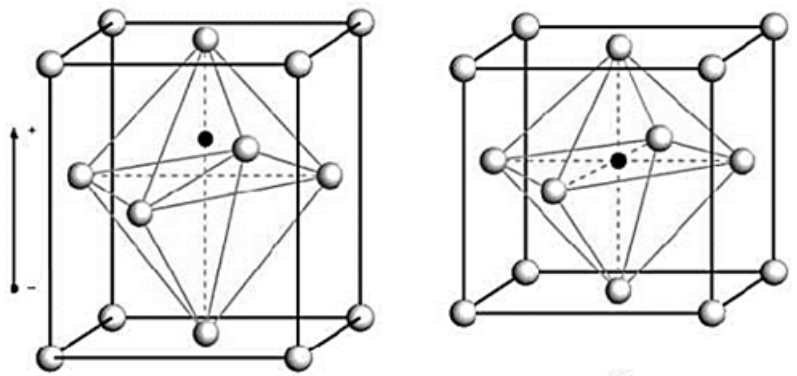


Figure 2-2 Piezo Crystal Structure (Left = Polarised, right = charge equilibrium at critical temperature [8]

The direct piezo effect is used in energy harvesting in the presence of vibration or the tension and compression of an object. A popular piezo material used is PZT Pb $[\text{Zr}_x\text{Ti}_{1-x}] \text{O}_3$, developed by the Tokyo Institute of Technology around 1952. PZT is a combination of lead and zirconium and is manufactured at elevated temperatures

(800°C and above). PZT has favourable characteristics as it withstands temperatures of up to 300°C before depolarisation, has a reliable strength and is chemically inert. It is also widely available and inexpensive [12].

Piezoelectric materials characteristics differ depending on the direction of the applied force or electric field as shown in Figure 2-3, and subscripts are used to represent the directions: X, Y, Z as 1, 2, 3 and 4, 5, 6 are shear in X, Y, Z. For example the d_{15} - shearing, the first subscript represents “1” the polling direction and the second subscript “5” is the force direction (90° angle between polling and force).

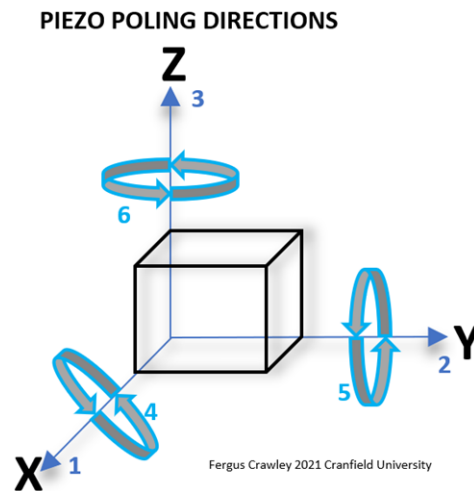


Figure 2-3 Piezo Poling Diagram

Electrical generation due to compressive material deformation in parallel with the pole direction can be measured by the piezoelectric voltage constant (g_{33}) which represents the ratio of voltage (potential difference) per meter deflection to the input force (Vm/N) [13].

Equation 2-1

$$V = \left(-g_{33} \times h \times \frac{F}{A} \right) = - \left(g_{33} \times h \times \left(\frac{F}{\pi r^2} \right) \right)$$

- V =voltage (V)
- g_{33} = piezoelectric constant (Vm/N)
- h = length/thickness of piezo material (m)
- F = Force applied (N)
- A = Area (m²)

The (g_{33}) piezoelectric effect is the result of the piezoelectric constant (d_{33}) and the dielectric charge constant (ϵ_{33})[14]:

Equation 2-2

$$g_{33} = \frac{\text{Strain}}{\text{Applied charge density}} = \frac{d_{33}}{\epsilon_0 \epsilon_{33}}$$

Equation 2-3

$$d_{33} = \frac{\text{Strain}}{\text{Applied Field}} = k_{33} \sqrt{\epsilon_0 K_3^T s_{33}^E}$$

Equation 2-4

$$K^T = \frac{C_0 h}{\epsilon_0 A}$$

- k_{33} = Electromechanical coupling factor
- K_3^T = Dielectric constant
- C_0 = Measured Capacitance (F)
- h = Distance between electrodes (m)
- ϵ_0 = Permittivity of open space (8.854×10^{-12} F/m)
- A = Area of electrode (m^2)
- s_{33}^E = Elastic Compliance (m/N)

The power P (watts) can then be calculated through resistance R load (ohms) testing against the voltage (volts) produced. Current can also be used I (amps).

Equation**2-5**

$$P = V \times I = I \times R \times I = I^2 \times R$$

Another factor of piezo material that determines the electrical output from the mechanical input is the electromechanical coupling factor, which is the ratio of mechanical to electrical or vice-versa [15].

Equation 2-6

$$\text{Electromechanical coupling factor } k = \sqrt{\frac{\text{Mechanical Energy Stored}}{\text{Electrical Energy Stored}}}$$

Equation 2-7

$$\text{Charge Constant} = d = \frac{\text{Short circuit charge/Electrode area}}{\text{Applied Stress}} \text{ (C/N)}$$

Equation 2-8

$$\text{Voltage Constant} = g = \frac{\text{Strain}}{\text{Applied charge density}} = \frac{\text{Field}}{\text{Applied Mechanical Force}} \left(\frac{\text{Vm}}{\text{N}} \right)$$

Equation 2-9

$$\text{Elastic Complainance} = S = \frac{\text{Strain}}{\text{Stress}} \left(\frac{\text{m}}{\text{N}} \right)$$

From the equations in this section, the limitations for Piezoelectric materials are the amount of charge and voltage available per unit of force applied; g_{33} (eq. 2-2) & d_{33} (eq. 2-3), and the coupling factor and elastic compliance that dictates the structures deformation under load and ability to convert this deformation into electrical energy. This indicates that to increase power density of a device without improving the material, the mechanical to electrical coupling and the strain deformation must be maximised to increase the electrical output.

2.3.1 Spring-mass Piezoelectric Energy Harvesting System

A Spring-mass system uses mechanical movement of a mass attached to a spring to create compressions and tensions in the piezo material, storing some of the energy in the spring and converting the energy into an oscillation. The oscillation allows the piezoelectric element to harvest energy over a longer period. The theoretically energy of a mass-spring system governed by the equations:

Equation 2-10

The force from accelerating mass:

$$Force (N) = ma (kg/ms^{-2})$$

Equation 2-11

Maximum Potential Energy and stored by a spring:

$$E_{Potential}(kgm^2s^{-2}) = \frac{1}{2}mad$$

$$Energy \text{ stored by a spring}(kgm^2s^{-2}) = \frac{1}{2}kd^2$$

- k = the spring rate (N/m),
- d = deflecting distance (m),
- m = mass (kg)
- a = acceleration (m/s^2).

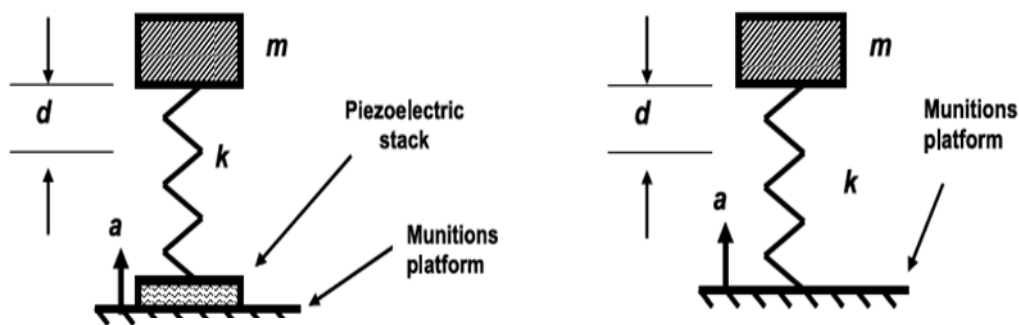


Figure 2-4 Piezo Spring Mass System schematic [17]

The spring-mass system has been demonstrated to be capable of generating electrical energy under high acceleration and in confined spaces. Prototype designs by J. Rastegar using a spring and mass system for high acceleration and high impact

energy harvesting have been tested with a piezo in a stack configuration. Washers have been used for the spring and for the preloading force, with the high acceleration from firing (in ammunition), the spring elongates with the mass, producing a force oscillation on the piezo, giving the desired electrical energy output. [16]

For a prototype module of 20 mm diameter, 45 mm long (Fig. 5 [17]) that was set to experience high acceleration the test configuration was:

- Spring rate (k) = $168 \times 10^3 \text{ N/m}$
- Mass (m) = 7.6 g
- Natural Frequency = 750 Hz
- Acceleration (a) = 176580 m/s^2
- Displacement d = 5 mm

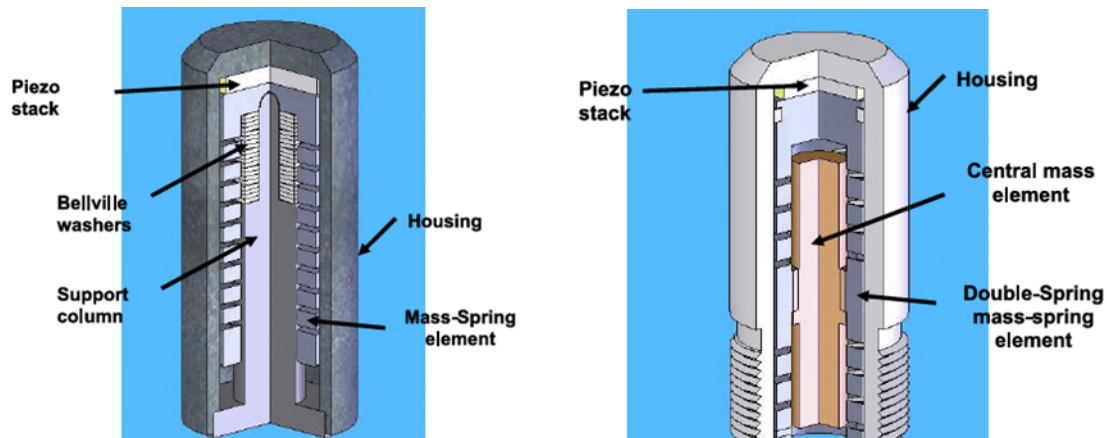


Figure 2-5 Piezoelectric Spring-Mass Prototype Harvester [17]

Force and energy calculations are shown thus:

$Force = ma$	$Maximum\ force\ of\ mass = 0.0076\ kg \times 176580\ \frac{m}{s^2} = 1342N$
$E_{Potential} = \frac{1}{2}mad$ $E_{Spring} = \frac{1}{2}kd^2$	$= 0.5 \times 0.0076\ kg \times 176580\ \frac{m}{s^2} \times 0.005\ m = 3.355\ J$ $= \frac{1}{2} \times 168 \times 10^3\ \frac{N}{m} * (0.005\ m)^2 = 2.1\ J$

The amount of energy in the moving mass is calculated at 3.355 joules, but the spring rate (and the amount of movement) dictates what energy can be transferred to the spring which is calculated at 2.1 joules. The stored spring energy does not consider friction and losses in the piezo from mechanical to electrical coupling. This spring-mass design demonstrates the importance of tuning the spring stiffness to the input force to maximise available energy, and the structures that can be used such as Belleville springs and machined springs.

2.3.2 Acoustic resonance Piezoelectric Energy Harvester

Wind energy piezo harvesters are those that can harvest turbulent wind-induced vibrations. The desired wind-effects are flutter [18], [19], galloping [20] and acoustic resonance [21]. Flutter is the result of aerodynamic flow over a surface and the induced vibration created by turbulence. Galloping is like the flutter effect but is the result of the angle of attack of the incoming flow. Acoustic resonance modelling can overcome some limitations of solid systems, such as the structural design, vibration frequencies and stability. Acoustic resonance has also been shown to work with electromechanical systems as shown in Figure 2-6 connected to a piezoelectric element.

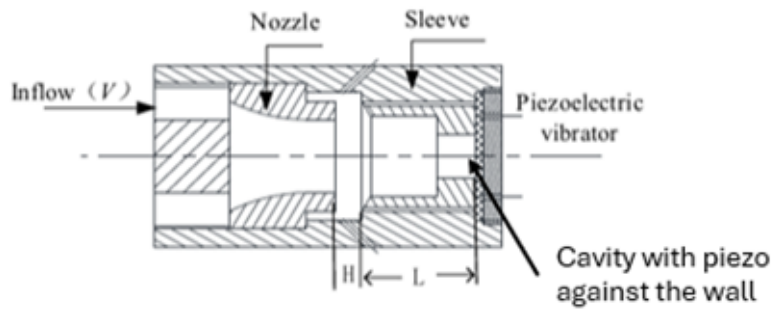


Figure 2-6 Piezoelectric Acoustic Energy Harvester [21]

The mechanism works because the air flows through the inlet to an annulus that creates a vortex hitting the cavity wedge (Wall). The vortex hitting the wedge creates a vibration (Edge tone) and a standing wave inside the cavity causes the Piezoelectric structure to vibrate (harmonic resonance) and generate electricity [21].

The edge tone is created by a high velocity fluid hitting a solid edge and splitting, creating turbulence and vortexes. It is empirically represented by:

Equation 2-12

$$f_s = \frac{v}{4H(1 + M_a)}$$

The f_s represents the generated frequency of the edge tone (Hz). v represents fluid velocity (m/s); H represents distance from the nozzle to the wedge (m) and $M_a (= v / c)$ (where c =Speed of sound in m/s)) represents the Mach number. With an increase in air velocity, the edge tone frequency is shown to increase. When the edge tone frequency reaches the acoustic mode of the resonant cavity, the whole system will

produce a noticeable sound. This is caused by the Vorticity acoustic coupling effect, caused by vortex shedding and vortex excitement [23][21]. [21] Figure 2-7 represents the acoustic system as an electrical circuit equivalent.

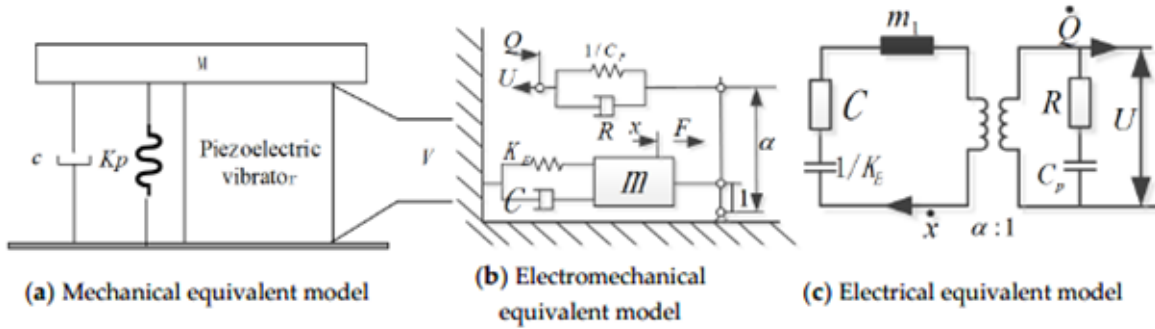


Figure 2-7 Piezoelectric Acoustic Energy Harvester Schematics [21]

The equation to represent the sound production:

Equation 2-13

$$\frac{H}{L + 0.61R + 0.4H} \approx \frac{v}{c + v}$$

- L = length of the resonance cavity (m).
- R = diameter of the resonance cavity (m).
- H = distance from the nozzle to the wedge (m).
- v = flow velocity (m/s²)

Energy of the jet flow can be calculated:

Equation 2-14

$$E = \frac{1}{2}mv^2 = \frac{1}{2}\rho S\Delta t v^3$$

Equation 2-15

$$Power = \frac{E}{\Delta t} = \frac{1}{2}\rho S v^3$$

- E is kinetic energy (J).
- ρ is air density (kg/m³)
- V is airflow velocity (m/s)
- Δt is time (s)
- S is nozzle area (m²)
- M is mass (kg)

The results from Zhipeng [21] show the maximum power output reached of this device in the experiments is 5.3 mW.

The research into acoustic vibrations is limited to laboratory testing of the device and only has results up to a certain air velocity. Compared to the other examples of piezoelectric generation, this type does not offer the same energy density. There is the potential for a combination of multiple systems depending on the overall complexity of the production process. It is not shown clearly whether changes to atmospheric temperatures, which can affect the air density and the speed of sound, could also impact this design and limit the efficiency. There is also the possibility of degradation of components, as it requires an open chamber that could unintentionally trap moisture, which could block and alter the acoustic effect.

2.3.3 Rotational/plucking

The rotational energy harvesting design spawns from the Seiko Watch Cooperation's kinetic watch with a built-in electromagnetic motor powered by the original self-winding mechanism but switching from spring wound to electromagnetic generator charging [22]. The issue with using an electromagnetic motor/generator is acquiring useful rotation speed, which can be resolved using a complex gear system. Another technique proposed by Hanif [23] is the rotational vibration of a piezo element.

Plucking can be set up using a bimorph two-layer stack or unimorph beam, the proof mass is set up like a spring mass system as in Figure 2-8, but the frequency at which the beam is struck and thus flexes is determined by a rotation structure in the form of poles such as the structure in Figure 2-9.

*Note: Bimorph = A bimorph is a cantilever used for actuation or sensing which consists of two active layers. It can also have a passive layer between the two active layers. In contrast, a piezoelectric unimorph has only one active (i.e., piezoelectric) layer and one passive (i.e., non-piezoelectric) layer.

*Note (plucking is the act of hitting the beam to cause vibrations, like a string)

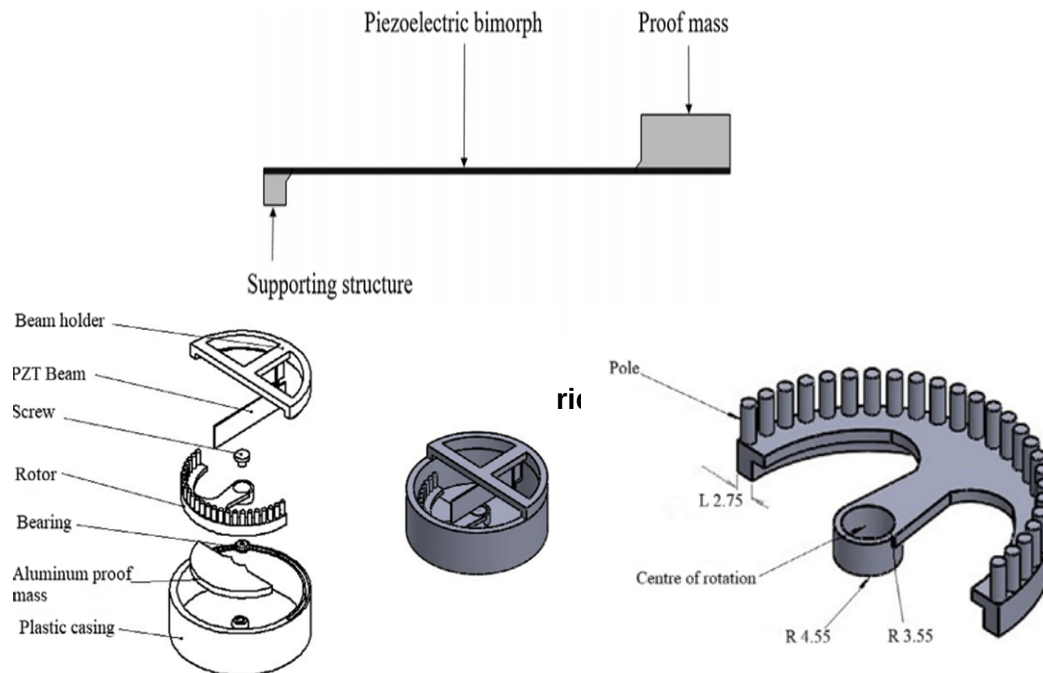


Figure 2-108 Piezoelectric Bi-morph Pendulum Energy Harvester (Plucking)
[124]

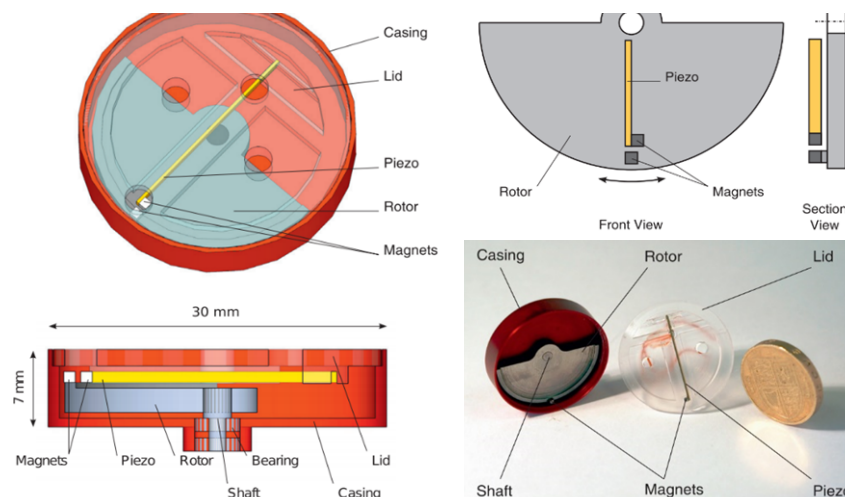


Figure 2-9 Piezoelectric Bi-morph Pendulum Energy Harvester [124]

With designs using plucking, that physically contacts the poles there are disadvantages. The impact force between the beam and the poles can cause contact

damage and lead to piezo layer degradation. Using a magnetic mechanism with permanent magnet coupling to pluck the beams can stop this direct contact and prevent impact damage.[24]

To adjust the kinetic energy calculation to rotational energy, the equation changes:

Equation 2-16

$$K.E. = \frac{1}{2}mv^2 = \frac{1}{2}I\omega^2$$

- I = rotors movement of inertia (kgm^2)
- ω = the angular velocity. (rad/s)

The power equation can be derived as:

Equation 2-17

$$P_{max} = \frac{\omega^3 \Omega_0^2}{4} \cdot I$$

Equation 2-18

$$I = \frac{mR^2}{4}$$

- Ω = excitation amplitude (m)
- R = radius (m)

The characteristics that affect the power generation in this mechanism are:

- Length of beam
- Thickness of beam and piezo element
- Piezo material

The beam shown in figure 2-8 is a bimorph two-layer stack, made up of lead zirconate titanate (PZT-5H) with a copper plate separator. The bimorph design doubles energy production without significantly changing dimensions. Longer beams researched by Hanif et al showed lower peak frequency inputs from given human motion, at 78 Hz, which caused resonant frequency and produced the highest mechanical vibrations and thus voltage output.

The resonant frequency of the cantilever beam is represented with the proof mass equation:

Equation 2-19

$$f_r = \frac{v_n'^2}{2\pi L^2} * \sqrt{\frac{K}{m_e + \Delta m}}$$

- L = length of beam (m)
- K = spring constant (N/m)
- $V_n = 1.875$ (eigen value) for the fundamental vibration $v_n'^2 = v_n^2 \sqrt{0.236/3}$
- Δm = proof mass (kg)
- $M_e = 0.236mwL$ (the effective mass of the cantilever, m is the mass per unit length of the beam and w is the width of the cantilever)

*Resonant frequency is inversely proportional to the square of the length of the beam.

The rotor design has small nodes which are responsible for plucking the piezo beam, this is a changeable feature and can be adjusted for the rotational resistance and used to adjust the frequency of plucking.

The equation for calculating the maximum energy potential per volume is described as

Equation 2-20

$$\frac{P_{max}}{Vol} = \rho s a f$$

Equation 2-21

$$f = \frac{\omega}{2\pi}$$

Equation 2-22

$$a = \omega^2 Y^0$$

- ρ = proof mass density (g/mm³)
- S = displacement (mm)
- α = Acceleration (m/s²)
- f = frequency (Hz)

From this research it can be viewed that the rotational plucking design has the obvious advantage of harnessing the rotational energy and converting it simply via piezo activation. This design example has only been used on slower rotational scenarios and additional research would be required to make sure the same effect can be achieved at much higher velocities and under high accelerations. The dampener also

needs to space to move which might create dead space inside a small device unless the design can overcome this. This design could offer a high energy output if it can be correctly utilised for higher rotational velocities.

2.3.4 Centrifugal/Centripetal spring-mass system

In a high-speed rotating object, internal components will be subjected to centrifugal force pushing heavier components outwards. With the right mechanism, the force applied outwards can be used to create centrifugal stiffening or softening – basically applying a force to a structure which is either unloaded or already under load [25]. This has been demonstrated in a mechanism that as the rotational speed increases, the mass pulls the beams and creates a deflection, activating the piezo material and creating a charge demonstrated in Figure 2-11.

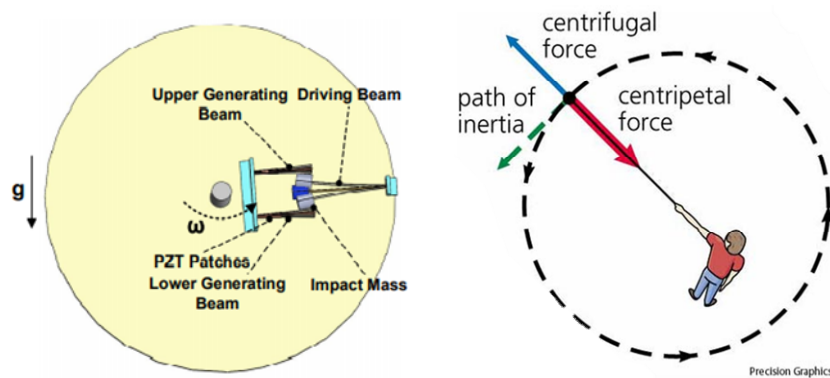


Figure 2-11 Piezo Centripetal Spring Mass System [25]

The amount of force created by rotation can be calculated by:

Equation 2-23

$$F = ma = m\omega^2 r$$

Equation 2-24

$$\alpha = \omega^2 r \text{ (rad/s}^2\text{)}$$

Equation 2-25

$$\omega = \frac{\Delta\theta}{\Delta t}$$

- F = Force (N)
- m = Mass (kg)
- a = Acceleration (m/s^2)
- ω = Angular Velocity (rad/s)
- r = Radius (m)

Currently systems that have a centripetal design are usually not used for energy harvesting, as they can be found on types of wind turbines and cranes for the braking system. Using a mass and a spring of a known stiffness, if the turbine is being forced to spin faster than the maximum operating speed of the system (during high winds or storms), a mechanical failsafe centrifugal braking system, which is being pulled out by the spinning force, pulls the brake pads to the edge, and starts acting as a friction brake.

This type of system is not popular for rotational piezo energy harvesting and has less research in the subject. The range of uses is limited to package volume, speed, and mass of the working parts. But in a high rotational speed scenario, a large centrifugal force could be used to activate spring mass or piezo beam harvester.

2.3.5 Shear Mode

Another type of harvesting energy from Piezo material is using shear mode. The main difference between shear mode and the other modes comes from the piezo electric coefficients and the way the material is manipulated (Figure 2-11).

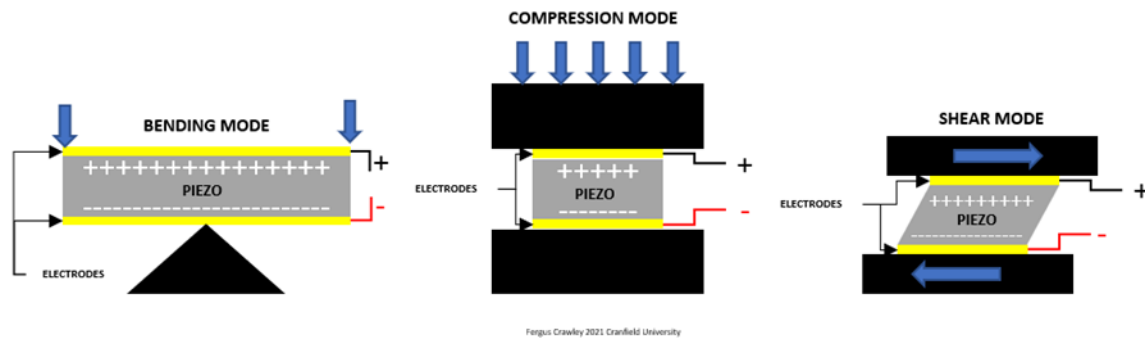


Figure 2-12 Piezoelectric Activation Modes

The table below shows the different mode characteristics and the charge constants (d_{xy}):

Table 2-2 Piezoelectric Material Charge Coefficients

Piezoelectric coefficients	PZT-4A	PZT-5H	PZT-5A	PZT-7A
$d_{15}(\text{pm V}^{-1})$ [SHEAR]	496	741	584	360
$d_{33}(\text{pmV}^{-1})$ [LONGITUDINAL]	286	592	374	153
$d_{31}(\text{pmV}^{-1})$ [TRANSVERSE]	-123	-274	-171	-60

Malakooti [26] has determined that the yield of shear mode over transverse and longitudinal mode has been shown to produce 50% more electric energy for the same volume of material. The reason for less use of shear mode over the more normalised compressive and bending methods stems from designing an effective system to create shearing without part failure.

Improvements in energy dense materials such as Piezo Electric Single Crystals (high performance relaxer crystals PbTiO_3) which offer up to 3480 pCN^{-1} (compared to PZT 5H at around 700 pCN^{-1}) can further increase the energy output of a shear mode mechanism. Table 3 shows the crystal material charges in more detail.

Table 2-3 Single crystal and soft ceramic piezoelectric material charge coefficients

Material	d_{15} [pC N ⁻¹]	$\varepsilon_{11}^T/\varepsilon_{15}$	$\tan \delta$	g_{15} [$\times 10^{-4}$ VmN ⁻¹]	$d_{15} \times g_{15}$ [$\times 10^{-10}$ CVmN ⁻²]
PIN-PMN-PT	3480	10,500	0.005	3.725	1.296
Soft ceramic PZT	920	2700	0.023	3.872	0.359

An example of a shear mode mechanism is the Bridge-Shear mode Piezo Electric Harvester (BSPEH). Using downward force, the piezo material top layer is forced outwards. The simple bridge structure can be seen in Figure 2-12.

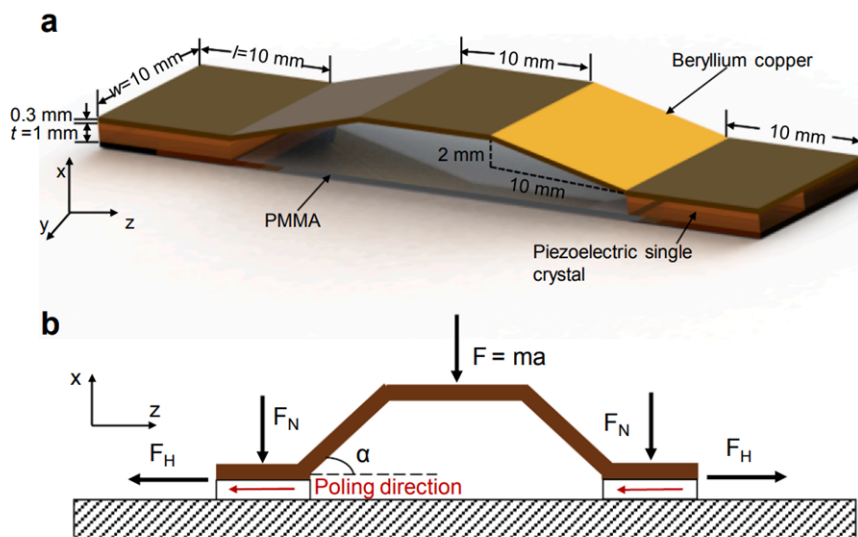


Figure 2-13 Piezoelectric Shear Mode Bridge Structure [27]

The bridge design with single crystals reported by Gao [27] has reached energy densities of $1.378 \times 10^4 \text{ Wm}^{-3}$, with a noted 5.5 times the energy density of the piezo ceramic material. The design is can also be stacked in series to increase the power outputs. Experiments with this type of energy harvester have also been shown to withstand high frequency vibrations and are polarised at 100°C. The material chosen as the top electrode is beryllium copper, this is because of the material having a suitable conductive and elastic properties.

The shear mode piezoelectric bridge generator design can also be turned into a bimorph structure and made circular, as per Figure 2-14. The circular design

is referred to as a cymbal transducer structure, this structure is noted to have strong mechanical stability and low fabrication costs [28].

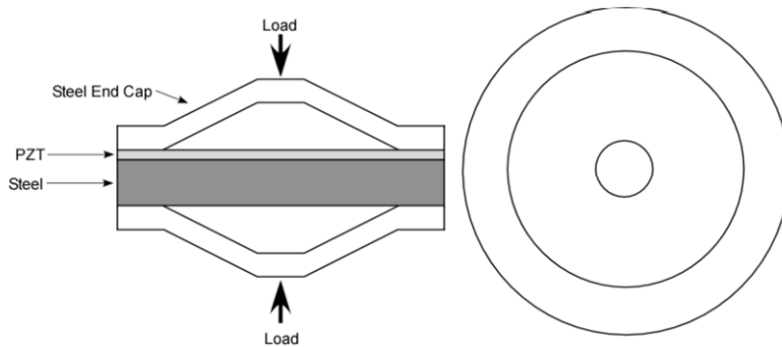


Figure 2-14 Double Cymbal Piezoelectric Generator [28]

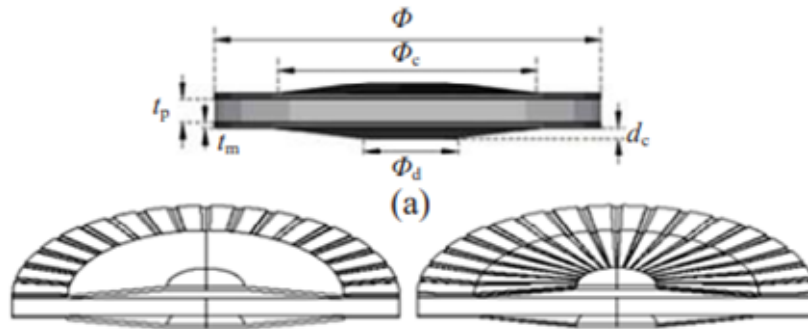


Figure 2-15 Slotted Cymbal Transducer Piezoelectric Energy Harvester [29]

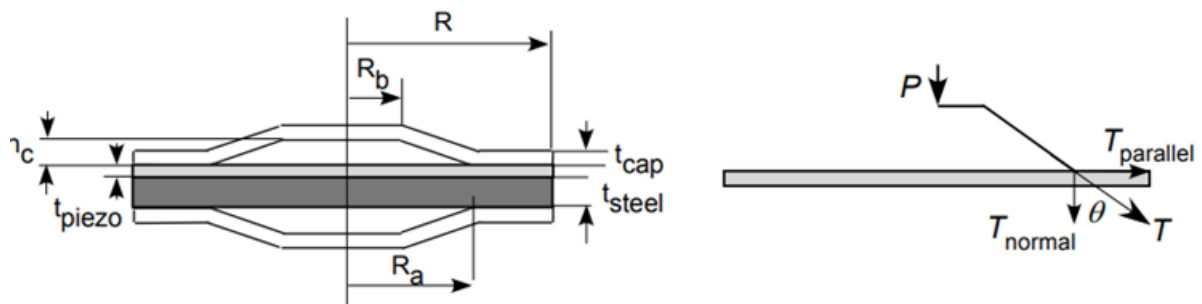


Figure 2-16 Piezoelectric Cymbal design variables (as used in Belleville Spring equation above) [28]

In further development of the cymbal piezo transducer energy harvester, a limiting factor of the design has been seen to come from the circumferential stress of the end

caps on expansion, which results in the loss of mechanical input energy and thus electrical energy. To stop the stress build-up, radial slots are introduced to the circumference creating further shear deformation and resulting in higher electrical power output [29].

This slotted piezo energy harvester boasts more simple fabrication and has a robust design, there is an air gap which introduces dead space and reduced energy density, but compared to other Piezo mechanisms could prove easier to scale down to a small system package with a high-power output.

2.3.6 Preloading Piezo Structures

PZT material structures are normally limited by their tensile strength, limiting the maximum power output through strain, but in the reverse (under compression), piezo materials are very strong. Pre-loading is the introduction of initial compression. The effect of pre-loading allows the structure to shift the operational stress range, and this can produce a larger stress amplitude and a higher electrical power output. [30]

Magnetic loading

Different preloading structures can be used to keep the piezo under stress constantly and allow for a shift in the operational stress range. Magnetic loading uses a magnet and a piezo stack configuration in a force magnification frame, that when structurally pulled apart, squeezes the stack together. The magnets are constantly attracting and pulling the frame down (this force is determined by the power of the magnet and the

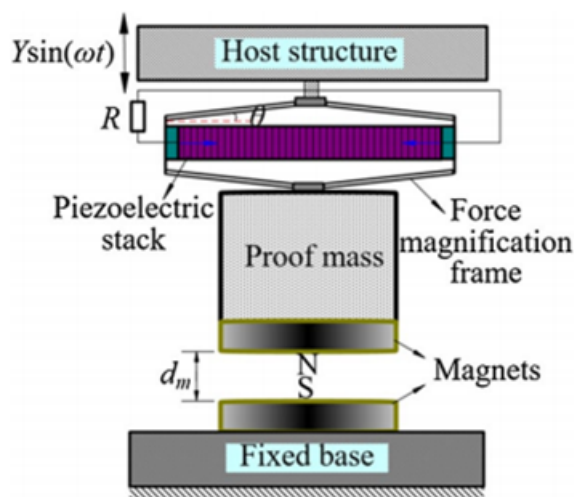


Figure 2-17 Piezo stack pre-loading and force amplification structure [31]

distance between magnets). For lower frequency and low force applications, magnetic preloading has demonstrated system energy increases of over 40 times the voltage output of a system without magnetic loading [31].

Buckling/post buckling

Buckling is another technique demonstrated by N. Chitasz and S. Xiang [32], was used to pre-load a piezo structure. Buckling is adding a bend or buckle into the structure, this allows the piezo to be in compression or tension before any force is applied. This is like magnetic loading mentioned before but without the mass mechanism being added. The fabrication process can be created via a delamination process and mechanical adjustment of the base plate structure. Buckling can increase the electrical potential up to 40% in some cases.

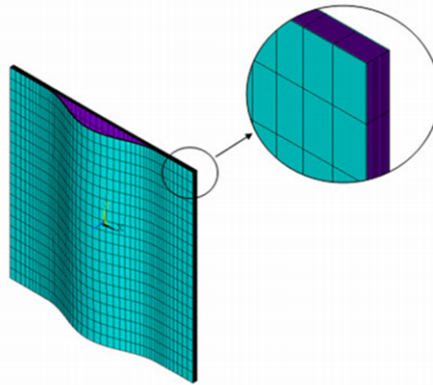


Figure 2-18 Buckled structure on Piezo [32]

S. Xiang [33] optimised the buckling design with the zig-zag shape investigating the additions of folds over the surface structure of the Piezo material, which in theory increases the surface area and changes the force loading to shear displacement. Larger shapes are easier to fabricate to create a pre buckled structure, with the size of the buckle relating to the distance from the beams stable state (flat). The shape is categorised as a snap through buckling design and is shown to provide a better performance over a wider range of frequencies in comparison to a flat beam oscillating [34].

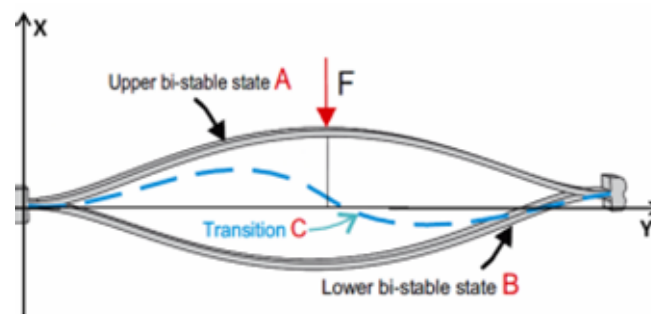


Figure 2-19 Snap through buckling design [34]

Creating buckled out-of-plane piezo structures does take up more space than a traditional sheet or ceramic disc of piezo and thus increases the overall volume of the harvester and the manufacturing complexity.

2.4 Electro-magnetic energy harvesting

Electro-magnetic systems utilise magnetic fields to induce electric fields and currents into a circuit. Modern electro-magnetic systems use large scale rotating magnetic fields to produce continuous electrical power in the form of AC (Alternating Current), which is converted to DC (Direct Current) for electronic applications. The principal of electromagnetic power generation can be calculated using Faraday's Law, discovered by Michael Faraday moving an electrical conductor through a magnetic field, thus inducing a voltage (Electromotive force - EMF in the opposite direction). Faradays law measures the voltage as the time of the magnetic flux to pass through the conducting circuit:

Equation 2-26

$$V = -\frac{\Delta\phi}{\Delta t}$$

- V = Voltage (V)
- ϕ = Flux linkage (Wb)
- Δt = Time (seconds)

Using this principle, the circuit and the magnetic flux can be varied, increasing the number of coils of conducting wire or increasing the magnetic flux (using a stronger magnet) will lead to increased voltage induction. This can be calculated using the same equation, but adding in a coil multiplier (N):

Equation 2-27

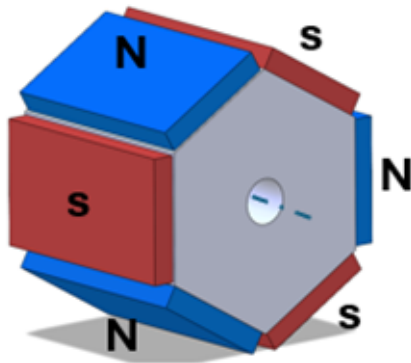
$$V = -N \frac{\Delta\phi}{\Delta t}$$

Electromagnetism can be used in micro energy harvesting, either using rotational energy or vibrational energy, based on the system design.

2.4.1.1 Rotational Permanent Magnet Energy Harvesters

There are two main types of Permanent Magnet (PM) and coil orientations for rotational electrical energy generation, radial and axial. Radial has the magnets and cores working facing at a perpendicular angle to the rotating shaft (left on Figure 2-20). Axial generators (right) have the coil and magnet facing each other. The advantages and disadvantages of both types of generator configurations have been explored in depth for use in industrial scale energy generation.

Radial Magnetic Generator



Axial Magnetic Generator



Figure 2-20 Radial & Axial Magnet Orientation Diagram

Axial-flux PM generator

Axial flux generators have their magnets parallel to the axis of rotation in a pancake design. They can be advantageous when a shallower depth motor is required, and they can be designed to utilise the magnetic field on both sides of the magnets when compared to the radial design.

Radial-flux PM generator

Radial flux generators are a very common design format of generators. There are different configurations for permanent magnet placement, on the inner core or the outer shell. The radial design is comparatively heavier than the axial generator counterpart.

Micro Permanent magnet generator systems are a suitable method for using rotational energy at any frequency and converting it to electrical energy. With the availability of magnets and ability to acquire micro magnets, micro generators can be achieved as either radial or axial flux configuration, with a micro axial generator shown in Figure 2-21.

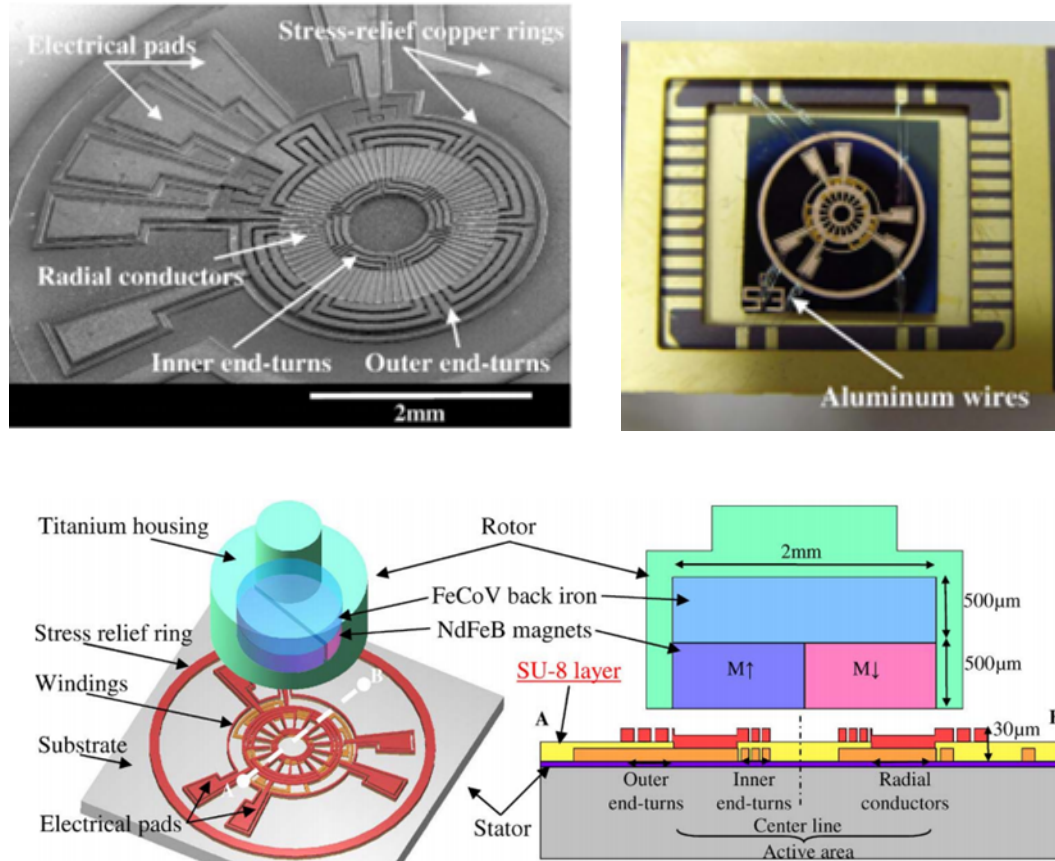


Figure 2-21 Micro Electromagnetic Axial Generator [35]

Constraints of miniaturisation of PM generators comes from the manufacturing process as the surface finish of a micro scale system can drastically affect the performance, this is more a problem with magnet fabrication and the magnetic flux. The stator windings are also not as effective unless ferrite cores are added, and fabrication methods, such as etching can cause limitations in coil cross sectional area when compared to a 3D wire coil. Scaling down a generator also requires higher rotational speed to provide useable outputs, and at higher rotational speeds the system is exposed to higher mechanical stresses. Previous experiments have succeeded with micro fabricated generators up to speeds of 305,000rpm [35].

Magnet material is a variable factor as the strength can depend on the material construction and there are trade-offs between magnet strength and durability. SmCo Samarium Cobalt (SmCo) magnets are around 25% weaker than Neodymium (NdFeB) but can withstand temperatures up to 300 °C (compared to 80 °C for SmCo) [35].

The axial PM generator system using NdFeB magnets can achieve 2.2 mW at 392,000 rpm per phase, and 6.6 mW for a 3-phase system with a package size of 3.4 mm³. (1.95 W/cm³).

2.4.1.1.1 Flow driven PM Microgenerator.

Using magnets to harness rotational energy does need a mechanism to create the rotation. One method is with fluid flow and the integration of a turbine. The combination of turbines with an axial or radial PM generator configuration can be scaled down, using the addition of micro ball bearings as the support mechanism [36].

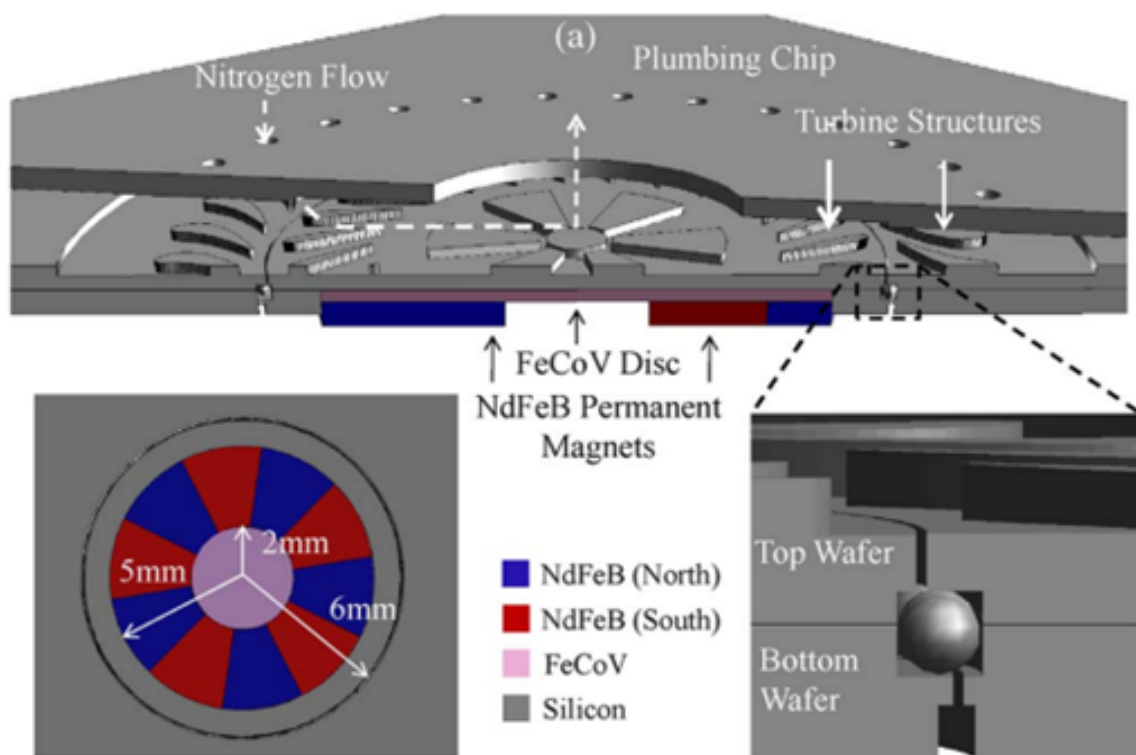


Figure 2-22 Micro Turbine with integrated Electromagnetic Generator [36]

An Integrated Permanent-Magnet Micro-turbogenerator Supported on Micro-ball bearings uses flow from combustion to turn the magnets over the coils and thus inducing voltage. Depending on the package size, the design is fabricable by

machining, but for micro systems in the μm range the method of fabrication is chemical etching. For energy harvesting applications flow driven magnetic systems do show advantages of versatility at higher rotational velocities over other energy harvesting mechanical designs, but this does come with a high level of complexity for manufacturing in comparison to other energy harvester designs.

2.4.1.1.2 Flow driven PM Radial Generator

Rotational magnetic harvesting that was created for tracer projectiles has been created and patented by The Charles Stark Draper Laboratory using counter rotating bodies (2 pieces) in the slug producing 2 Watts for a time of 100 milliseconds. The design uses aerodynamic flow veins allowing - the rear structure to not spin with the front structure (or at least not at the same velocity). The system uses a stator, and a magnetic radial generator set up, and a bearing is present to allow for high rotational velocities of 120,000 rpm [37].

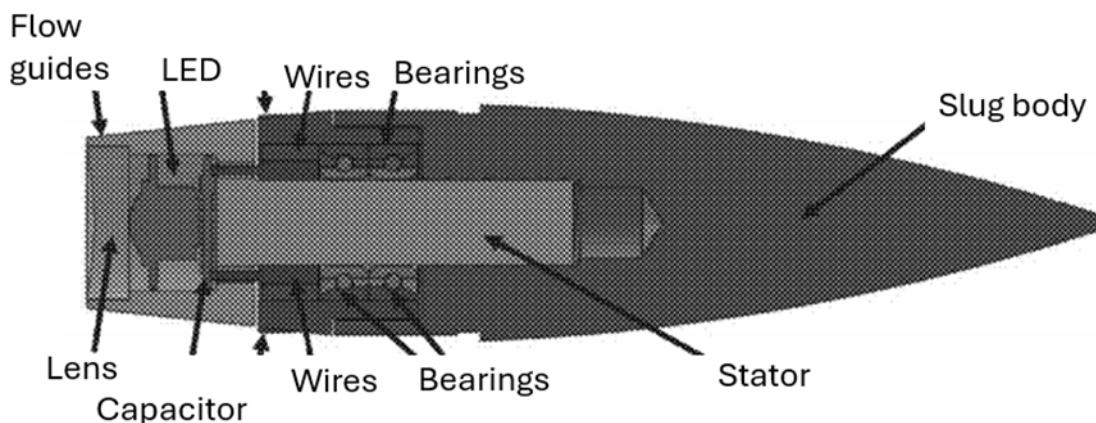


Figure 2-23 Flow Driven Electromagnetic Radial Generator Bullet [37]

The advantage of this system is the harvesting of high-speed rotation for electromagnetic power generation. The aerodynamic feature is highly interchangeable with more fins or different angles of attack which would vary the spin speeds. This design also can be scaled up and down for various user cases for different electronic components.

The disadvantages of such a system come from having 2 separate moving bodies. There is an air gap in the system, this could lead to mechanical failures from environmental exposure and in the case of storage in damp or hot conditions, corrosion, thermal expansion, and fouling/clogging of bearings could occur. Although

the system is relatively simple, micro manufacturing of individual components could lead to a more expensive mass-produced product.

Both orientation types of rotational magnetic energy harvesters do show that there is sufficient energy created in the rotational spin of the tracer, but both are complex in design, and this may not be good for high volume manufacturing. Both systems require a mechanism to create spin, there must be 2 bodies one with a magnetic field and the other with coils spinning in opposing directions to allow the electromagnetic field to fluctuate and induce a current. With more moving parts there is also a lot of room for mechanical failure, with very tight tolerances and high forces, there could be part expansion preventing rotation, or material degradation such as rusting that could cause the moving parts to seize.

2.4.2 Inertia/Setback Generators

Inertia Generators are another type of electromagnetic generator that is used in linear mechanisms and does not require rotation. The Inertia Generator (figure 2-25) is a simple mechanism that converts mechanical displacement into instant electrical energy and is typically used in military applications for fuses. The basic structure uses a permanent magnet, a coil for magnetic induction and a shear holding plate. On activation of the mechanism through high acceleration, the magnet moves away from the coil - inducing voltage in the coil, which is stored via diode-capacitor circuit. [38]

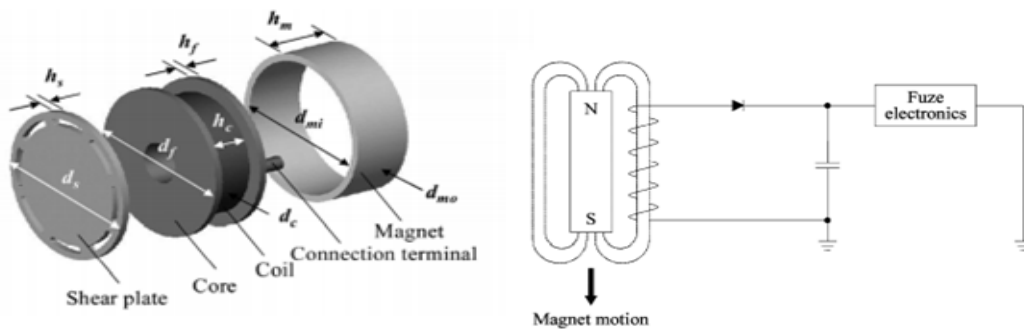


Figure 2-24 Exploded-View Inertia Generator [38]

This generator is bound by Faraday's law:

Equation 2-28

$$V = \frac{d\Phi}{dt} = \frac{d(NA\mu_0\mu_r H)}{dt}$$

- V = Voltage induced (V)
- $d\Phi$ = Magnetic Flux (Wb)
- dt = Time (s)
- N = Number of turns in the coil
- A = Cross sectional area of the coil (m^2)
- μ_0 = Permeability of a vacuum (N/A^2)
- μ_r = Relative permeability (N/A^2)
- H = Magnetic field in the coil (kg/s^2A)

The power produced by the system is directly related to the strength of the magnet, size of the cross-sectional area, the number of turns in the coil and rate of change of the magnetic field.

The maximum energy of the Inertia Generator is seen to be the electrical energy induction over a period, calculated as half sine wave as the magnet does not return once it passes through (or over) the coil.

Equation 2-29

$$V = E_0 \sin(\omega t)$$

- E_0 = Amplitude
- ω = Frequency (Hz)

The mechanism is secured with a shear plate that prevents the magnet releasing, which is useful for storage and handling and good for safety. The shear plate is designed to break and release the magnet when an applied force/acceleration (calculated to be much higher than any accidental forces), is received, energy is required to overcome the holding force and therefore implies an energy cost to the overall system output.

The plate undergoes shear stress calculated by the equations:

Equation 2-30

$$\tau = \frac{F}{A} = \frac{ma}{A}$$

- τ = shear stress (N/m²)
- F = Force (N)
- A = Cross sectional Area of shear surface (m²)
- m = mass of magnet (kg)
- a = Acceleration (m/s²)

Scaling down of the setback generator can be used to make smaller electrical harvesters. Proof of concepts have reached sizes of radius 14.8 mm by 3.9 mm in length for the complete package delivering up to 14.2 V at 0.68 ms, charging a 30 μ F capacitor from 30,000G of acceleration which is equivalent to 3 mJ of energy [38]. Because of the loss of efficiency in scaling electromagnetic generators, methods to boost the magnetic flux have been explored by Fu [39] to boost the overall power outputs using metal composite-magnet construction. The resulting performance boost is simulated to be at around a 40% energy increase. Figure 2-26 shows an inertia setback generator scaled down and the relative simplicity of the system design (right).

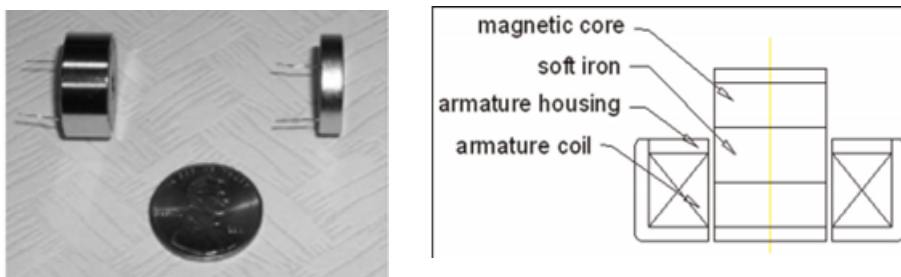


Figure 2-25 Inertia Generator Prototype [38]

Setback generators are very dependent on the user case, as they require large activation energy normally created by acceleration. This means that there is no one-for-all design that can encompass multiple levels accelerations. Smaller systems can have much larger accelerations but have very limited space for coils and magnets. Whereas larger systems have much larger internal space for coils and magnets and other electronic components, but a slower acceleration (see Figure 2-27).

Other factors for setback generator design also include the amount of dead space inside the device to allow for magnet travel, as the further the magnet can travel through coils, the higher the voltage and power output, but this can also affect the weight of the device as more space is left unfilled [40].

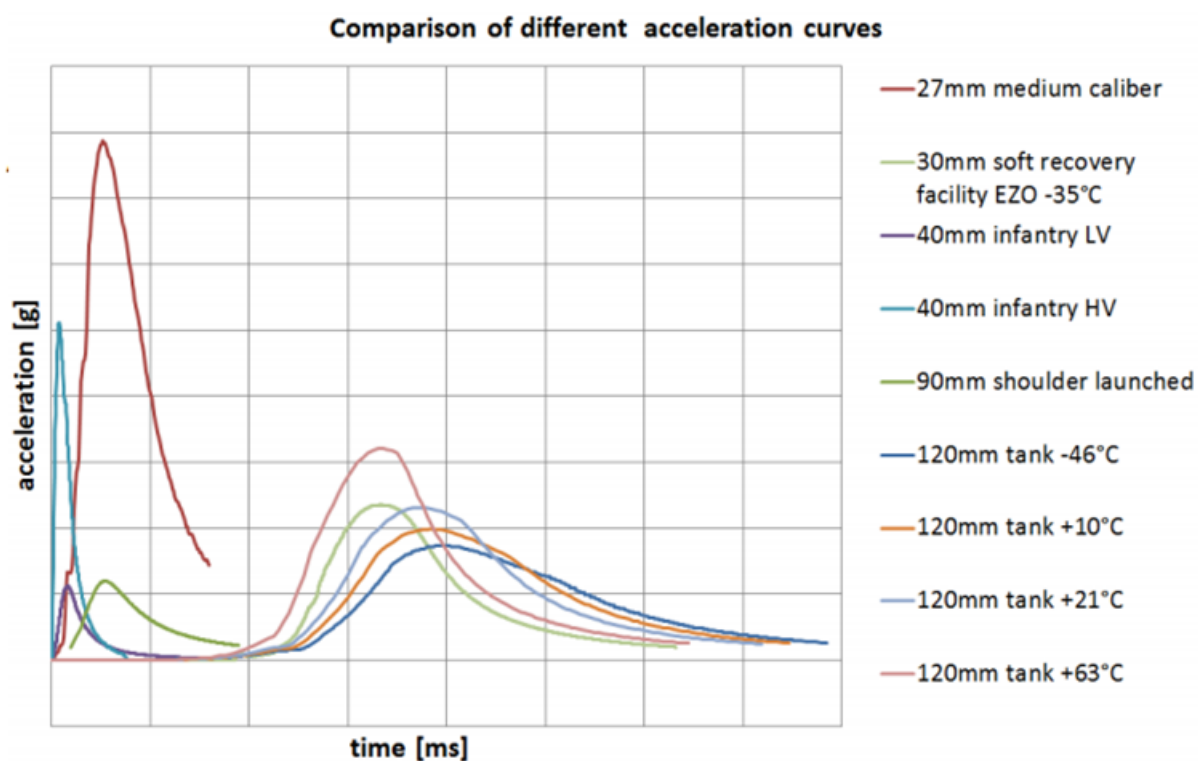


Figure 2-26 Munition Acceleration curves for Inertia Generators [40]

2.4.3 Spring-Mass Oscillatory Electromagnetic

A design of an Electro-magnetic system can be a mass-spring resonator using spring or electrical inductance as the dampeners, the electro inductance becoming the useable electrical energy harvested through coils, and the mass of the system being a permanent magnet (Figure 2-28). This system is tuneable through the spring stiffness, coil turns, magnetic strength and mass. As the spring and mass oscillate the magnet passes through the coil and thus induces voltage (EMF). This type of system is very well suited to high impact forces and high accelerations [41].

The linear oscillation generator can also use magnets (Figure 2-29) instead of springs. Removal of springs can save weight of the device and create high magnetic damping levels [42].

Equations of spring-mass motion:

Equation 2-31

$$m\ddot{z}_m + c_e(z_m)\dot{z}_m + c_m\dot{z}_m - F_{rep}(z_m) = -m\ddot{y}$$

Equation 2-32

$$P_e = c_e(z_m)\dot{z}_m^2$$

Equation 2-33

$$c_e(z_m) = A_{ce} \cos^2\left(\frac{2\pi}{p}z_m + \beta\right)$$

- | | |
|---|---|
| • m = Mass (kg) | • z_m = Periodic function of mass position |
| • $\ddot{y}$ = Reference direction of movement | • A_{ce} = Amplitude |
| • P_e = Dissipated Electrical Power (W) | • p = Magnetic period of multipolar mass (kg) |
| • c_m = Constant mechanical damping coefficient | • F_{rep} = Magnetic repulsion force (N) |
| • c_e = Electrical damping coefficient | |

The electromagnetic oscillation system is heavily dependent on the amplitude of the moving mass and the size of the mass (weight/density) dictates the mechanical energy available to convert into electrical energy. The number of coils (Maxwells theory) also dictates the electrical damping and induction.

When scaling the electromagnetic linear oscillator energy harvester system, the system in Figure 2-28 experiences a loss in power density, this is demonstrated as the scaling factor (k). When the system is scaled down, the energy density decreases exponentially. The losses stem from coil types and their configurations and energy levels required to pass diodes used for rectification. The coils are separated to reduce electro-dampening. Power density levels reached $44 \mu\text{W}/\text{cm}^3$ when the system size was decreased to a package size of 613.6 mm^3 ($L = 31.25 \text{ mm}$, $\varnothing = 5 \text{ mm}$) [42].

Scaling down linear oscillating electromagnetic systems below the $0.38 k$ factor does show an energy drop off to below 10^{-2} mW (Figure 2-29) which is not sufficient to power small electronics for example and LED. Also highlighted from the setback generator design, there is a large percentage of the system that is open space which decreases overall power density and would lower the mass of the system. Optimising this type of electromagnetic system requires the addition of springs to increase oscillations and improving magnetic and wire materials to increase magnetic flux and reduce resistance.

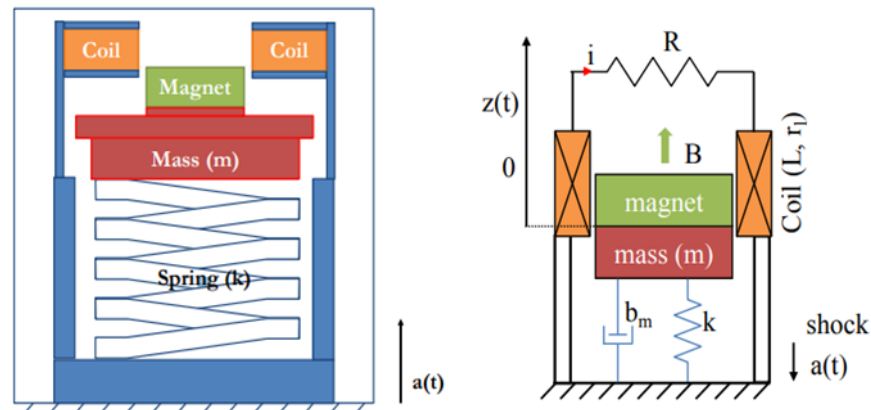


Figure 2-27 Spring-mass Electromagnetic Generator Schematic [41]

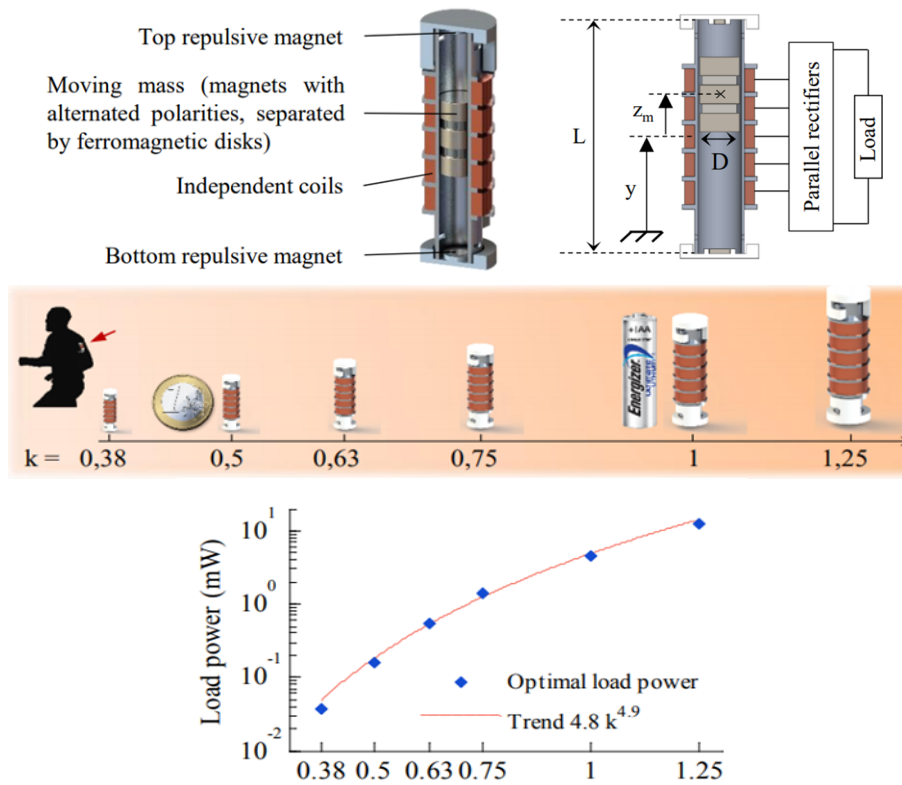


Figure 2-28 Magnetic-spring Electromagnetic Energy Harvester Prototype [42]

2.4.4 Compression into rotational energy

Electromagnetic energy harvesters are also useful for rotational energy harvesting. A design by Y. Zhang [43] to turn downwards pressure to rotational energy uses a spring and a twisted shaft (Figure 2-30). The vertical downwards pressure is converted to rotational energy which allows the magnets to spin and interact with the coil fields, and the spring stores the energy to spin the magnets in the opposite direction back to the start position.

This design is dependent on the magnet and coil configuration, spring stiffness and twist rate of the central drive. The output of the system is AC and dependant on the input force frequency and device configuration. A simple circuit with a rectifier, 1 mF capacitor storage and LED bulbs uses the energy to convert to light (Figure 2-30 – right).

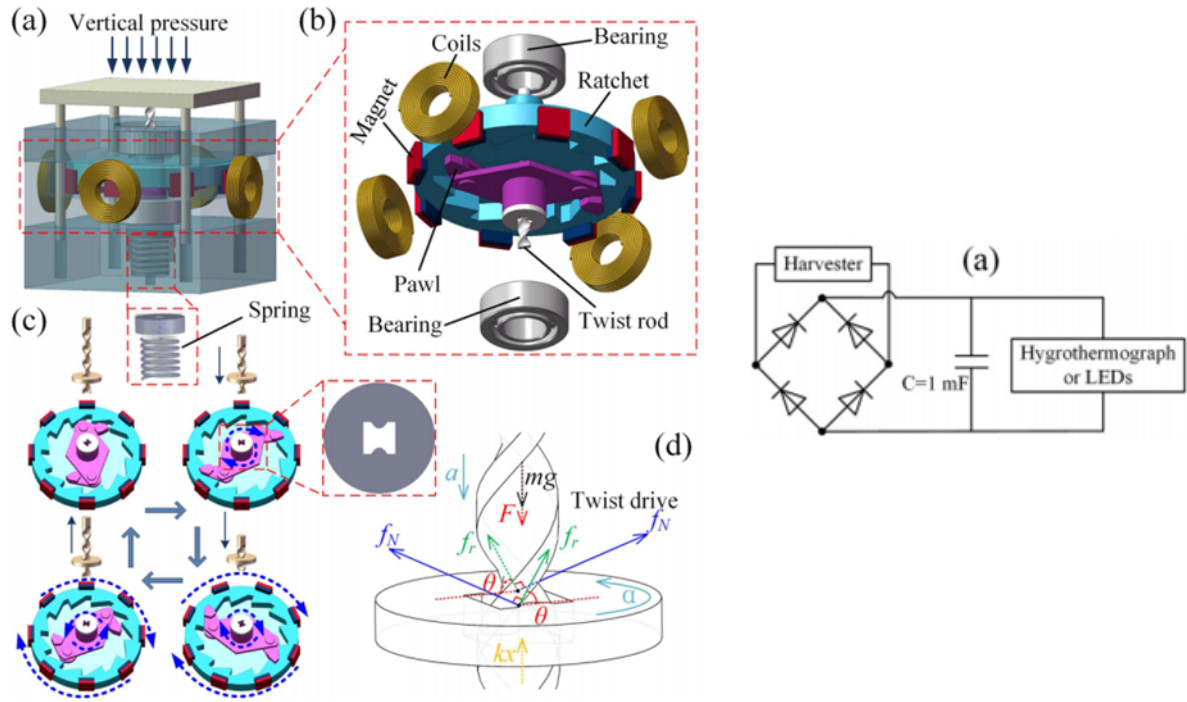


Figure 2-29 Compression to Rotation, Ratchet Electromagnetic Energy Harvester Prototype [43]

The equations for this system are:

Equation 2-34

$$F + mg - kx - 2f_r \sin \theta - 2f_N \cos \theta = ma$$

- θ = Thread angle ($^\circ$)
- x = Displacement (m)
- k = Spring stiffness (N/m)
- F = Force (N)
- f_N = Force on thread (N)
- f_r = Friction force (can be expressed as μf_r) (N)
- μ = Friction coefficient

Equation 2-35

$$I \propto (2f_r \sin \theta - 2f_N \cos \theta - f_{Damp})r$$

Equation 2-36

$$\tan \theta = \frac{a}{\alpha r}$$

- I = Inertia of rotational structure (kgm²)
- α = Angular Acceleration (rad/s²)
- f_{damp} = Mechanical damping force (air & friction) (N)
- r = radius of threaded rod (m)
- a = Acceleration (m/s²)

Equation 2-37

$$\alpha = \frac{r(F + mg - kx)(\tan \theta - \mu) - rf_{damp}(\mu \tan \theta + 1)}{I(1 + \mu \tan \theta) + (mr^2 \tan \theta (\tan \theta - \mu))}$$

The electro inductive force in the coils is calculated by:

Equation 2-38

$$\varepsilon = -N \frac{d}{dt} (BS \cos \omega t) = NBS\omega \sin \omega t$$

- N = Number of coils
- B = Magnetic field density (T)
- S = Area of coil (m²)
- ω = Angular Velocity (rad/s)

The spring-twist rod design is a capable system of creating electrical energy using pressure and converting it into rotational electro induction, with a 7 mW output at only 1Hz. However, the effectiveness at higher forces with increased torque and much higher frequencies is not known. Size is also a limiting factor of this design, as it has a work volume of 97 cm³. Scaling down the system would require keeping the central twisted rod to still be stiff enough to guide the rotating ratchet moving parts and would add high complexity in terms of manufacturing.

2.4.5 Rotational Pendulum Electromagnet/triboelectric generation

Electromagnetic energy can harvest rotational energy using an axial design spinning around a central column. C. Hou [44] created a hybrid device using a free spinning pendulum holding a magnet, voltage can be induced into a coil array. Hybrid systems can be used to combine more than one type of energy harvesting technology for electrical power generation. As an example, Triboelectric energy harvesting can also be used alongside rotational electromagnetic harvesting.

The pendulum design has been developed for many applications from harnessing ocean waves to absorbing human movement and has many different system set-ups as described by T. Wang [45] and J. Chen [46] showing that the pendulum does not have to be constrained to 1 plane of motion and can be fitted with all types of mechanicals to electrical conversion technologies. Double pendulum systems have shown an advancement in efficiency over the single pendulum design due to the increased useable frequency bandwidth.

With the pendulum energy harvester design, considerations are needed for the size of the system because of the requirement to “off-balance” the pendulum. The volume requirements, to allow the pendulum to move freely enough and to spin at its own velocity, needs to be considered as open space contributes to a lower power density. In previous experiments, the systems have only been utilised at lower rotation speeds ranging from 0.2Hz to 557.31 RPM [46], the effects of higher speeds and forces are unknown. The pendulum does have other benefits to certain environments shown by J. graves [47], because it can also be used as a dampener for unwanted motion received by waves and turbulence, using the system in a boat to dampen movement while generating electricity.

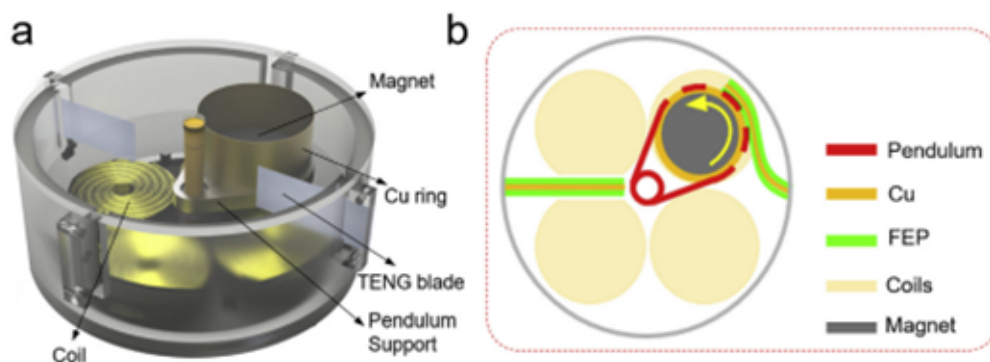


Figure 2-30 Electromagnetic & Triboelectric Pendulum Energy Harvester Prototype [44]

2.5 Triboelectric energy generation

Triboelectric energy generator devices use the triboelectric effect to generate electricity. Triboelectric Nano Generators (TENGs). TENGs work on the principle of contact electrification between different materials. A common electrical phenomenon, static electricity, is a result of triboelectric effect. Electrons of the different dielectric materials can move upon contact, the dielectric materials used for generation are either more prone to gain electrons or lose electrons but do not conduct electricity, but rather store it in an electric field. Charge density is dependent on the surface area and overall material charge that is either positive or negative [48].

The mechanisms for Triboelectric power generation (Figure 2-33) are:

- Vertical contact separation mode (CS)
- In-plane sliding mode or lateral sliding (LS)
- Single electrode mode (SE)
- Contact or Separated - Freestanding triboelectric layer mode (CFT or SFT)

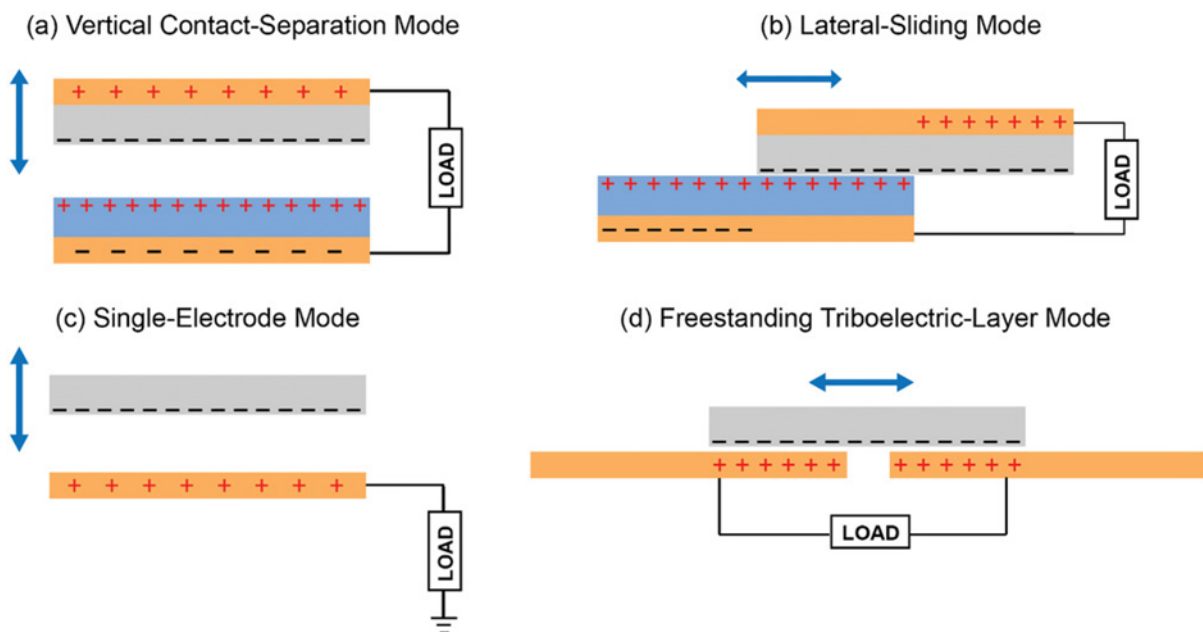


Figure 2-31 Triboelectric generation modes [49]

The electrical mechanism of the TENG generators is calculated using Maxwells displacement current:

Equation 2-39

$$J_D = \frac{\partial D}{\partial t} = \epsilon \frac{\partial E}{\partial t} + \frac{\partial P_s}{\partial t}$$

- D = Displacement field (C/m²)

- ε = Permittivity of medium material (F/m)
- E = Electric field (V/m)
- P_s = Polarisation (surface)

For the example of the mechanism of contact-separation, the dielectric materials collect opposite charges from contact electrification, and this oppositely charges the materials and pushing the free electrons in the electrodes (metal material – charge carriers) through the load creating an AC voltage/current. The power produced is related to the surface charge density ($\pm\sigma_{tribo}$) of the opposing dielectric materials. The charges are trapped in an electric static field which when moved is the driving force of electrons through a load. The quantity of charge ($\pm\sigma_{tv}$) on the electrodes is a function of mechanical-to-electrical displacement current (z). [49]

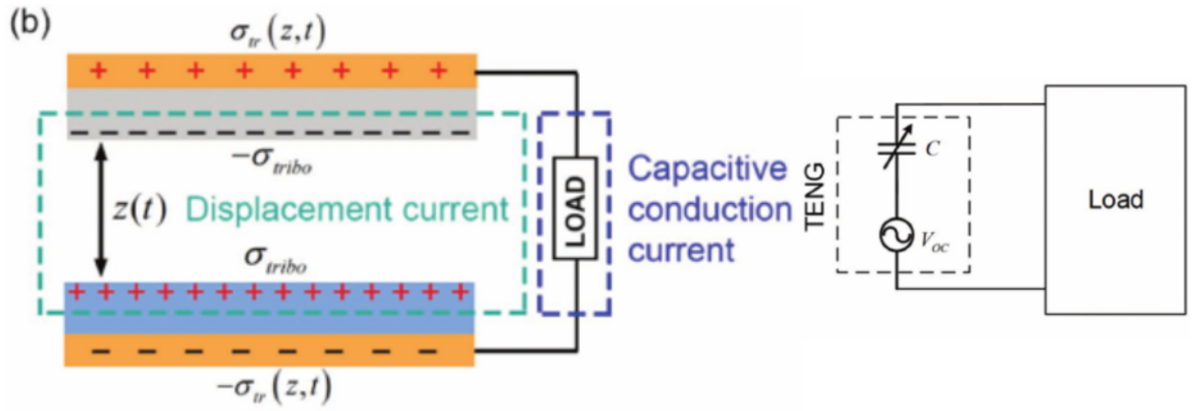


Figure 2-32 Triboelectric Energy Harvester Schematic [49]

Equation 2-40

$$J_D = \frac{\partial D_z}{\partial t} = \frac{\partial \sigma_{tr}(z, t)}{\partial t}$$

- $\pm\sigma_{tribo}$ = surface charge density (C/m²)
- $\pm\sigma_{tv}$ = Charge accumulation (C)
- z = Displacement (m)

The opposite charged faces can be viewed as a variable capacitor controlled by the separation distance. This allows the equation:

Equation 2-41

$$I = \frac{dQ}{dt} = A \frac{d\sigma_{tr}}{dt}$$

The output voltage can be written as:

Equation 2-42

$$V = -\frac{1}{C(z)} \times Q + V_{oc}(z)$$

2.5.1 Triboelectric figure of merit

The figure of merit is a performance guide to clarify the effectiveness of a material or device. As Triboelectric energy harvesters are not at the same level of development as other types of energy harvesting devices, the figure of merit system is new and split between material (FOM_M) and structural (FOM_S) with and overall performance merit (FOM_P).

The calculation for structural merit:

Equation 2-43

$$E_m = \frac{1}{2} Q_{SC,max} (V_{OC,max} + V'_{smax})$$

Equation 2-44

$$FOM_S = \frac{2\varepsilon_0}{\sigma^2 A} \cdot \frac{E_m}{x_{max}}$$

Equation 2-45

$$FOM_P = FOM_S \cdot \sigma^2 = \frac{2\varepsilon_0}{A} \cdot \frac{E_m}{x_{max}}$$

- $Q_{SC,max}$ = Max transferred charge (C)
- $V_{OC,max}$ = Max Voltage (open circuit) (V)
- V'_{max} = Max Voltage (V)
- ε_0 = permittivity of a vacuum (F/m)
- A = Area of Tribo-electrification (m²)
- σ = Charge density (C/m²)
- x_{max} = Displacement (m)
- E_m = Energy output (W)
- FOM_P = Figure of merit (Performance)
- FOM_S = Figure of merit (structural)

Using the standard figure of merit for structure, it has been found that Contact Freestanding-layer Triboelectric Mode (CFT) has the best performance. [49]

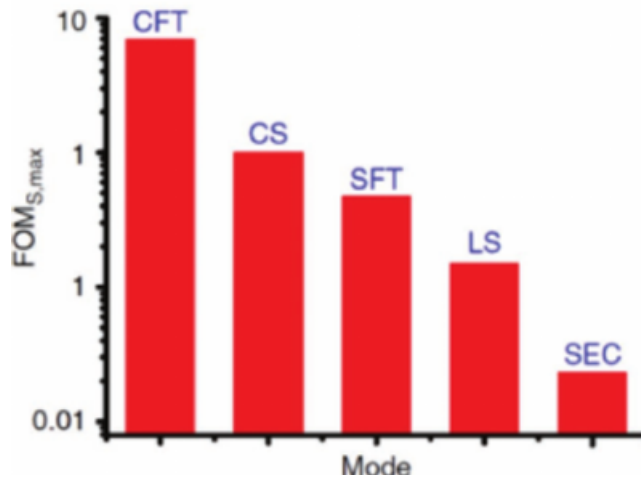


Figure 2-33 Triboelectric: Mode of activation Figure of Merit (Structure) [49]

2.5.2 Triboelectric Generators/ Energy Harvesters

Micro Triboelectric generators or energy harvesters can be utilised alone or complement another generator type, such as a Piezo (PE-TE) or electromagnetic (EM-TE) harvester, as they are thin filmed and can be used on boundaries and sliding surfaces. Y. Qian [50] developed a Hybrid Energy Harvesters (HEH) using novel materials showing a promising power density over the current configurations (Figure 2-36). This has a power density (2D film area) of 6.22 mW/cm².

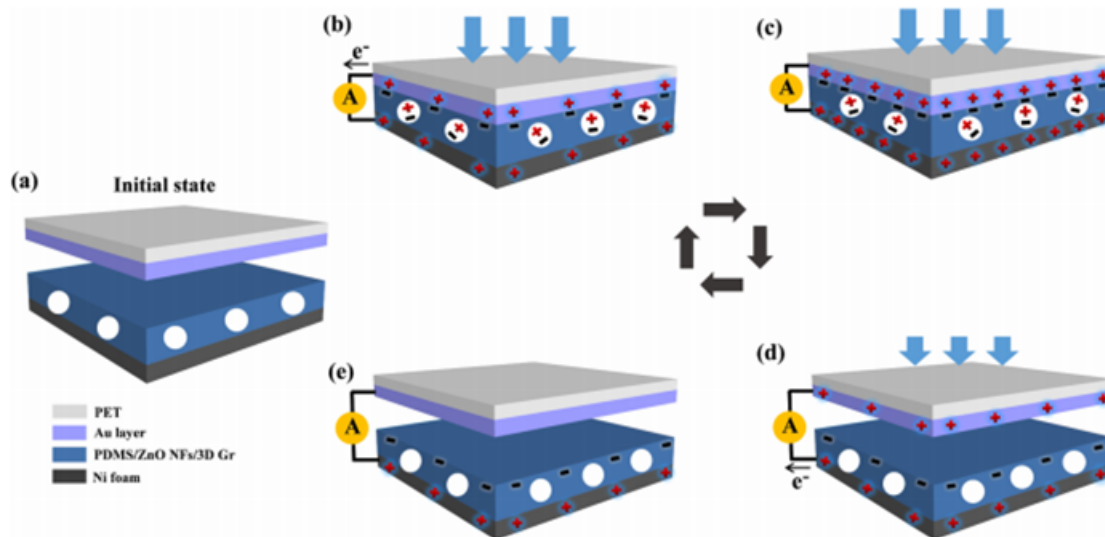


Figure 2-34 Hybrid Piezoelectric & Triboelectric Energy Harvester [50]

A HEH system for Electromagnetic and Triboelectric can also be achieved but it has been noted that Electromagnet (EM) and Triboelectric (TE) can negatively impact each other [51]. The design of the electromagnetic system uses the spring mass system to induce electricity on the coils and combines the Triboelectric mechanism into the walls of the moving mass. This has been demonstrated in multiple configurations. The generation by the Triboelectric generator outputs high voltage and low current, and the Electromagnetic Generator outputs low voltage with high current [52].

The Halbach magnet array magnet orientation combined with a Contact free-standing mode Triboelectric generator (CFT) has shown to produce 11.75 mW and has a power

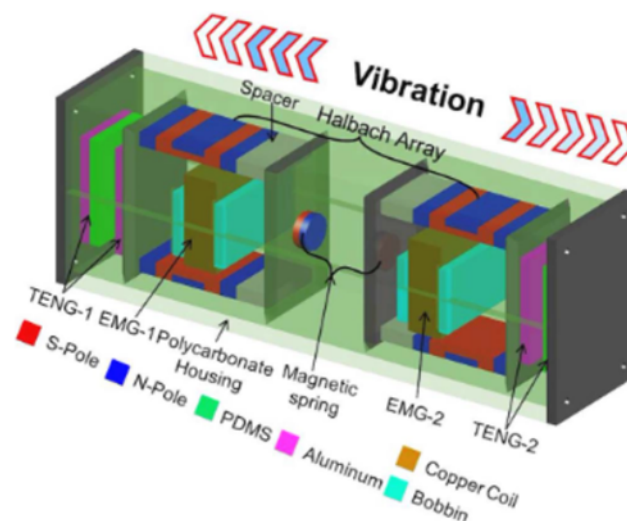


Figure 2-35 Hybrid Triboelectric & Electromagnetic Halbach Array Energy Harvester Prototype [53]

density of 381 W/m^3 (0.381 mW/cm^3) at a frequency of 5Hz at low accelerations of 0.5g (Figure 2-36) [53].

A similar design that uses 3 magnets, one magnet as the oscillating mass again with Contact Free-standing Triboelectric generator integrated to the oscillating mass walls. This configuration produced 0.128 mW/cm^3 at 7.5 Hz (Figure 2-38) [52]. If this system was to be scaled down to a micro system, then the output would likely be less than 0.128 mW/cm^3 .

Similar to a conventional oscillating electromagnetic energy harvester, this design demonstrates a modest enhancement in energy generation capacity with minimal additional system complexity. However, the system contains a significant amount of unutilized space, which continues to pose challenges for scalability. Additionally, the presence of two distinct outputs may necessitate supplementary electronic components for effective energy storage.

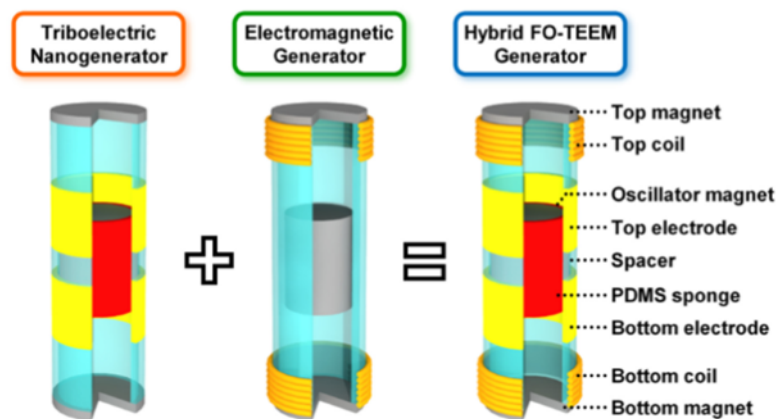


Figure 2-36 Hybrid Electromagnetic & Triboelectric (Magnet Spring) Spring Mass Energy Harvester Prototype[52]

2.6 Summary

The review was aimed at looking at energy harvesting systems able to harness kinetic energy from high acceleration and rotational forces that are also suitable to be scaled down effectively to a mm-scaled device that can power an electronic load. When comparing all the technologies for energy production and comparing the sizes, the highest power output of 2 W over for a 100 ms duration at a low volume of 3.4 mm^3

(this volume is not inclusive of the fins and other components required to make the system spin) is from the rotational permanent magnet turbine configuration. These designs are micro fabrications and involve silicon chemical etching and precise material deposition. The way these energy generators have been configured requires the energy input to be consistent and it is unclear if the mechanism would function under large input forces, linearly and rotationally. One prototype, the flow driven permanent magnet turbine has been developed to work in bullet system which has high energy inputs, and the physical shape of the system has had to be altered to allow for air flow to spin the magnetic field. The drawbacks of the flow driven electromagnetic system have already been discussed in this paper and is summarised as complex to produce and susceptible to environmental failure.

The next highest power density devices suitable for scaling down, and require less complex fabrication, come from piezo energy harvester configurations. These configurations are much better suited to a high force environment because of the material characteristics of piezo materials being tougher and working well under compression forces. Although there are not many designs that can encompass rotational energy effectively into small packages, the possibility to harvest energy from shocks and linear acceleration and effectively scale down to create a higher energy density package are promising. The designs for a piezo energy harvesting device also seem to be less complicated in fabrication and there are also multiple avenues in system redesign and enhancement that cannot be added in the other technologies, (pre-loading, force magnification structures, thermal compressive materials, multi-mode material activation, force spreading structure re-design).

The table comparison (Table 4) shows that most of the previously researched devices have low energy outputs. Although the table shows the highest energy outputs, it doesn't represent efficiency. Some of the systems are receiving abundant energy at fixed frequencies, compared to others that are receiving infrequent vibrations or shocks.

Table 2-4 Summary of Energy Harvester Power Outputs

Technology	Description	Area mm ²	Height mm	Volume mm ³	Power output mW	Power density mW/cm ³	Starting Page Number
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Piezo	Bellville washer Piezo - Shear Spring mass system	20.00	45.00	14137.17	2100.00	148.54	20
	Acoustic Piezo resonance	10.00	8.00	628.32	5.30	8.44	23
	Rotational Plucking Piezo (low frequency)	30.00	7.00	4948.01	0.01	0.00	26
	Shear Mode Slotted Cymbal transducer	35.00	5.00	4810.56	16.00	3.33	34
Electromagnetic	Axial PM generator (high speed)	2.00	1.08	3.39	6.60	1945.23	41
	Inertia/setback generators	16.80	10.00	2216.71	9.25	4.17	45
	Spring-Mass Oscillatory Electromagnetic	3.00	18.75	132.54	0.04	0.29	50
	Compression into rotational energy	42.00	55.00	97020.00	7.70	0.08	51
	Rotational Pendulum Electromagnet/triboelectric generation	71.00	40.00	158367.69	21.00	0.13	53
Triboelectric	Halbach magnet array magnet orientation combined with a Contact free-standing mode	468.00	65.00	30420.00	11.75	0.39	58
	Triboelectric generator integrated to the oscillating mass	13.00	30.00	3981.97	0.509	0.128	59
							Useful Power

2.7 Conclusion and future perspectives

As electronics continue to become more versatile, compact, and widely integrated, there is an increasing demand for energy harvesting systems with higher energy densities and reduced form factors. These systems must be capable of either charging an energy storage device or directly powering low-complexity applications, such as sensors or lighting. For example, a basic 1.6V LED circuit requires a minimum power of 32 mW and a total energy of 32 mJ to remain constantly illuminated for one second, unless more advanced pulsing circuitry is employed which would drastically reduce the energy requirements.

Among the technologies reviewed, only the Belleville Spring piezoelectric harvester and the integrated flow turbine bullet system demonstrated sufficient output power to meet this requirement. Other systems could potentially be optimized by storing higher voltages in smaller capacitors to achieve the necessary power levels, but whether they could be producing enough energy for is not conclusive. The analysis highlights that both the mechanical design and the operating environment are critical factors influencing energy generation efficiency.

While many of the reviewed mechanisms are limited to low-force applications, they provide valuable insights into the constraints associated with miniaturization and manufacturability. Piezoelectric generators, when paired with high-force spring washers, offer relatively simple configurations compared to micro-turbine electromagnetic generators, which involve a greater number of components and rely on counter-rotating bodies rather than the simpler linear oscillators. Triboelectric harvesters appear less effective than both piezoelectric and electromagnetic systems, exhibiting known challenges such as charge leakage and material durability concerns. For a cost-effective device that straightforward to manufacture and a higher reliability, the electromagnetic and piezoelectric show the most promise for small scale energy harvesting.

3 Piezo Shear Structures - HIGH FORCE COMPRESSION MODE TO SHEAR MODE PIEZOELECTRIC ENERGY HARVESTING

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Statement of Contributions of joint authorship

Fergus Crawley conducted all simulations, experiments and writing for this manuscript. Fergus also created all figures and graphical data. Zhenhua Luo proof-read and assisted with improving the manuscripts details and structure.

Abstract

This study is to develop structures with the ability to convert a compression force into radial extension or shear force, to increase power output through piezo shear mode. In this work, a piezoceramic-spring system was developed with two types of force-spreading spring configurations, the Belleville disc springs and the crinkle washer. A force loading profile is applied to a piezoceramic element and structure causing the force to be distributed in different directions when compared to a conventional helical spring damping system or compression. The performances of these novel structures were studied using Multiphysics simulation and experiments. This work shows that both the Belleville disc and crinkle washer produce improved energy output between 15-22% compared to compression alone, whilst the Belleville disc spring outperformed a crinkle washer in both simulations and experiments. The results show that converting compression to shear force in energy harvesting could be a potential approach to increase the energy efficiency and energy density.

Keywords: Wave, Belville, Crinkle, Washer, Shear, Piezo, Piezoelectric, Energy Harvester

Piezo energy Harvesting

3.1 Introduction

Energy harvesting is used in any scenario where energy is wasted in an inefficient process (combustion systems such as engines, general motion of vehicles or humans[69], [70] from high drag or friction) or ambient energy that is harvestable such as light, heat and kinetic[71], [72]. Energy harvesters are gaining traction in electronic devices such as sensors in structural health monitoring[73], [74], wearable electronics, and mobile phones or Internet of Thing (IOT) devices[75], [76]. Wireless sensors in remote environments are an area where the possibility to provide energy harvesting systems to electronics that communicate with the Internet of Things is a big advantage over continuous re-supplying of batteries [77], [78], [79], [80]. With lower energy consuming electronic devices, some energy harvesting systems that were once seen as un-feasible because of the low power output are now verging on capable [81], [82], [83]. Further research is needed in the power density and activation structures that not only allow or more stable and reliable electrical energy production but can increase the efficiency of mechanical force to electrical energy.

Piezoelectric energy harvesters are systems that require the input of mechanical force and can convert it to an alternating current (AC) output, combined with a power rectification component (full bridge rectifier), the AC can be converted to Direct Current (DC), this electrical energy can be stored in batteries, capacitors or used directly in electronics.[84]

The mechanism that activates a piezoelectric material is stress and strain on the internal crystalline structure of the piezoelectric element, which results in electrical polarisation and forms charge fluctuations that can be collected by electrodes and further stored in capacitors and batteries. The method by which the piezoelectric element is stressed or strained determines the electrical output in proportion to the force applied. The mode of mechanical energy transfer to the piezoelectric structure determines the amount of energy that is converted to useful electricity. Compression, bending/stretching, and shear movement are the 3 modes of piezoelectric activation. There are limitations to each mode of piezoelectric activation, with piezoceramics being a brittle material, bending and stretching will lead to cracking and quick failure of a piezo structure[85], [86], [87]. The challenge is the adding of a structural

mechanism for even load distribution for maximal electro potential activation of the piezo and understanding the feasibility of manipulating compression force to shear force.

A piezo element can be activated in a 3-Dimensional sense, and the energy produced is characterised by the piezo materials charge constants (d_{33} , d_{15} , d_{31}) and voltage constants (g_{33} , g_{15} , g_{31}). Simply, if a force is applied to a piezo material, depending on the direction of the input force, an electrical field and voltage potential-difference is produced which can be collected by electrodes and stored.

Shear force activation is not as simple to achieve as PZT (Lead Zirconate Titanate) and piezoceramic elements in general are often brittle materials. Thin discs and plates would require first compression to create adequate grip/coupling. Another issue around the converting compression to shear force for most applications is being able to match the input force and frequency with a spring mass dampener into limited space but with capable stiffness and spring rate.

Different manors of system design have been demonstrated to activate shear stress on discs. Rastegar [17] demonstrated the use of Belville washers (Figure 3-1[A]) for absorbing much high forces combine with a piezoelectrical system and a mass, with

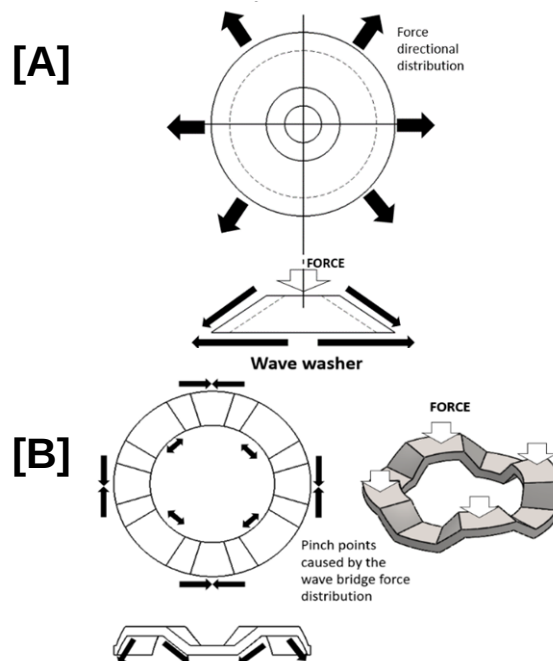


Figure 3-1 Belville Disc Spring[A] & Wave/Crinkle Washer[B]

the system achieving 1-2 Joules in a device $\varnothing = 20\text{mm}$, height = 45mm. Further

experiments in cymbal transducers have led to the novel shapes such as the wagon wheel [59], from the first conception of rectangular structured bridges [88], and the earlier conception of the cymbal by Fernandez and Dogan [89]. The curvature structures mentioned distribute the force on a piezoceramic element's face between compression and shear mode, activating the d_{33} & d_{15} [27], [90], [91], [92].

A different kind of spring or washer construction is the wave spring design. The wave spring design has been seen to store similar forces to conventional springs at a reduced size, the crinkle washer, which is a simplified version of the wave spring (Figure 1-B), [93] which also shows the characteristics of radial expansion and shearing. Implemented by Zhu [94], this wave shape is a circular washer that integrates bridge structures concentrically to the circumference. This works with the same principle of the bridge structure or cymbal, transforming compression into shear force, but in the case of the wave washer it is perpendicular to the cymbal force direction. However, the crinkle washer is a lesser explored structure compared to that of a cymbal or Belleville disc [95], [96], [97], [98] (disc spring - Figure 3-1-A) which have been the focus of much research for shearing piezo elements but has the potential to exhibit similar radial shearing and could allow for a higher energy density structure for multi-stack piezoelectric devices. The effects of this washer are pinch points and expansion points leading to alternating pressure distributions on the piezo element's face. With multiple waves in the design, the face of the piezo element no longer has a singular directional displacement and instead it becomes an alternating pattern of compression and expansion, this might negatively affect charge collection on the electrodes as there is the presence of opposite charges on the same electrode face, effectively cancelling out the charge, but designs in the electrodes could overcome this.

In this work, both disc spring and crinkle washer were studied by simulation and experiment to understand their deformation mechanisms and shear mode performance created by their rotationally symmetrical structures. The Crinkle washer structure has an added customisable variable compared to the disc spring, which is number of waves in the circumference which allows it the stability to sit against 2 faces. This characteristic is explored to demonstrate it can be beneficial in converting compression into shear force in piezoelectric discs with the aim to develop a novel and

highly tuneable force spreading structure, which is more powerful and compact for end use in a high force energy harvesting structure.

3.2 Methodology

Piezo compression equations - Voltage & Electrical Energy

Voltage produced is a key output to calculate the electrical energy produced. Voltage is calculated using the following equation:

Equation 3-1

$$V = -(g_{33}hT) = -\left(g_{33}h\frac{F}{A}\right)$$

V =Voltage, g_{33} = Piezoelectric Voltage Constant – force direction (3) parallel to poling direction (3) (Vm/N), h = Thickness (m), T = Force applied/area (m^2), F = Force (N) in the direction (3), A = Area (m^2)

Using the equations stated below, the theoretical energy produced can be calculated:

Equation 3-2

$$E = \frac{1}{2}(C_0V^2)(1 - k_t^2)$$

E = Energy, C_0 = Capacitance (Farads), Voltage = V , q = Charge), k_t = Coupling factor (Compression of a thin disc $k_t < k_{33}$)

Piezo shear equations

The shear calculations are the same as the compression calculations, but they use the d_{15} , g_{15} and k_p .

Equation 3-3

$$g_{15} = \frac{d_{15}}{\varepsilon_{11}^T}$$

g_{15} = Piezoelectric Voltage Coefficient (Shear strain) (Vm/N), d_{15} = Piezoelectric Charge coefficient (shear strain) (C/N), ε_{11}^T = Permittivity of ceramic (F/m)

Equation 3-4

$$V = -(g_{15}hT) = -\left(g_{15}h\frac{F}{A}\right)$$

V =Voltage, g_{15} = Piezoelectric Voltage Constant (Shear strain) (Vm/N), h = Thickness (m), T = Force applied/area (m²), F = Force (N), A = Area (m²)

Equation 3-5

$$E = \frac{1}{2}(C_0V^2)(1 - k_p^2)$$

E = Energy, C_0 = Capacitance (Farads), Voltage = V , q = Charge), k_p = Coupling factor (Shear of a thin disc)

Equation 3-6

$$\varepsilon_{11}^T = \frac{\varepsilon_{11}^T}{\varepsilon_0} \cdot \varepsilon_0$$

ε_{11}^T = Permittivity of ceramic (F/m), ε_0 = Permittivity of free space = 8.85×10^{-12} (F/m)

Power equations with matched circuit resistance

Equation 3-7

$$P_{max} = \left(\frac{V}{Z_1 + R_L}\right)^2 \cdot R_L$$

P_{max} = Power max (W), V =Voltage, Z_1 = Impedance (Ω), R_L = Matched circuit Resistance (Ω)

The Piezo disc samples used in this study are made from the material PIC 255 by PI Ceramics. The sample chosen is **PRYY+0170** (*properties in the appendix).

Simulation

A simulation was created to mirror the setup of the experimental system, using a material with close electrical properties (PZT 5A) and importing the load and velocity profiles from the experiment into the COMSOL Multiphysics.

Experimental

To create a force input, an Instron 5kN press with programmable force and speed inputs is used to compress a Piezo disc between 2 machined aluminium plates acting as the piezo holder (lower plate) and compression face (upper plate). The Instron Model used is a 5965 with a max return speed of 3200mm/min and a max load of 5kN set up with 2 flat plates for compression (Appendix).

Washer Loading Force

A pre-test was needed before the electrical testing was started to understand the loading characteristics of the washers themselves, with this, the spring rate and the flattening force is understood. The set up used just the parallel metal compression plate faces of the Instron, and a 4KN maximum limit was set to protect the machine and load cells.

Piezo electrical set-up

The second stage of testing various washer designs on the top piezo face. Electrodes made of thin metal tape with conductive adhesive were used on either side of the piezoceramic disc because of the ease of cutting to shape, strength, and flexibility.

The electrical set up consisted of 1: AC (directly to oscilloscope) and 2: DC (with electrodes connected to a full bridge rectifier, variable resistor and then to oscilloscope) measuring the voltage outputs (Appendix). The output voltages can be referenced to the hand calculations that show the predicted voltage and power outputs and the COMSOL simulation voltage and power outputs. The testing included different sizes and thicknesses of Disc Spring; the disc spring chosen to directly compare to the crinkle washer (**Disc Spring Type 1**) refers to the thinnest disc spring used of 0.4mm thickness, (the crinkle washer used was 0.55mm thick). When exploring off-the-shelf washers with different thicknesses, the inner and outer diameters correspond to the bolt diameters. To keep consistency, simulation was used so that one variable, the thickness, of the washer could be changed,

System fabrication & set-up

Using an Instron 5965 in compression mode, the system can be compressed to a known force and with a known velocity. The base plate of the Instron does not move in this assembly, but the Instron upper plate does and travels downwards. The piezo is contained between the top and bottom aluminium holder plates (Appendix) and the force is applied vertically. The piezo has limited moving capability in the horizontal direction because of the base plate walls holding it in place. This can be seen in the section view diagram. The aluminium holder was coated in paint to prevent electrical leakage. A Silicone layer was also applied between the base plate and the piezo to allow small adjustments, this is important with a machined surface that may have small machining grooves.

Instron Variable Force & Acceleration Inputs

The first Instron experiment, (Variable force), uses a RAMP profile (Figure 3-2-C) that incrementally compresses the piezo from a pre-compression of 40N in steps of 200N, up to 2200N at a velocity of 0.75mm/s. In this experiment the piezoceramic disc stays the same and is not changed (unless destroyed) and washers are changed to compare voltage outputs produced by the change in design.

The second Instron experiment (Variable speed) (Figure 3-2-D), incrementally increases the velocity by 0.2mm/s from 0.2mm/s – 1mm/s. Ramping the velocity does introduce a change in force caused by the Instron feedback system limitations. Above 1mm/s, the system feedback was not fast enough to stay at 1500N and began exert more force.

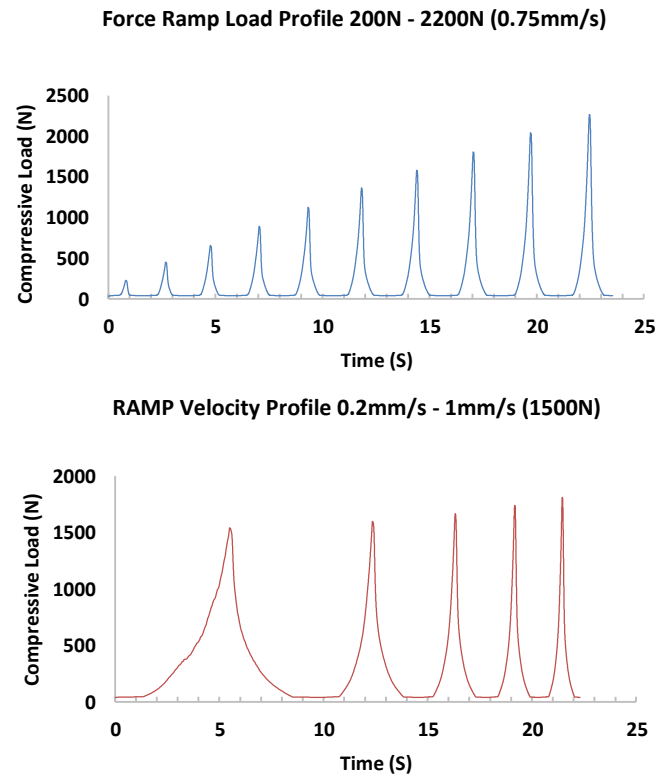


**Figure 3-2 Instron Force Ramp Load Profile[C] &
Instron Velocity Ramp Load Profile[D]**

3.3 Results

Theoretical results

The theoretical calculations (Figures 3-3) are static calculations (or stationary) that does not take into consideration un-even/non-uniform spreading, previous states of the system over time, piezo breaking, different force concentration spots on the piezo and other real-world losses.

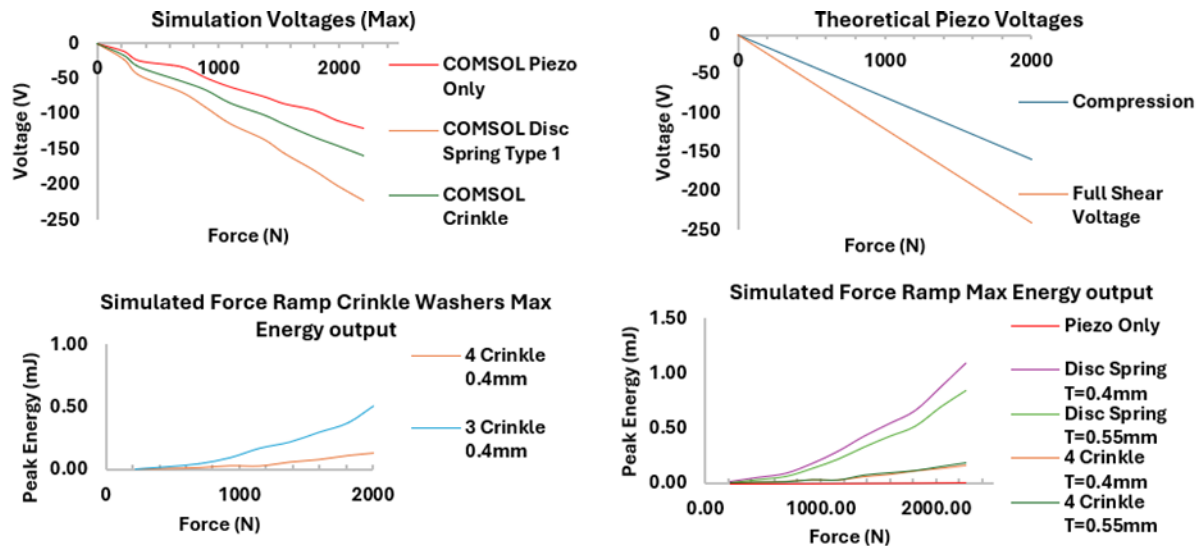


Figure 3-3 Theoretical Piezo Voltages, Simulated Voltages (stationary), Simulated Force Ramp Energy Outputs (stationary), Simulated Crinkle Washer Energy Output (Thickness and wave changes)

The shear results have a much higher voltage output than that of only compression and shows the maximum voltage value if there were perfect conditions.

Simulated Force Ramp Simulation

The simulation was set up to use the Instron load profile (Figure 3-3 - H). A function plot: Interpolation and importing the Force/Time data. The Piezo material used in the simulations was PZT 5A as it is of similar characteristics (table 1). The voltage characteristics under no load correspond with the results from the experimental tests and close to the theoretical calculations. Thee electrical and mechanical dampening conditions were set to isotropic loss factor of 0.00625 (although the material is anisotropic, otherwise it would require populating the young's modulus on all directions), this calculated by the equation $\eta = \frac{1}{2Q}$ with Q = Quality Factor of 80[99]. The simulation pictures have been stopped at 21.4 seconds to analyse the force and electrical distribution at the time of the highest force input.

The simulations did allow for a faster turnaround in testing different thicknesses and, (for the Crinkle washer), more variations in the design such as number of crinkles (waves). It was seen (Figure 3-3 middle) that decreasing the number to waves to the minimum number of 3 and effectively increasing the angle between the piezo surface and washer wave, tripled the energy produced from 0.17mJ to 0.61mJ.

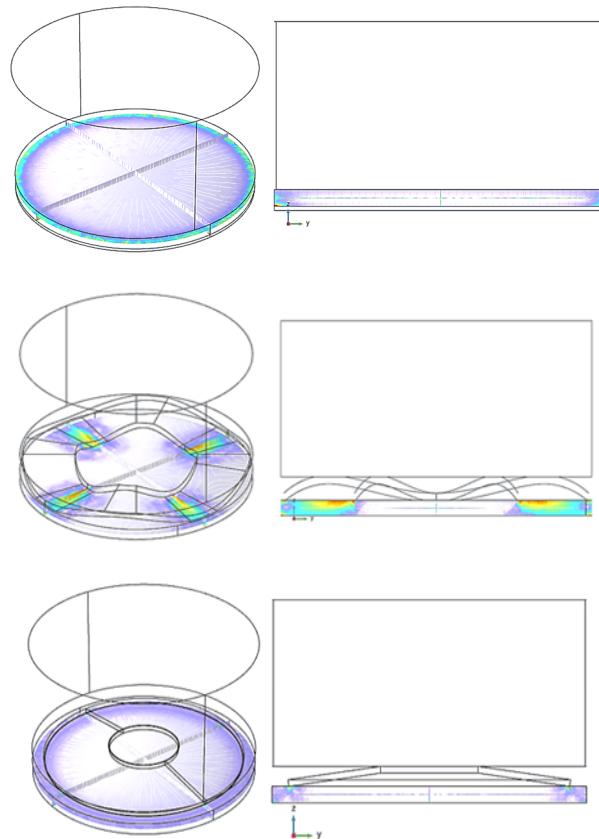


Figure 3-4 Piezo Only Compression[top], Crinkle Compression[middle] & Disc Spring Compression[bottom]

Table 3-1 Characteristics PZT 5A & PIC255

	PZT 5A	PZT PIC255
D ₃₃ [C/N] - Compression	3.74 e ⁻¹⁰	4 e ⁻¹⁰
D ₃₁ [C/N] - Tension	-1.71 e ⁻¹⁰	-1.81 e ⁻¹⁰
D ₁₅ [C/N] - Shear	5.84 e ⁻¹⁰	5.5 e ⁻¹⁰

Compression of the piezo shows minimal electrical potential created in the horizontal plane and nearly all the force in the vertical plane which would keep most voltage in the compression d_{33} range. The edges do receive small shear movement, but this is because of the material having no other direction to expand into and the base of the piezo being fixed (Figure 3-4 top).

The crinkle washer has produced electrical potential in the horizontal plane where it touches the piezo disc. There is also electrical potential produced in the vertical plane. This indicates that the crinkle washer can convert compression into shear d_{15} (Figure 3-4 middle).

The disc spring washer shows a strong indication of electrical potential in the horizontal plane and small areas of electrical potential in the vertical plane where the disc spring is touching the Piezo disc (Figure 3-4 bottom).

The COMSOL simulation results show that the shear activation does increase the voltage when the force is increased in standard compression with the Disc Spring Type 1 have the largest voltage increase.

The Crinkle Washer has also improved the voltage output but not as much as the Disc Spring Type 1 with a difference of 0.9mJ energy (only 15% of the disc spring systems energy) at 2200N. There is a clear effect the Crinkle washer is producing which differs from the Disc Spring in terms of the field direction, with them being perpendicular to each other.

Simulated Velocity Ramp

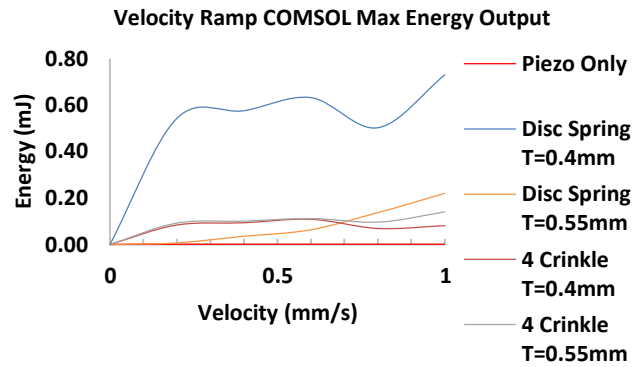


Figure 3-5 Simulated Energy Outputs

The immediate results from the change in velocity of impact (Figure 3-5) show that the Disc Spring has the biggest impact on the energy produced, the crinkle spring does also have an increased energy output over the piezo alone. The piezo alone shows minimal energy produced, and this could be from how COMSOL is setup with the simulated mass face in contact with the piezo deforming before the piezo ceramic disc.

Experimental Validation of Simulated Results

Washer Force Loading Profiles

Using a loading capacity of up to 4 kN (to protect the load cell and Instron system) the crinkle washer and disc spring were tested until flattening (table 3-2).

The results (Figure 3-6) show that the crinkle washer is stiffer than the Disc Spring and more force is needed to compress the structure fully.

Table 3-2 Washer Force/Extension Rates

Name	Disc Spring Type 1	Crinkle Washer
Outer Diameter OD (mm)	18	19.6
Inner Diameter ID (mm)	6.2	10.5
Washer Thickness T (mm)	0.4	0.55
Washer Height H (mm)	1.2	1.7
Zone 1 Rate (N/mm)	112	198
Zone 2 Rate (N/mm)	167	731
Zone 3 Rate (N/mm)	9426	2758

The crinkle washer has a more gradual force/displacement in comparison the disc spring which has a much smaller extension (Figure 3-6). This difference could be due to the disc springs shape constricting the shapes expansion until it experiences a buckling overload. There are 3 different spring rate zones for all the disc spring washers:

- first zone rate in which there is easy extension to minimal force.
- second zone there is the most extension
- third and last zone rate where there is little extension, and the washers are going towards flattening.

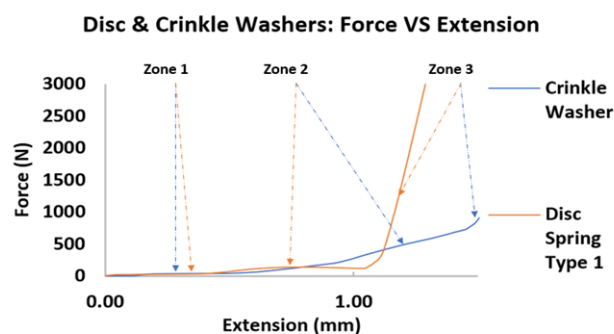


Figure 3-6 Instron Load Profiles for both washer types

The characteristic of all the washers in the final spring rate zone is the steep vertical force displacement when there is no longer a spring characteristic, and the washer is flattened and still under continued compression (which did cause permanent deformation). The washer characteristics shown in zone 2 show the most extension and the results show that the thickness and potentially the design affects the washer stiffness, the crinkle having the highest extension.

Experimental Force Ramp Experiment

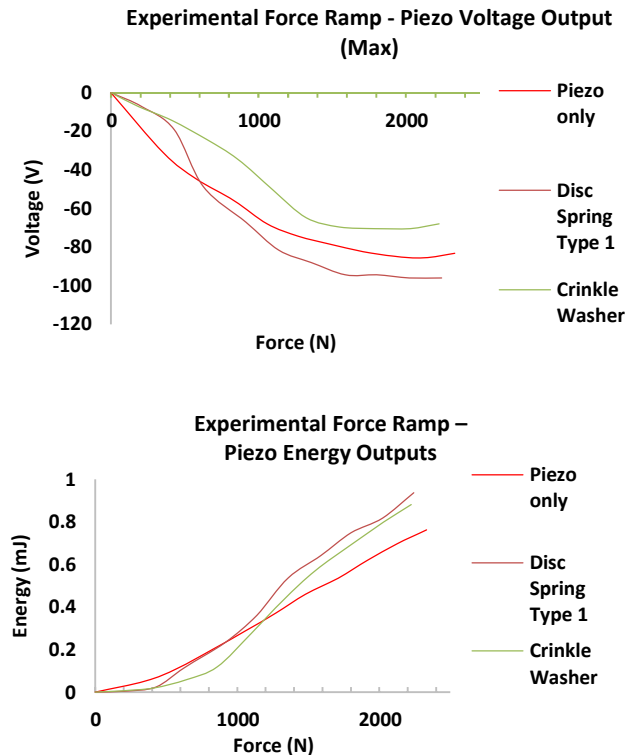


Figure 3-7 Instron Force Ramp Voltage Outputs[top] & Instron Force Ramp Energy Outputs[bottom]

The first set of tests focused on the change in force at a fixed velocity. These tests were carried out between 200N - 2200N and velocity of 0.75 mm/s, the speed and force range chosen was simply to get results while staying in the working limits of the Instron and maintaining accuracy (Figure 3-7).

Compared to the theoretical static calculations and simulations, the energy output was slightly lower for the disc spring but not the crinkle washers. Many real-world conditions that are not seen in simulation such as mechanical imperfections in the piezo, uneven surfaces, friction, thin material layers (paint, foil electrodes). Also, electrical isolation and washer alignment may also have been detrimental to the experiments results, causing short circuiting and uneven loading. The washers themselves may have not had a good bonding to the piezo disc surface and slid instead of gripped the piezo face, reducing transmitted shear force. Breaking was an obvious loss of energy caused by excess radial space, uneven loading, and a loose disc.

The force ramp experiment energy results show that the shear structures work in their intended manor and do increase electrical energy output. The experiment produced

less energy than predicted by COMSOL, which is expected. There was an added dampener to the real experiment that could also have slightly increased the energy output (silicon), this was not added to the simulations because of increased degrees of freedom and much bigger and time-consuming simulations. The Instron machine itself was not always the same each test and time variations did occur, especially in the piezo only experiments, which, with no extension, reached force much faster than the other experiments with washers.

Experimental Velocity Ramp Experiment

The variable velocity results (Figure 3-8) show that there is increase in generated electrical energy with a Disc Spring shear-structure and energy loss with the crinkle washer compared to a piezo disc alone. The results are comparable to the COMSOL simulations with energy produced, except the piezo only that produced minimal in simulation. The crinkle washer caused the piezo disc to fail as gaps allowed the piezo to shift into open space and deform in the centre. (Radial compression could limit this issue). The experiments produced less energy than the COMSOL simulation, again because of the experimental losses not accounted for in a simulation. The Disc Spring still produced noticeable more energy with a steeper gradient and proportional relationship of velocity to energy.

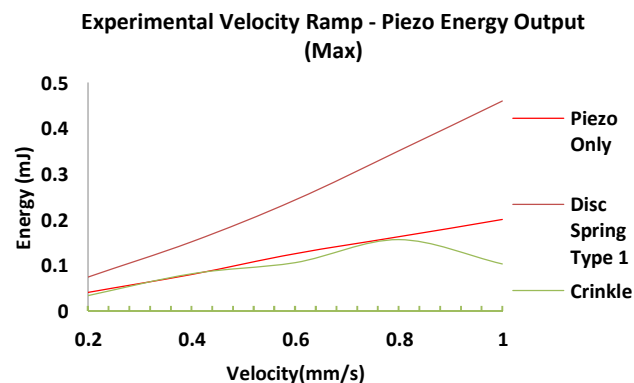


Figure 3-8 Instron Velocity Ramp Energy Outputs

Disc Spring & Crinkle Washer Piezo Disc Failures

During the testing, many Piezo Disc samples experienced breakages that caused results to shift, and energy loses in some circumstances. The patterns can be seen (Figure 3-9) as concentric rings and breaks in the outer circumference, due to the high force expanding the piezo outwards, the concentric rings are likely due to open space created by the Disc Springs & Crinkle Washer under full compression and the washers' sharp edges digging into the surface.

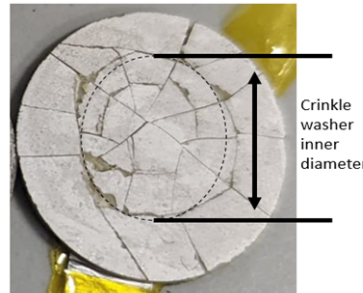


Figure 3-9 PIC255 Piezo Disc Breakages

3.4 Discussion

These experiments show that Disc Spring and Crinkle washers can activate shear mode when under compression as they deform and expand radially, and the outer circumference expands while gripping the piezo face. This shear mode activation generates an increased electrical energy output of a piezo disc under compression. The highest experimental recorded energy outputs ranging from 0.76mJ (Piezo only) to 0.93mJ (Disc Spring) from a single hit (Instron Force Ramp) showing a 22% energy increase, with the Crinkle washer achieving 0.88mJ, a 15% energy increase.

The simulation results showed a maximum of 1.1mJ from the Disc Spring in the mirrored experimental set up. The Crinkle washer showed a minimal energy of 0.19mJ which under predicted the energy output produced on the Instron, but by changing the crinkle thickness and number of waves/crinkles as shown in simulated force ramp (Figure 3-3), the maximum energy jumped to 0.61mJ, a 220% energy increase.

Under changing velocity, in the experiments the Disc Spring showed more reactivity with a definite upward trend and yielded a higher energy output with the highest being 0.45mJ at 1mm/s compared to the 0.1mJ from Crinkle Washer which fell under the piezo alone. The simulated Velocity Ramp experiments show a similar trend to the experiments, with the 0.4mm Disc Spring producing 0.73mJ at 1mm/s and the 0.55mm

Crinkle Washer producing 0.13mJ and the same velocity. However, the Crinkle result was plagued by multiple failures in piezo discs in this experiment which could have disadvantaged the results in the case for the Crinkle washer and would need further investigating.

Failures in the experiments could have been from the open internal radius of the Crinkle Washer and the Disc Spring enabling the piezo element to bend into the open space, expand and break. Force concentrations caused by the Crinkle washer having only 4 points touching the surface, and the potential for unevenly loaded edges could have also been the reason for some of the breakages. The Disc Spring does not suffer from this as often as it has a uniform circular face touching the piezo disc and 1 point of force input, but the sharper edges could eventually cause piezo disc cracking.

Methods which could prevent the breaking of the piezo could include radial compression, even load distribution, centred washer/springs, and removal of sharp edges, and using adhesive bonding over a larger surface area.

In the simulation the crinkle washer was observed to create some radial expansion like the disc spring with added pinch points also observed in the experiments. The pinch points exhibited high electrical potential, whereas areas of expansion did not. A decreased spring deflection of the crinkle washer (the washer height) could be matched to the maximum expansion limit of the piezo disc, and this could stop mechanical failures from occurring which was the biggest issue with the crinkle washer. The simulations also showed that the crinkle washer when customised by changing the height, inner and outer diameter lengths, thickness, and number of waves showed a correlation with energy generation. The disc spring in comparison can also be customised with height, inner and outer diameter lengths, and thickness, before having to alter the shape entirely. Losses of energy in the disc spring has been identified and seen in the study by Ganilova [16]. The limiting factor is attributed to the stress build up in the outer and inner circumference of the disc, with the solution to add radial cuts into the circumferences thus allowing further expansion, but negatively affecting the spring rate. The stress build up is clearly visible in the simulations as shown in Figure 3-10. The Crinkle Washer also exhibits stress build ups created by the inner radius of the crinkles.

Despite this study showing the disc spring outperforming the crinkle washer, the advantage of the crinkle washer can be utilised using multi-stacked piezoelectric discs. These washer designs both have similar characteristics of radial expansion, which increase energy generation by activating the piezo in shear mode. The crinkle washer does not produce as much useful shearing as the disc spring but is able to do the same shearing action on both surfaces (upper and lower) (Figure 3-10) which the disc spring cannot achieve as a single washer. Using the results found in this research, it

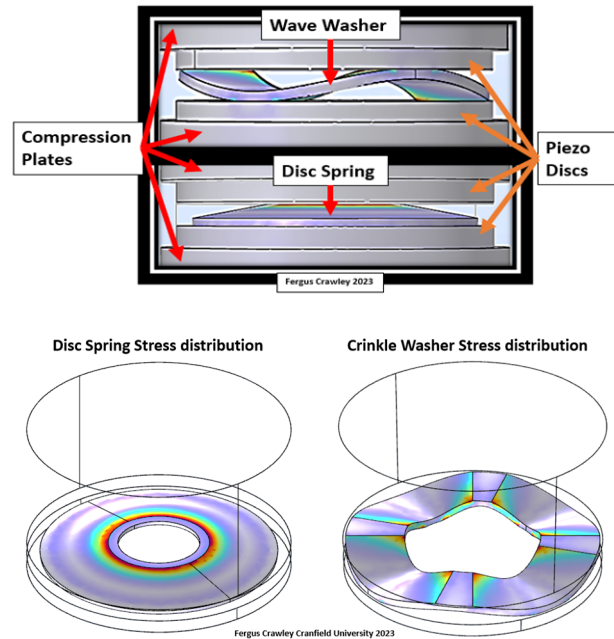


Figure 3-10 Washers in Piezo Stack (dual face), Disc Spring & Crinkle Washer Under Stress

is possible to see that there is a potential for a combination of these washer structures to create a structure that can harness the best traits of each with decreased internal stresses and dual face radial expansion. Replacing disc springs with crinkle washers would effectively remove the requirement for 2 separate washers and could reduce open space inside a piezoelectric stack device. Removing open space (dead space) inside an energy harvester would decrease the package volume.

3.5 Conclusion

In this paper, a theoretical and experimental analysis of two types of washers was performed to characterise the shearing effects of a crinkle and disc spring structure and what electrical response is created on a piezoceramic disc for the purpose of improving power generation in a high force piezo electrical energy harvesting device.

The experimental results are limited to the commercially available washers which sizes did not perfectly correspond to each other, but the correlations and characteristics, could be investigated and paralleled. The energy generated was compared to identify the best performing structure for use at high forces and high velocities.

The Disc Spring compared to the crinkle washer as a force spreading structure has shown superiority for working with a piezo in a mechanical to electrical generator. The Belleville disc spring increasing electrical energy produced by a maximum of 22% under changing force and a maximum of 125% in changing velocity.

The Crinkle Washer design, although not as effective showed a power improvement of 15% under changing force and -50% with changing velocity, although this result suggests the piezo breaking caused large electrical losses.

The Crinkle Washer does have important differences compared to the Belleville disc spring with the extra degrees of tunability which was seen by changing the number of waves in the circumference, which added 220% more energy. The difference in these washer types does show that both washers are doing a similar function at different angles.

Future work could refine these designs to create a washer that can both perform the radial expansion with or without the pinch points, with the ability to mirror the shearing effect on both the upper and lower faces. In this research there is evidence that the inner diameter of the Crinkle washer and the disc spring should be adjusted to remove the stiffness build up and allow better shear force distribution. This would allow piezo electric devices and piezo stacks to benefit from shear mode and allow for space saving in the device, which would then increase the power conversion and power density.

4 Optimising shear structures: Multiphysics Shape and Topology Optimization of a Disc Washer in a Piezoelectric Energy Harvester System

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Statement of Contributions of joint authorship

Fergus Crawley conducted all simulations, experiments and writing for this manuscript. Fergus also created all figures and graphical data. Zhenhua Luo proof-read and assisted with improving the manuscripts details and structure.

Abstract

Shape and topology optimization of off-resonance Piezoelectric energy harvesting systems adds a new dimension when designing an energy harvesting system that has a tailored force spreading structure to match the application environment. The cymbal washer has been found to work effectively in converting compression force into shear force for improved mechanical to electrical energy generation, but with energy harvesters being utilized in different industries and with distinct size requirements, there is a need for optimisation as one size does not usually fit all. The cymbal washer when applied to a piezoceramic disc, allows increased shear movement that has also be found to increase piezo electrical generation. Using optimization, the cymbal shape can also be further refined in shape and overall design, creating novel features to further increase electrical generation that can be maximised to harness specific force and frequency inputs.

4.1 Introduction

Piezoelectric material converts the mechanical deformation into an electric field, polarised piezo crystals are aligned under force creating a potential difference across the piezo [100] and this potential difference is collected on outer electrodes and channelled through various electronic components (diodes & capacitors), this is known as the Inverse Piezoelectric Effect. Piezoelectric materials such as PZT, are imbedded in Energy harvesting devices and convert kinetic energy (vibration, bending, shearing & compression) from ambient sources[101][102]. There are many sources of kinetic energy as many real-world processes are either inefficient and produce friction, noise, and vibration (cars and trains) or objects that are subjected to external forces.[4]

One of the challenges facing Piezoelectric energy harvesting is the kinetic to electrical efficiency and the overall energy density of a harvesting device. The material characteristics of a Piezoceramic affects the energy conversion because of the anisotropic properties, meaning not all properties are the same in each direction of deformation inside the material[12], [100]. The difference in energy conversion efficiency is then determined by several factors including which mode the piezoceramic is deformed. Shear mode activation of a piezoceramic material (PZT 5A) has a higher energy conversion efficiency than compression[103]. Using shear structures to convert a compression force into shear force is a straightforward way of harvesting more energy and improving electrical output.

The charge density of PZT 5A in the shear plane is $d_{15} = 550 \times 10^{-12} \text{ C/N}$ compared to the compression plane $d_{33} = 400 \times 10^{-12} \text{ C/N}$, this is a 37.5% increase in charge

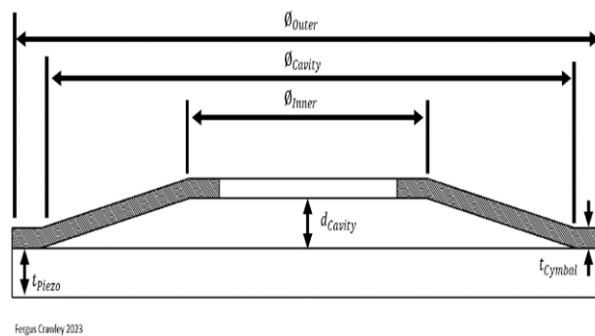


Figure 4-1: Disc Schematic

generated by compression alone, but this is only achieved in this structural design if

100% of the compressive force can be converted into shear stress which is not possible due to the friction and spring structure retaining energy. But a shearing structure (disc) plays the important role of converting some of the compression to shear which can still improve energy outputs though a higher force to charge conversion coefficient [27], [104].

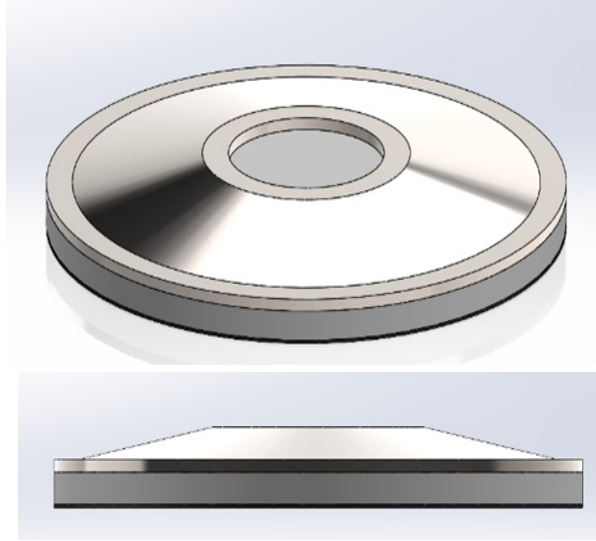


Figure 4-2 3D Piezo & Disc Spring

A method of changing the way a force is applied on a Piezoceramic is by using a structure that will channel the force in a beneficial way. Cymbal washer transducers are metal circular bridge structures that sit on the face of a Piezoceramic disc and create force amplification. The shape of a cymbal was conceptualised by Tresslar, Dogan & Fernandez[89] in the 1990s for the use in Direct Piezo effect electronics, example being undersea radar. The parameters of the cymbal (Figure 4-1) have a direct link to the behaviour of the Piezo element attached (d_{Cavity} , $\emptyset_{Inner}$, $\emptyset_{Outer}$, t_{Piezo} , t_{Cymbal}).

The cavity depth (d_{Cavity}) relating to mass and piezo displacement and stiffness of the cymbal, and the other dimension effecting resonance frequency and cymbal stiffness, (d_{Cavity} , $\emptyset_{Inner}$, $\emptyset_{Outer}$, t_{Piezo} , t_{Cymbal})[59]. The cymbal material was also found to be an important factor of the cymbal behaviour, with higher metal stiffnesses decreasing overall displacement, but allowing for much higher loads.

Moving away from the standard cymbal transducer structure and the trapezoidal shape, other cymbal shapes such as arches which employs sloping of the cymbal cavity walls has resulted in the production of higher piezoelectric conversion efficiencies.[88] Other designs have also been conceptualised and evaluated that

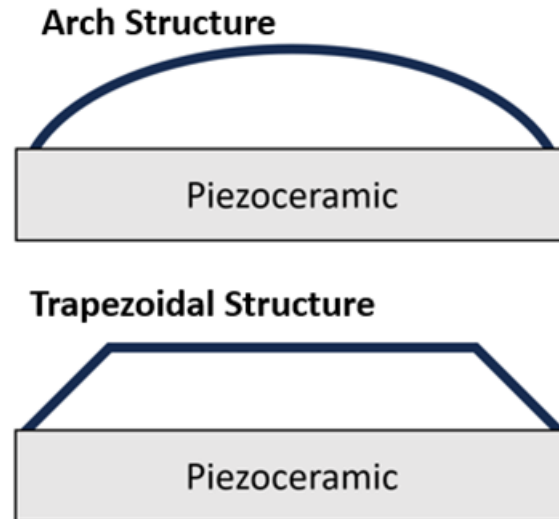


Figure 4-3 Arch & Trapezoidal Structures

investigate material removal in the cymbal structure, the structural changes observed by Yuan et al. [29] explored adding slots to the outer circumference and this has improved compression to shear energy transmission and reduced circumferential stress build up in the cymbal, which equates to a loss in force conversion.

The use of bridge structures by Zhao[88] on a rectangular piezo structure also identifies that the shape of the cymbal/bridge and material thickness have a large impact on voltage generation and thus efficiency, and the difference between a trapezoidal and arched bridge[88], [105] More specifically, cymbal piezo systems have seen further shape and power density development, Zhao and Ganilova[59] have explored further the work of Fernandez[89] characterising the dimensions and the impact of shape alterations on the piezo material, with the wagon wheel cymbal introducing slots[29] that improve axial to radial displacement and shearing.

What has been identified in previous research by Zhao and many others is that the design and shape of the cymbal has not yet been fully optimised for converting compression to shear mode electrical generation in combination with a piezo element. There is performance increase by removing sections in the outer circumference and decreasing the internal stresses shown by the wagon wheel cymbal that has shown

energy improvements and lays the foundation for future optimisation based on iterative simulation instead of just design. An observation suggests that internal stresses in the circumferences prohibit radial expansion and reduce electrical generation.

With the advances of design and simulation software, it is possible to rapidly simulate and redesign structures, making small progressive changes that contribute to an improved structure. This work focuses on enhancing a cymbal structure using topology optimisation, and to further identify structural changes, structural patterns, and material removal in the cymbal to create improved expansion and mechanical to electrical energy conversion in a piezoelectric harvester. Shape optimisation is also used to evaluate the cross-sectional shape of the cymbal and better develop the stress distribution characteristics.

4.2 Simulation

The three COMSOL options for Gradient-based optimization solvers are MMA (Method of Moving Asymptotes), SNOPT (Sparse Nonlinear Optimizer) and IPOPT (Interior Point Optimizer). The MMA solver created by Professor Krister Svaberg [106] has been used previously for Topology Optimization and was developed for this purpose. It works by creating the sub problem (set of objectives such as increased power) and iteratively solving for each stage.

The solver used in this study was MMA. The base equation (minimise example) where the variables are:

Equation 4-1

$$x = (x_1, \dots, x_n)^T \in R^n$$

$$y$$

Equation 4-2

$$y = (y_1, \dots, y_m)^T \in R^m$$

Equation 4-3

$$z = \in R$$

The equations:

Equation 4-4

$$f_0(x) + a_0z + \sum_{t=1}^m (c_1y_1 + \frac{1}{2}d_1y_1^2)$$

$$f_1(x) + a_1z - y_1 \leq 0$$

$$x \in X, y \geq 0, z \geq 0$$

Equation 4-5

$$X = \{x \in R^n | x_j^{min} \leq x_j \leq x_j^{max}, j = 1, \dots, n\}$$

x_j^{min} and x_j^{max} are real numbers that satisfy x_j^{min} and x_j^{max} for all values of J in $f_0, f_1, \dots, f_n$, a_0, a_i, c_i , and d_i is a real number that satisfies $a_0 > 0, a_i \geq 0, c_i \geq 0, d_i \geq 0$ and $c_i + d_i > 0$ for all "i". Also $a_i c_i > a_0$ for all the occasions "i" with $a_i > 0$.

The simulation allows for rapid testing of a Piezoelectric structure with of multiple design variants which would otherwise require constant design iterations manually and take longer.

4.2.1 Shape Optimisation

Shape optimization is a tool that can evolve the shape of a structure based on the specified control variables. This then means dimensions are incrementally adjusted while considering the objectives which can be set to maximise or minimise [107]. In this model the shape being optimised is the cymbal, with an objective of increasing the electrical energy output and keeping the structure within defined boundaries. The main dimension variables are the shapes inner faces between the mas and the piezo disc, this means the shape is free to curve and material can be added or subtracted to improve the force distribution and electrical output of the system.

4.2.2 Topology Optimisation

Topology is loosely defined as the organisation of a structure and internal spaces in which the structural properties are preserved or improved but allow for the optimal material mass. Density Topology optimization is a COMSOL technique that can improve structures when given an objective. The Topology optimization assesses the model and adds or removes material on the structure [108].

Topology can be used along with the Piezoelectric module to optimise the shape of the cymbal to increase the electrical energy production and view potential clues as to structural characteristics that better lead to perform performance.

4.2.3 Model Definition

Table 4-1 Simulation Model specifications

Body	Material	Dimensions
1 - Mass	Structural Steel	O.D.=10mm H=20mm
2 - Cymbal	Structural Steel	H=1.4 I.D.=6mm O.D.=20mm
3 - Piezo Disc	PZT-5A	O.D.=10mm H=1mm
4 - Silicone Layer	PDMS	O.D.=10mm H=0.1mm

The model is split between 2D and 3D. It consists of 3 materials and 4 bodies, with the mass and a structure made of structural steel, the piezo disc from PZT-5A, and a thin layer of PDMS under the piezo. The force of the mass is defined by its weight and an acceleration variable. The whole geometry is in union, with the PDMS having a fixed base, and there is an outer roller boundary preventing outward spill.

The mass is accelerated into the structure and thus the Piezo disc, converting some of the mechanical energy into electrical energy. The starting structure is a cymbal washer acting as a force spreader to improve the shearing mechanism that improves piezoelectric energy conversion. The proposed system is confined to a solid outer wall (not visible) which does not allow horizontal movement, as the device would be inside a protective case in a real example.

2D Model (Revolved)

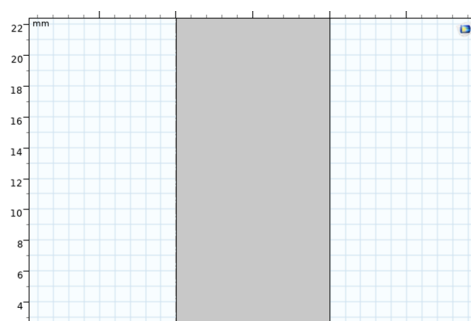


Figure 4-42D Simulation Model

$R=0$ is the axis of symmetry or revolution in which this 2D design can be turned into 2D revolved (3D). This model is calculated much faster due to greatly reduced mesh nodes calculated on a singular plane, but the electric potential in the 3D revolved mode may not show the real characteristics of an anisotropic material such as PZT-5A.

4.2.4 3D model

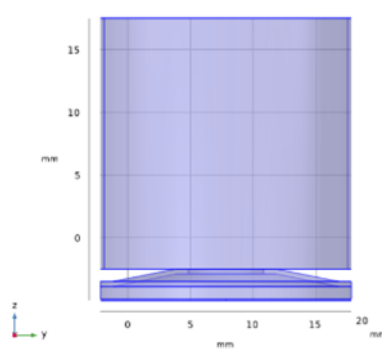


Figure 4-5 3D Simulation Model

The 3D model is the full dimension without the use of symmetry. This model gives more accurate predictions of the shear movement, and the electric potential generated

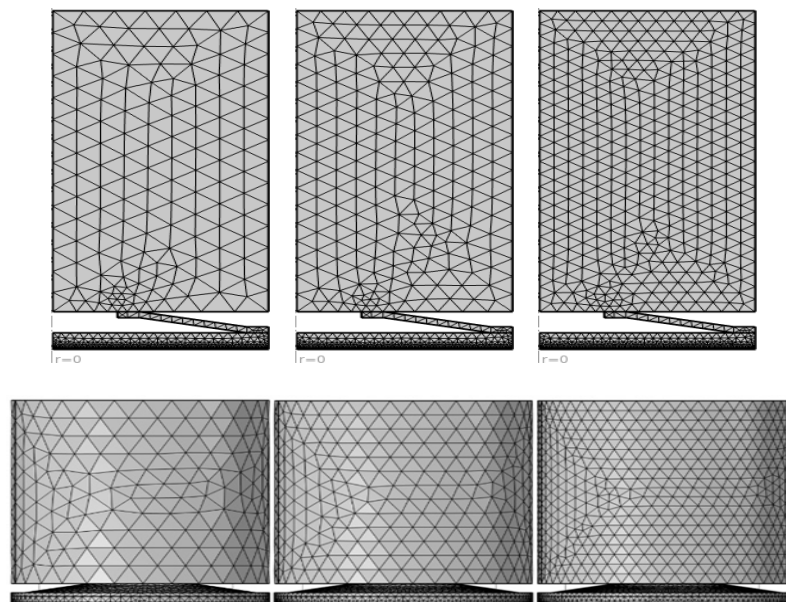


Figure 4-6 2D & 3D Simulation Model Mesh sizes

on the Piezo disc.

4.2.5 Meshing

A mesh sensitivity study is run for analysing the mesh convergence, compare the solutions and to decrease the level of error in the simulations. Adding more nodes does increase the time taken to run a simulation.

Table 4-2 Mesh Sizes

Mesh number	Mesh Size
Mesh 1	Normal
Mesh 2	Fine
Mesh 3	Finer

4.3 Results

4.3.1 Benchmark Results with Mesh Sensitivity

To test the efficiency of the optimisation, the simulations needed to run to find what energy is produced initially.

4.3.2 2D Mesh

Table 4-3 2D Mesh Sensitivity Results

2D Stationary				
Domain Elements	Boundary Elements	D.O.F.	Mesh	Energy (mJ)
1009	252	5559	Mesh 1	0.188937
1134	261	6077	Mesh 2	0.18902
1508	283	7655	Mesh 3	0.1893

The 2D mesh refinement resulted in very similar results with a small increase in the energy in the Piezo disc. The transient tests gave higher energy feedback compared to stationary as the transient simulation simulates the behaviour off the system up to the max force value compared to the stationary simulation which does not. It is noted that the more elements, the longer the simulation run time became.

4.3.3 3D Mesh

Table 4-4 3D Mesh Sensitivity Results

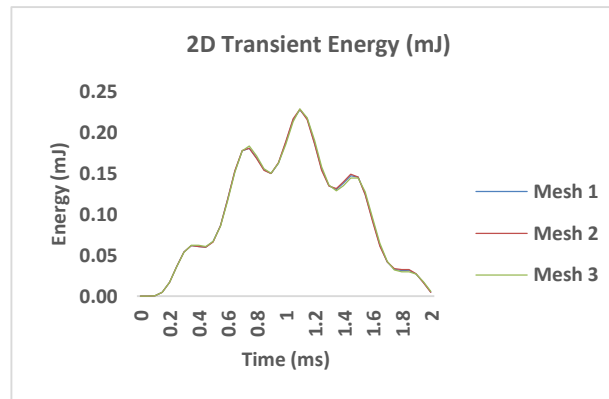


Figure 4-72D Transient Mesh Sensitivity Results

3D Stationary					
Domain Elements	Boundary Elements	Edge Elements	D.O.F.	Mesh	Energy (mJ)
54835	16272	846	291114	Mesh 1	0.18814
173287	42584	1196	918647	Mesh 2	0.18928
484171	98338	1662	2540172	Mesh 3	0.18965

In the 3D mesh tests, the stationary simulations showed little change to the energy output. In the 3D Transient tests, there higher energy produced again like in the 2D simulations due to the difference between transient and stationary solvers in COMSOL.

Issues did occur in the mesh 3 experiment as the simulation was much larger, introducing multiple meshes to the model allowed for increased domains on the mass, cymbal and piezo, while keeping the silicone layer the same, which reduced domains and increased the speed of the simulation. This trade-off is based on computing power and simulation speed.

4.3.4 2D Model Shape Optimisation Result

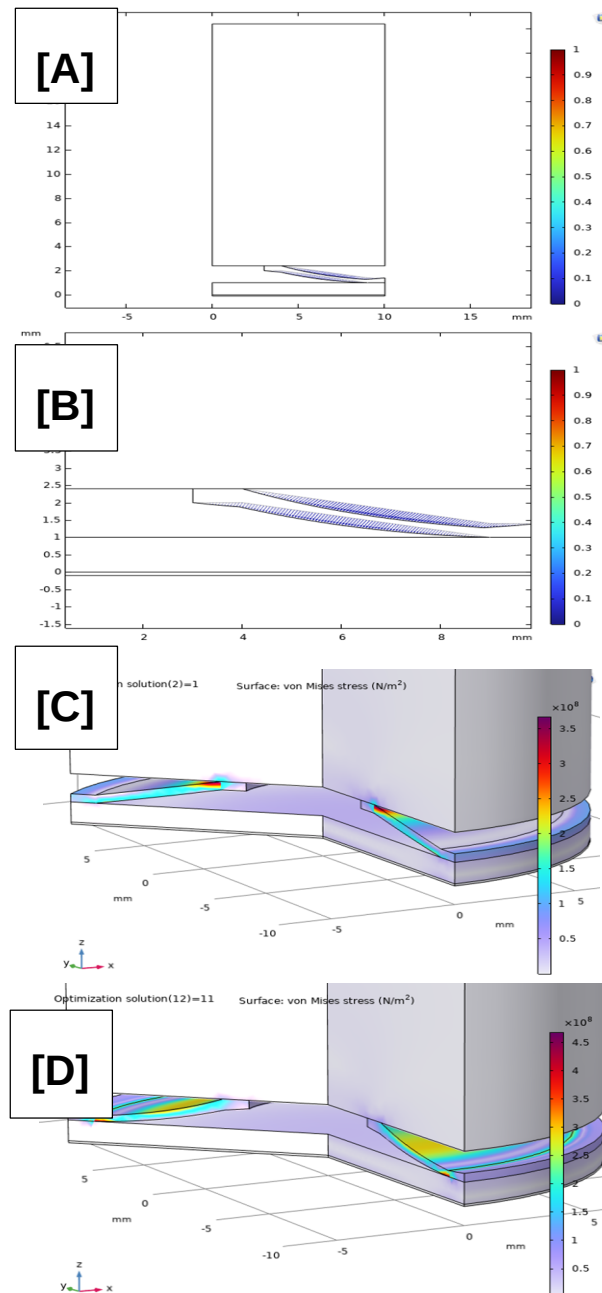


Figure 4-8 A&B 2D shape adjustment to the washer. C&D 2D Revolved Stress distribution before and after Optimization of Cymbal Washer

The 2D model optimization shown in Figure 4-8 shows a noticeable change in the cymbal profile, creating sloped angle with decreasing thickness towards the edges (Figure 4-8 - A & B). The verification of the new cymbal shape shows that the stress is no longer confined to the centre (Figure 4-8 – C) and instead is spread across the complete structure (Figure 4-8 – D). The energy output produced by the new shape is

increased and in Figure 4-9 it is possible to see a visual representative **of the optimisation iterative steps adding energy output until there are limited improvements**. The optimisation simulation was limited by the shape optimisation settings that confines the maximum shape change to a set distance increment, this can be adjusted, but it was found that increased movement can lead to errors and intersections of washer and piezo.

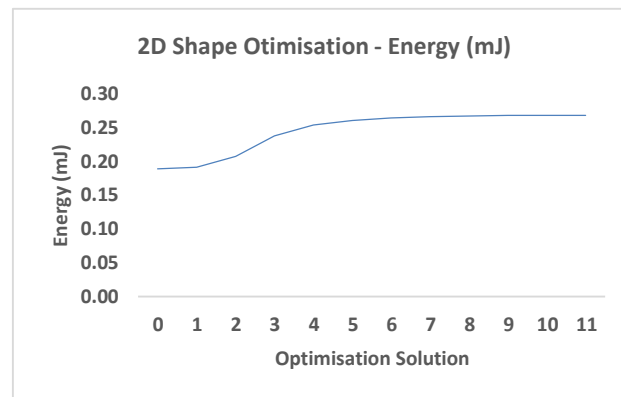


Figure 4-9 2D Shape Optimization solution steps

Using the new shape produced by the optimisation, a 2D verification simulation was used to measure the newer design against the original. Figure 4-10 is the transient simulation demonstrating the enhanced energy production over time with a higher energy output on above 0.3 mJ achieved by the optimised shape. The use of a transient simulation instead of a static simulation means that the shape optimisation is still applicable throughout the force input range and simulates the characteristics of

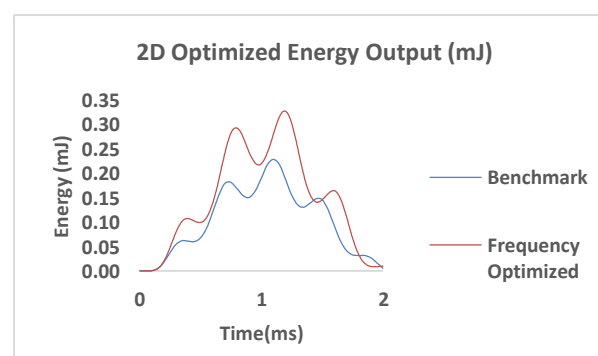


Figure 4-10 2D Optimized design energy verification

the full deformation over the experimental time range.

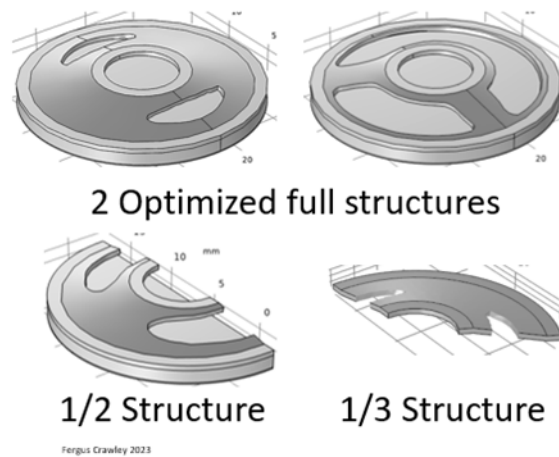


Figure 4-11 3D Topology Optimised Washer Results

The removal of material in the thickness of the disc allowed it to be more flexible and store less stress in the inner circumference, and even potentially creating buckling points mid washer. The shape of this optimised design can be linked to many previous studies that are also attempting to remove the stress build up in the circumferences by adding cuts, the optimisation however has reached a similar result by the use of gradually thinning thickness of the component for the center outwards.

4.3.5 3D Topology Optimized Results

The topology optimisation shown in figure 4-10 has demonstrated that there is excess material in the washer that is negatively impacting the stress distribution and not allowing the shearing mechanism to be utilised fully on the piezo surface. Improved stress distribution is observed in both the 2D and 3D simulations which allows more mechanical energy to transfer into the piezo and be converted to electrical energy. The amount of extra material correlates to the incoming force and stiffness required for displacement in the cymbal washer.

3D topology results, Figure 4-11, showed new shapes of similar design to original bridges, but ultimately had fundamental flaws when the verification test was done. Decreased mass and random mass distribution in some of the simulation cases lead to imbalanced structures that negatively affected energy output. A method to bypass this issue is introducing symmetry to make sure that the structure will balance. This was done by adding a plane of symmetry (Figure 4-11, half structure and 1/3 structure) to the structure. This method also increases speed of the simulations. Another method

to tune the topology is using topology for optimization at certain frequencies, this allows the structure to be tuned to an incoming force at a frequency (peak force acceleration), in this case the frequency being in the range of 250Hz. ($F=1/T=1/0.004\text{ms}$)

The resultant structure of these optimisations finished by producing 0.32 mJ (Figure 4-12) compared to the standard cymbal structure producing a maximum energy of 0.23 mJ. This is a substantial increase in mechanical electrical energy production for this case.

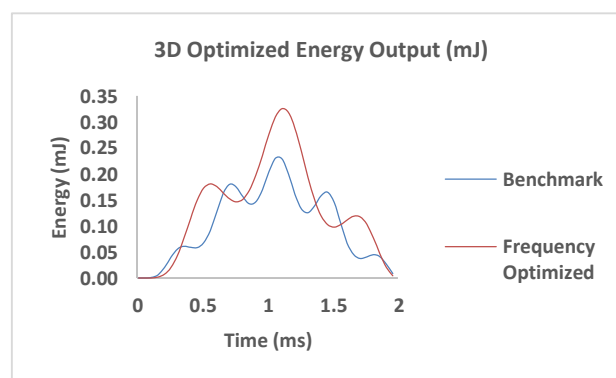


Figure 4-12 3D Optimized design energy verification

Using shape and topology optimisation has quickly defined structural changes that positively affect mechanical to electrical energy conversion. Shape optimisation in 2D proves a much faster method of producing the structural changes due to the decreased number of elements requiring solving. The overall energy gained theoretically by the adaption to the slope and thickness of the disc resulted in an electrical output of 0.32mJ compared to the initial design of 0.23mJ and overall increase of 39% verified by the transient simulation.

3D topology optimisation shows a potential further insight into the disc shape density, with areas being remove and creating similar structures to bridges. The time taken to run 3D simulations is much higher (due to increased elements) than 2D, so collecting and verifying results is a longer task. The drawback of the 3D stationary study in the verification stage, where after optimization the structure can be shown to produce imbalances and the lack of symmetry that leads detrimental energy loss as the mass

structure can move more freely and therefore deflects and reduces energy transferable into the disc deformation, this is not seen in 2D because of the symmetry used, which helps to keep the model balanced and prevent structural collision and thus energy loss, but it is not as accurate because it cannot identify the deflection issue. Using symmetry planes on the 3D model solver decreases the time of the simulations as to be expected from the decrease in elements, and it also speeds up topology and is also a way to create a symmetrical final component. To decrease COMSOL simulation time, the use of decreased movements steps by the optimiser and limiting density removal steps in the model parameters is a way to prevent the excess removal of the disc and get a verifiable result.

4.3.6 Shape and Topology Optimisation Feature Verification

Testing the conclusions from the different types of optimisation simulations, using the slope with a changing gradient, with a decreasing cross sectional area spanning from the centre shown by the 2D shape optimisation, and the removal of excess material seen in the 3D Topology Optimisation, a design was produced (Figure 4-13) to combine these features which has a similar look to the wagon wheel cymbal designed by Ganilova [59].

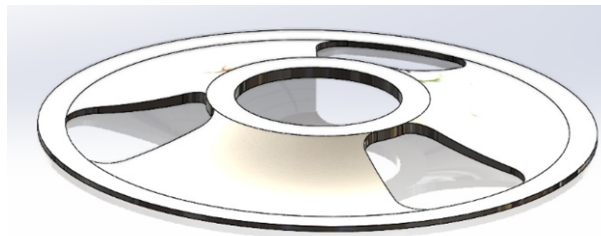


Figure 4-13 Slope, thinning and mass removed cymbal washer.

This design was subjected to the verification simulation to record the energy output, this resulted in a max energy output of 2.15 mJ (Figure 4-15), a 676% increase from the single parameter optimisation of 0.31 mJ. The stress is also seen to be mostly in the outer radius and the edges of the slope but shows less stress in the internal

diameter which has dropped from $3.5 \times 10^8 \text{ N/m}^2$ (figure 4-8[C]) to $2 \times 10^8 \text{ N/m}^2$ (Figure 4-14).

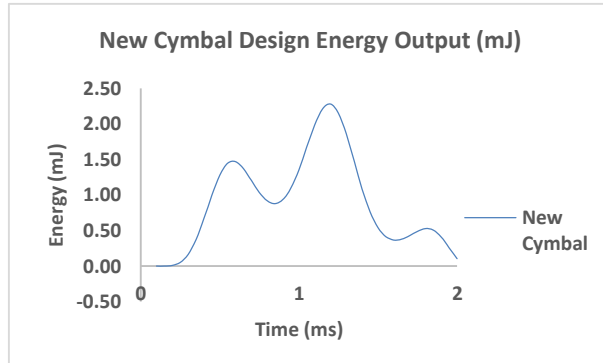


Figure 4-15 Modified Cymbal Energy Output

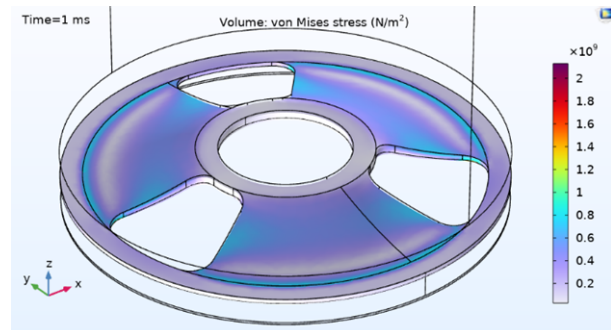


Figure 4-14 Modified Cymbal Stress Distribution

4.4 Conclusion

Optimization is a powerful tool that can be combined with other Multiphysics such as Piezo to further improve results based off initial experiments. In this energy harvesting case with a disc washer and piezo disc, the optimization tool has shown that the initial cymbal shape in can be improved when the slope undergoes a gradual thinning away from the centre and has a gradually decreasing slope, and the topology is improved with the removal of excess material reducing internal stress to further increases the deformation, these factors combined vastly improves shear force transmission to the piezo to convert to electrical energy. In the simulations there are various complexities of geometrical shapes that can also be simplified by introducing symmetry planes to allow for better simulation performance and balanced/symmetrical structures.

Completing a mesh sensitivity analysis was a useful tool to check that the numerical solutions were independent of the mesh size and gave accurate results, which was important when balancing the computational efficiency with the time taken for running the simulations. The simulations in the future could be further refined to adaptively mesh critical regions where the stresses concentrated to capture more details of the disc springs physical behaviour with higher accuracy.

These simulations of the individual characteristics (thickness and material volume) show that optimisation can increase the systems electrical energy density

performance in this case by 676%, which is a large improvement. Using the guidance of the generative design results, it is possible to combine and create an even better performing structure.

For scaling down components for user cases like munitions, the energy density becomes of high importance, which is why optimisation is fundamental for finding structural improvements. This study was conducted on a larger scale (20mm disc spring) to make the results more identifiable and simplified so that it can be compared to the other experiments. Optimisation has shown the potential doubling of energy density from chapter 3 results of 1.1 mJ using a of the shelf component, to 2.1 mJ with a tailored design.

5 Redesigned Crinkle Washer for Piezoelectric Shear force Generator

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Statement of Contributions of joint authorship

Fergus Crawley conducted all simulations, experiments and writing for this manuscript. Fergus also created all figures and graphical data. Zhenhua Luo proof-read and assisted with improving the manuscripts details and structure.

Abstract

Shear structures used for piezoelectric energy harvesters are used as a way of redirecting the path of an inputted force so that the piezoelectric element can better convert the force to electrical energy. A popular structure is the cymbal structure, with the ability to turn compression into radial expansion and thus create shearing on the face plane of a piezo. The drawbacks of the cymbal washer are found when multiplying the washer in a stack configuration, as the shape of the cymbal is only able to activate a single face. This research is continuing the comparisons of the wave (crinkle) washer against the cymbal washer and understanding the benefits of a washer that has a rotational symmetry that can be used to shear 2 piezoelectric elements simultaneously.

5.1 Introduction

Electrical energy is used in every aspect of modern civilisation. Since the improvement of battery technology, the development of low power electronic devices and a dependence on digital information, there is a growing need for self-charging devices that remove the requirement for a grid power source connection or routine battery replacement. Energy Harvesting devices are a potential solution and are a method of capturing and storing energy from non-grid sources such as wind, solar, kinetic motion. Other energy sources can be found in processes which produce wasted energy such as thermal (human body & internal combustion engines) and electromagnetic waves (radio & Wi-Fi signals[109]), all a potential source of energy.

Piezoelectric energy harvesting is a method of converting mechanical energy into electrical energy and requires mechanical force. The Piezoelectric materials internal crystal structure is orientated in such a way that the mechanical deformation allows the lattice structure to shift, forcing the internal electrical equilibrium into a polarised state and producing a fluctuating electric field within the material. This polarised state is used to create charge displacement in collector electrodes on opposing sides of the induced electrical field, which when electrically coupled with a storage device, can produce useful electricity.

Piezoelectric Stacks are a structural design for energy harvesting or sensing, where multiple piezoelectric elements are layered on each other. This layering effect is a method to increase voltage response, maximise capacitance and increase deflection or displacement in actuators.[110]

The electrical configuration of a stack uses a piezo element mounted on top of each other with alternating electrodes between each face [ADD DRAWING]. The method of activation is compression and force amplifying structures can be added to the outer casing to further amplify forces or deflection, an example being flex tensional & compressive transducers.[111], [112], [113], [114] Using a structure on the outside of a stack allows for pre-loading which can be beneficial for piezo ceramics. Using a pre-stress structure, the stack is always kept in compression, preventing the ceramic going into tension. PZT is known to have a weaker tensile yield strength than compressive yield strength, thus time spent in tension can be detrimental to the ceramic structure and lead to part failure.

Smaller bimorph structures such as cymbal transducers, which are dual layer beams that have a force spreading structure attached directly to the piezo element face can also be stacked. The difference of this construction is that the piezo element is subjected to not only compression but also shearing.

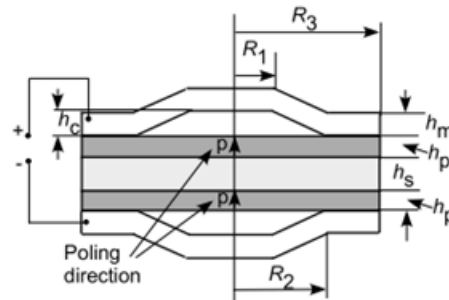


Figure 5-1 Bimorph Cymbal PZT Energy Harvester

The shearing effect or d_{15} on PZT has a higher charge coefficient than compression d_{33} and this allows for the conversion of more mechanical energy to electric energy under a compressive load. The cymbal structure has been the focus of much research to improve the shearing conversion and increase the power density through structural manipulation and optimisation.[28], [29], [59], [89], [115] These structural designs have

led to improved shearing and energy conversion characteristics, but simply the shape of the cymbal is still only 1 sided. The cymbal only works in a certain orientation and another cymbal – faced oppositely is required for further stacking.

Once stacked, there is not only increased dead space in the design, but there is an increase in required cymbal structures to activate the piezo as the cymbal can only activate a single piezo on the wider face plane (Figure 5-3). A crinkle washer on the other hand has shown to have the potential to be double sided and has already been shown to have shearing properties.[115] The wave like structure does share similarities with the cymbal such as rotational symmetry and an angled bridge or arch structure. But unlike the cymbal structure, there is limited research surrounding crinkle or wave shear-structures for piezo bimorphs or stacks. This research aims to further explore the crinkle wave structure and perform a design iteration and optimisation to obtain a novel structure for use in munitions with internal cylindrical volumes containing piezoelectric stacks used for energy harvesting.

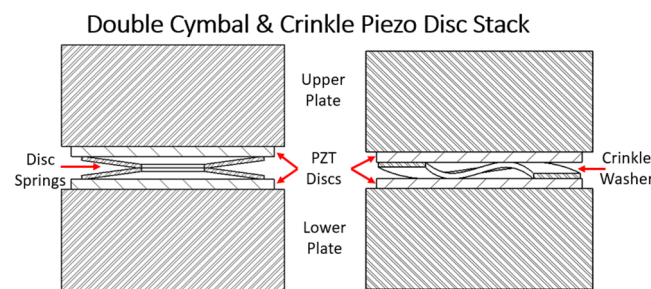


Figure 5-2 Piezo Spring Washer 2 stack configurations disc spring (left), Crinkle washer (right)

5.2 Methodology

Multiphysics software is used to set up a simulation that can be recreated on a dynamic force loading system (Instron). The crinkle and cymbal structure are easily created and redesigned to analyse the characteristics of each structure under force loading. Stress distribution and electro potential are good indicators of how the structure is interacting with the piezo and using the feedback from the simulations, it provides a starting place to iterate the design.

Previous simulations show how the inner radius of the cymbal and the crinkle concentrate force (Red zones); by decreasing this stress build up, the structure is freer to expand radially and thus increase shear of the piezo face attached. To standardise

the simulations a 3-wave crinkle was turned into a 3D model to use as a baseline for the simulations (Simulation 2). From there characteristic iterations were created logically created to test their impact on mechanical to electrical transduction.

Table 5-1 Simulation Variables table

Crinkle Simulation	Thickness (mm)	Inner Diameter (mm)	Height (mm)	Waves	Outer Diameter (mm)
1	0.25	10.5	1.7	3	19.6
2	0.55	10.5	1.7	3	19.6
3	1	10.5	1.7	3	19.6
4	0.55	5.5	1.7	3	19.6
5	0.55	15.5	1.7	3	19.6
6	0.55	10.5	0.7	3	19.6
7	0.55	10.5	2.7	3	19.6
8	0.55	10.5	1.7	2	19.6
9	0.55	10.5	1.7	4	19.6
10	0.55	10.5	1.7	3	19.6
11	0.55	10.5	1.7	3	19.6

Changing
parameter

The simulations are set up to observe the relationship of separate variables with piezo electric energy production. All the simulations use the same central crinkle washer to compare against (2) as these dimensions relate to a physical component. The first experiments (1-3) are to examine the effect of thickness change. Simulations (4-5) are

varying the inner diameter of the crinkle washer. Simulations (6-7) are to demonstrate the change in height of the washer. And the final simulations (8-9) are to examine how the number of waves influences energy output.

Simulations (10-11) are created off the observations of all the previous simulations.

The theoretical circuit used uses 2 full bridge rectifiers for each piezo disc with 2 individual capacitors C1 & C2. [fig]

Crinkle Washer Simulation Schematic

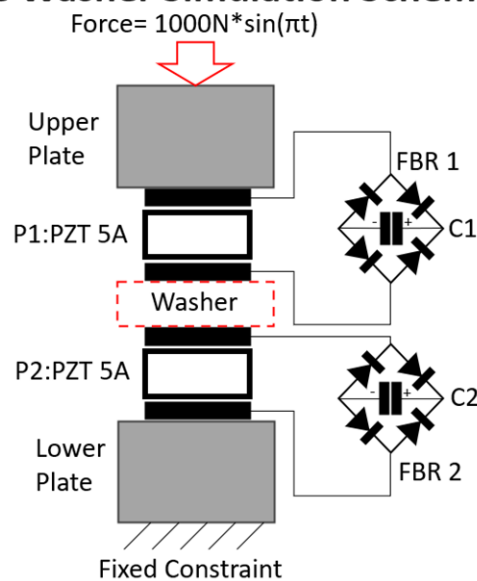


Figure 5-3 Double Piezo Stack & Storage schematic

5.2.1 Fabrication & Experiment

To produce a validate experimentally these simulation results is a challenge as the method of crinkle manufacture is done by using die cutting and forming tools that are expensive to manufacture for 1-off experimental shapes.

Therefore, the method of manufacture for experimental validation was metal 3D printing using FDM (fused deposition modelling) technology. The material chosen was stainless steel 17-PH by BASF.

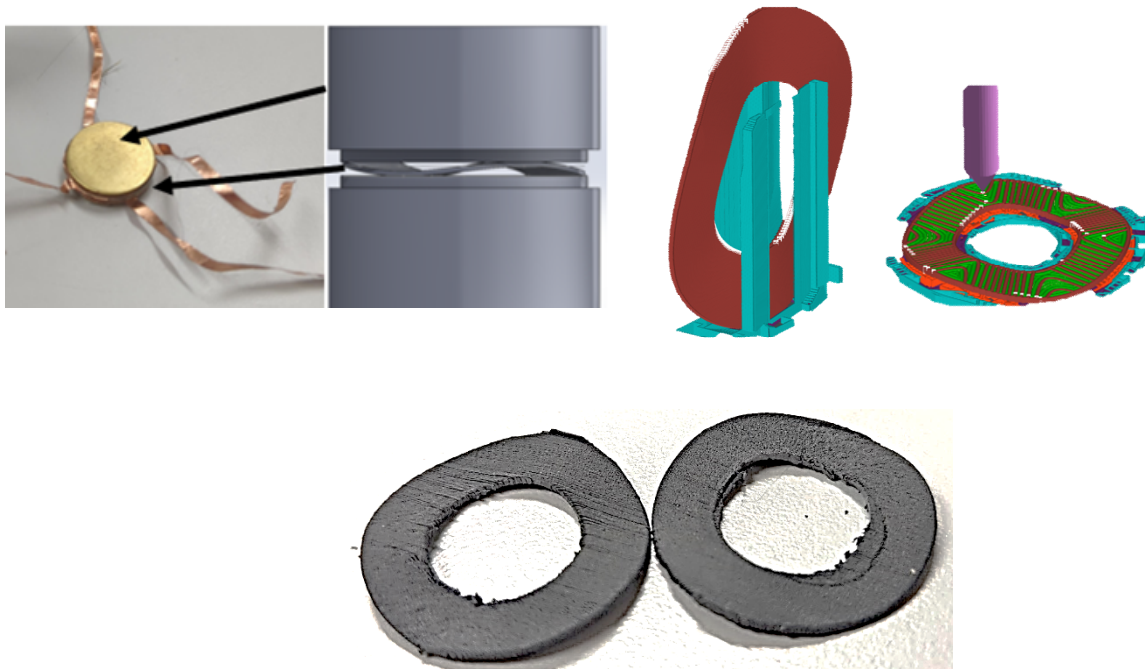


Figure 5-4 Crinkle Washer stack (Top left), 3D printing layer design (top right), Metal 3D printed crinkles – printed green parts (Bottom)

There are drawbacks of this method compared to the formed crinkle washer. 3D printing metals is a long process requiring post processing that causes shrinkage. Shrinkage makes it difficult to get the perfect design dimensions in the final component, making a full comparison to simulations not possible. Another drawback are layer lines that tend to be less prevalent after the sintering and fusion of the metal particles. The printed material will be much less ductile unless there is some level of annealing which could be performed after the metal part production, using in house inductive heating techniques.

Before the parts are post processed from the green part (still containing 20% volume of plastic) to the solid steel component, the parts are smoothed and edges de burred. The next stage is to mount them to piezo discs and run a force test using an Instron to the same load profile used in the simulations. The prototype wave washers will be benchmarked against the standard available size.

5.3 Results

Crinkle Thickness Testing

The results of the simulation (figure 5-5 – simulation 1-3), demonstrated that the thicker the crinkle became, the less it deflected. The less shear deflection resulted in less electrical energy is produced and stored in the capacitors. Noticeably, there is stress concentrations on the inner circumference that was in all 3 thickness tests.

Adjusted Thickness Simulation Results

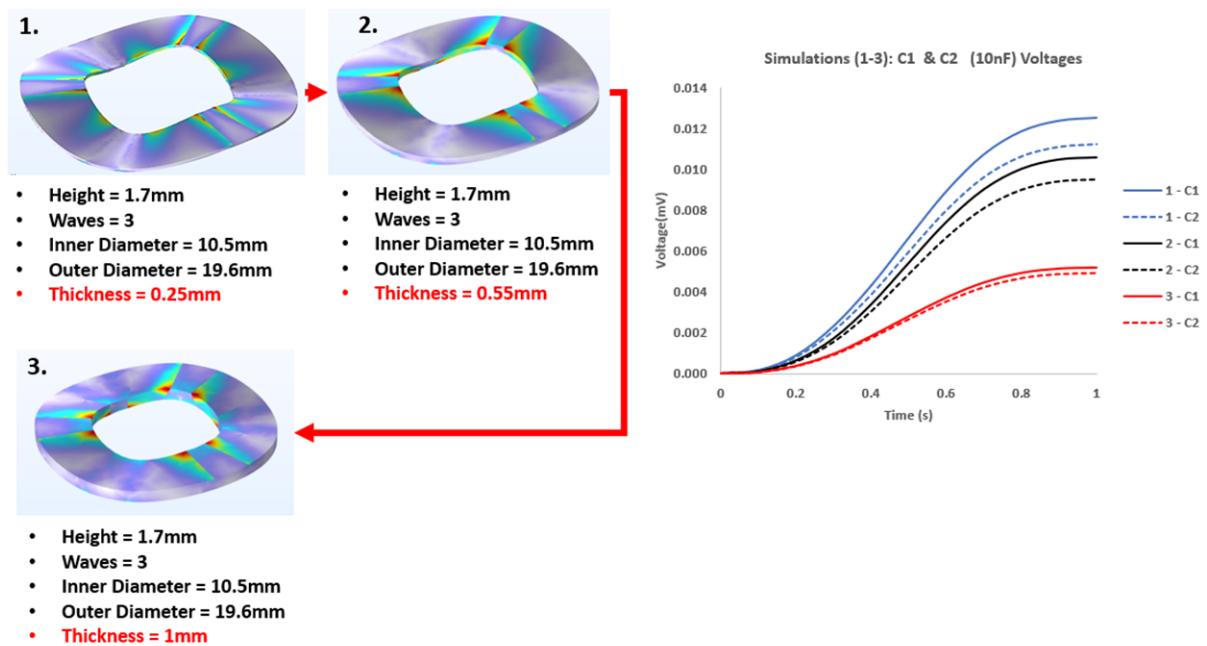


Figure 5-5 Crinkle Thickness Results

Crinkle Inner diameter Simulation

Increasing the inner diameter resulted in a noticeable energy increase, (figure 5-6 – simulation 4-5). There were also less high-stress concentration areas on the inner edges of the waves. Less stress meant better deformation and more shearing effect,

which improves electrical energy generation.

Adjusted Inner Diameter Simulation Results

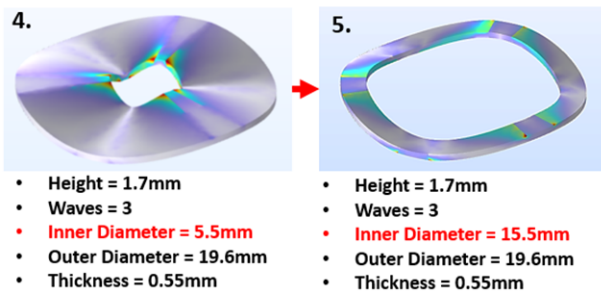
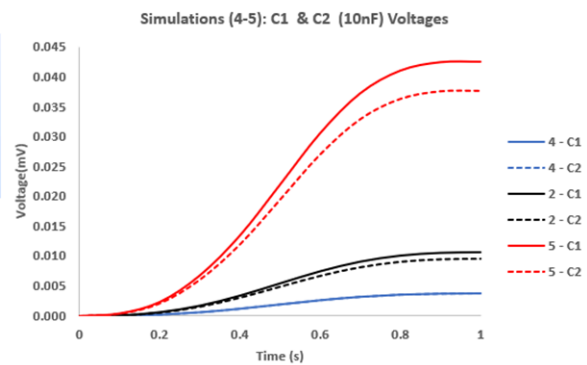


Figure 5-6 Crinkle Inner diameter results

Crinkle Height Simulations

The height simulation results (figure 5-7 – simulation 6-7), show that increasing and decreasing the crinkle washer height causes a negative impact on energy production, which would not be true. The height range 0.7mm to 2.7mm in which these simulations ran between might have been too large to encompass any peak points at which this washer is at optimal performance, further iterations would be required to get a clearer understanding.

Adjusted Height Simulation Results

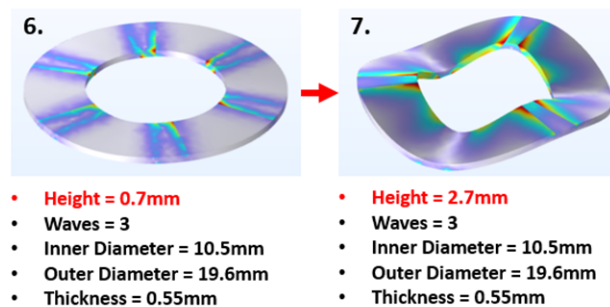
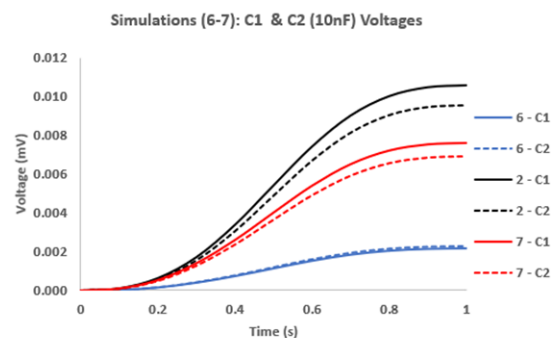


Figure 5-7 Crinkle Height results

Crinkle Wave Simulations

The wave simulations (figure 5-8 – simulation 8-9), show that the less waves in the circumference, the more energy produced. 2 waves produced a higher electrical yield

than 3 & 4 waves, producing 0.03mV compared to 3 waves 0.01mV

Adjusted Wave Number Simulation Results

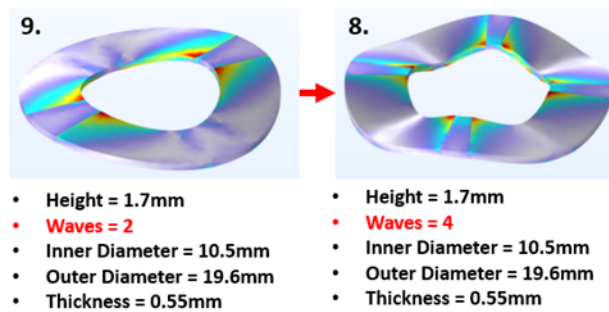
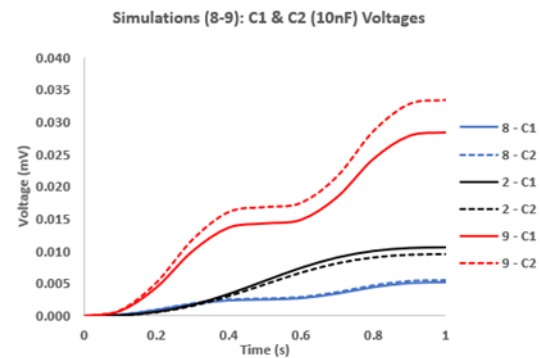


Figure 5-8 Crinkle Wave results

Crinkle inner Radia Simulations

The crinkle Inner Radia simulations indicate that the removing the inner radius from touching the piezo disc vastly increases electrical generation, as the deformation is shifter outwards. When the angle is tilted in the direction where the inner radius is solely touching the piezo disc, the stress is concentrated decreasing the power produced in the piezo.

Inner Radii – angle change Simulation Results

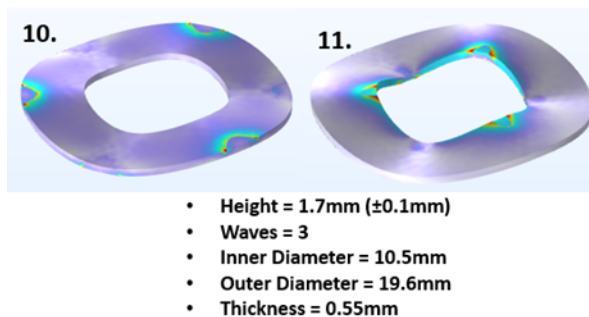
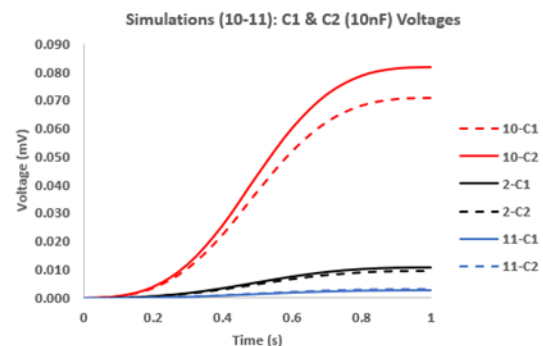
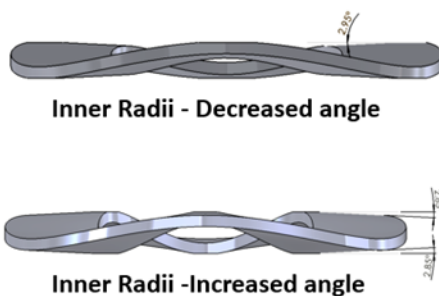


Figure 5-8 Crinkle inner Radia results

5.3.1 Observations

In these simulations, various parameters—such as thickness, number of waves, height, and inner diameter—were adjusted to evaluate their impact on energy production when two piezoelectric discs were coupled on each face of a crinkle washer. Across nearly all crinkle washer simulations, a consistent stress pattern emerged at the inner diameter. However, this stress pattern was less pronounced in one case (Simulation 5), where the inner diameter was significantly larger, thereby reducing the curvature of the inner bends.

When compared to disc spring or cymbal washers, it is evident that the angle toward the centre of these discs is the primary mechanism generating shear stress. In contrast, the crinkle washer, characterized by its radial waves, does not rely on this mechanism. By introducing an angle between the outer and inner radii, it is possible to merge the geometries of both the crinkle and cymbal washers. This could lead to the development of a novel combined wave-cymbal design, which offers several advantages: double-faced piezoelectric activation, single-part compactness, and enhanced energy generation and power density.

5.4 Crinkle Redesign Simulation

Based on the simulation results, the most significant energy increases were observed in simulations 1, 5, and 9. These findings suggest that a crinkle washer design with a thinner profile, increased internal diameter, reduced internal stress, and fewer waves would create a higher performance in energy generation. However, this design also increases the open dead space inside the body by decreasing the number of waves and thus total length of circumference of the crinkled washer.

To address this, decreasing the inner wave edge height on both the upper and lower faces of the crinkle washer could effectively reduce internal stress and shift the deformation toward the edges. This adjustment would help optimize the washer's performance by focusing the mechanical deformation in areas that maximize energy transfer, while also minimizing the impact of dead space.

The redesign simulation results indicate that by removing contact of the inner radius of the crinkle washer drastically improves energy generation resulting in a voltage of 0.082mV compared to 0.011mV from the standard crinkle washer. This is a near 60

times energy improvement over the standard crinkle washer. (eq.1) Sloping the angle outwards (increased angle) led to energy loss.

Further work to optimise the crinkle design removed the inner diameter waves completely to create a centred inner diameter. This version created no internal stresses and returned 0.15mV outperforming all previous crinkles variants.

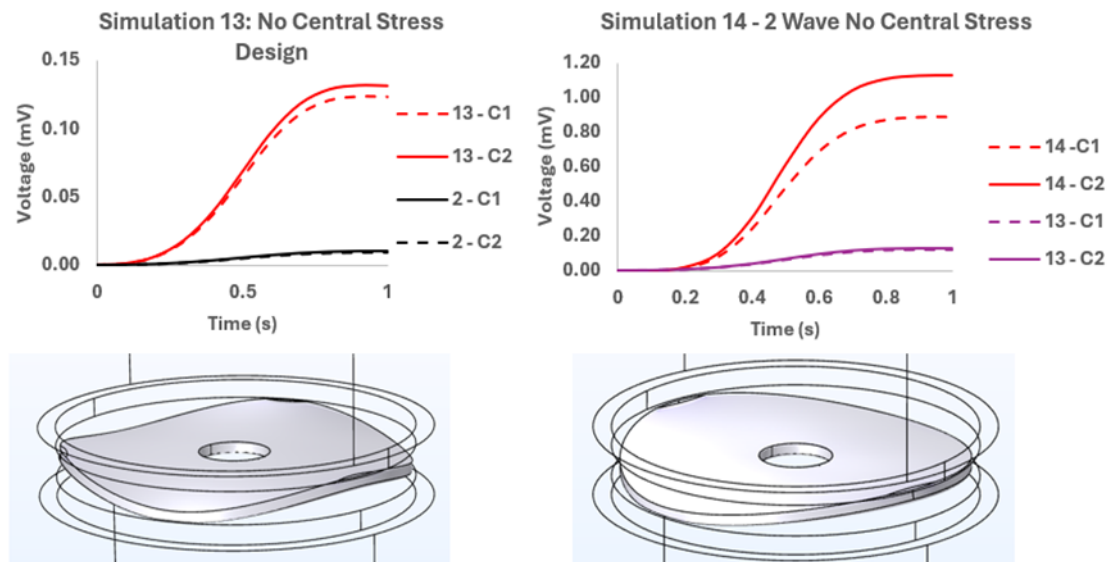


Figure 5-9 Crinkle redesign simulation results 13-14

The 2-wave version (figure 5-10, simulation 13-15) of this design begins to look like a hyperbolic paraboloid (Pringle crisps being a real-life example) and in the simulation, the result produces the highest voltage yet with Capacitor 1 (C1) changing to 1.13mV and Capacitor 2 (C2) to 0.89mV.

The hyperbolic paraboloid design (figure 5-9- right), is one that has been used by structural architects and engineers because of the stiffness and ability to absorb force into deformation [116], [117]. And from this research there is also clear evidence for compression to shear piezo electric energy harvesting potential.

Increasing the inner diameter of the hyperbolic paraboloid does further increase the energy generation following on from simulation 5.

The design can be likened to the disc spring when mirrored as seen in an earlier figure but integrated into 1 singular spring. The internal radius is removed, and all the force is concentrated into the dead centre of the structure, assuming the washer is perfectly balanced.

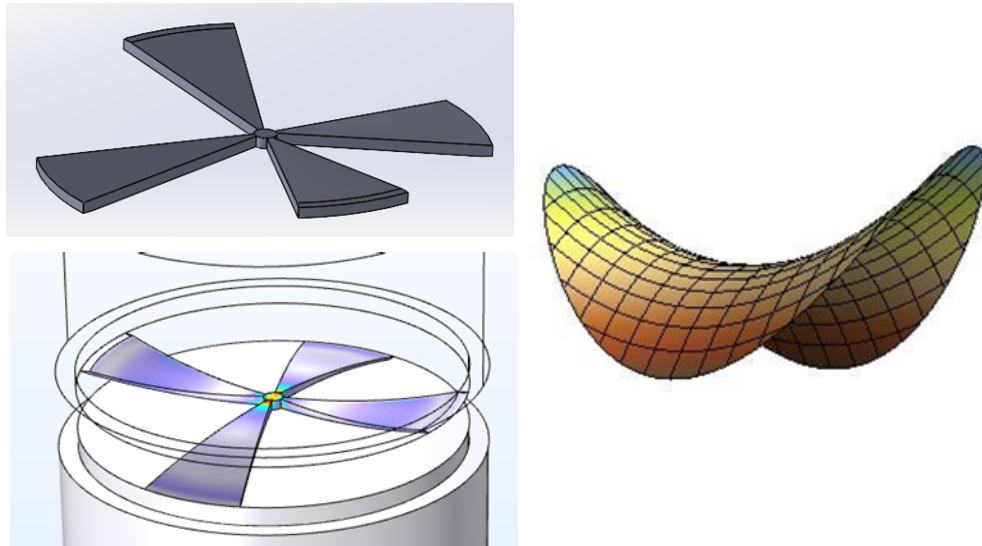


Figure 5-11 Hyperbolic Paraboloid Structure stress concentration washer redesign

5.5 Conclusion

This paper utilized Multiphysics simulations to analyse a crinkle washer and piezoelectric disc configuration, aiming to optimize mechanical-to-electrical energy conversion from linear forces. A standard off the shelf crinkle washer component was used as a benchmark and further iteratively optimised to understand impact of the individual parameters on a piezoelectric disc under a compressive load, simulating a shock from high acceleration. Like the previous chapter 4 with the disc spring, the parameters were then combined into a single model to observe if they could work in tandem with each other. The simulation results concluded that the final optimised design outperformed the original design with an output of 1.2 mV, up from 0.1 mV. When the parameters were merged, a known structural shape was produced called a hyperbolic paraboloid, which was further explored and showed central stress concentration and improved shearing potential when in a sandwich configuration between two piezo discs.

Manufacture of the prototype discs was attempted through additive manufacturing, but due to poor tolerances, warping and poor layer adhesion could not be further verified.

The manufacturing process was a limiting factor as to create prototype steel washers various methods, such as lithography or etching, stamping, and additive manufacturing required large upfront costs which made prototyping expensive. For industrial mass production the costs would be reasonable, but in small batches the cost is too high.

The overall concept of creating a piezo washer sandwich, which uses a single washer to allow for shearing in two planes, not only could make a device smaller and improve the energy density, but it could also make an energy harvesting device simpler in construction and cheaper in required parts. For munitions mass production, the difference between having a single crinkle washer vs having two-disc springs could cut spring washer costs in half while potentially increasing the energy harvested thus reducing cost and size of the harvester components.

6 Piezo Torsional 3D Printed Spiral Spring Rotational Energy Harvester

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Statement of Contributions of joint authorship

Fergus Crawley conducted all simulations, experiments and writing for this manuscript. Fergus also created all figures and graphical data. Zhenhua Luo proof-read and assisted with improving the manuscripts details and structure.

Abstract

This research aimed to develop a compact, low-complexity piezoelectric energy harvester capable of converting rotational energy into electricity. The system takes inspiration from linear versions of the spring-mass piezoelectric energy harvester. A novel torsional spiral-armed spring was designed and fabricated using a 3D-printed metal capable of storing torsional kinetic energy and exerting shear force on to a piezoelectric surface. The torsional spring system is designed with spiral arms that can transform rotational energy into radial shear force on the surface of the piezoelectric disc, which is then converted into electrical energy by the more energy dense shear mode activation of a piezoelectric disc. Simulation was used to rapidly test the prototype system construction and understand the characteristics of electrical potential in the piezo element experiencing shear force expansion. An Experiment was carried out to verify the theoretical analysis and the results demonstrated a voltage output across a capacitor of over to 200mV (storing 200 nJ over 1 second) at peak velocity of 4000rpm. This system demonstrates a novel mechanism and simple system for harvesting rotational energy with a torsional spring shear force actuator.

Keywords: Multiphysics, torsion, rotational energy harvester, torsion spring, spiral

Rotational Energy Piezoelectric Harvesting

6.1 Introduction

Energy demand in today's modern society has led to the increase in devices with inbuilt energy harvesting systems as the energy source for electronics[73], [74], [118]. Energy harvesting is the process in which a system absorbs ambient energy and converts it into electrical energy that can then be stored in a battery or used immediately[71], [72], [84].

Rotational energy harvesting is an area of energy harvesting that has been dominated by magnetic induction systems using rotating magnetic fields and producing Alternating Current (AC)[35], [36], [119]. Magnetic systems benefit from not having to physically collide and therefore are low friction and can operate at high rotational speeds. There are downsides of a magnetic system, from the materials themselves which utilise rare earth metals, efficiency with low frequency inputs, to the complexity of miniaturising electromagnetic systems that are freely rotating and have limited housing space for a magnet and coils. Another issue surrounding electromagnetic systems is the scaling factor, showing an exponential decrease in energy generation due to a square loss in decreasing coil and wire diameters [42].

Piezoelectric elements are materials that have an electrically polarised internal lattice that converts mechanical energy to electrical energy by creating a fluctuating electric field [10], [77], [100], [120]. The output is dependent on the input force, frequency, and direction, as piezo have anisotropic properties. The positives of Piezoelectric materials are that they are cheap and easily configured, relying on a small number of electronic components (Rectifier) to output a DC electrical output.

Using Piezoceramic materials to absorb rotational energy is dependent on the shape of the piezo element and the structure used to apply mechanical deformation. Previous research has realised two system options for harvesting rotation using a piezo element, a single body system that is like a linear spring mass system utilising centrifugal force and multi-body system that has at least two opposing bodies that interact through friction or even magnetic attraction or repulsion [24].

The common piezo structure implemented in a rotational energy harvester is the piezo beam bimorph, of which the mechanism of activation in the Piezo element is bending, an example demonstrated by Chen [121] with a mass at the end of a cantilever, bending due to rotational force on a car wheel, the results of which were a power output of 2308 μ W. With low complexity, this system demonstrates a simple solution to absorbing rotation.

For a small energy harvesting system, the method of converting linear force to rotation can be achieved relatively easily but requires a mechanical conversion system of varying complexity. The same issue is found in the inverse method to convert rotational force to linear. In our previous research [122] it shows the use rotational to linear motion using a mechanical cam & follower to produce an energy output of 923 μ W at the highest rotational speed test of 95 rad/s.

In comparison, the reverse (a linear to a rotational) electromagnetic system demonstrated by Zhu [123] using the rack and pinion design produces an output of 55.6 μ W per step. The added mechanical system depending on the complexity does add energy losses through friction and increases the system volume which effectively lowers the power density of the device but is a method to use rotational energy. The best system for energy harvesting should reduce the number of moving parts creating friction and directly couple the mechanical force to the technology producing the electrically energy.

The multi-body rotational piezoelectric systems are the second type of rotational harvester. Multi bodied systems have been demonstrated at a smaller scale to work with wearable technology. One such version is the pendulum system design; this system involves a weighted pendulum that always falls due to gravity, the pendulum mass exerts a force that is either directly plucking a piezo beam seen in the system designed by Mohamad Hanif Noor [124] and in the variation created by Pillatsch [24]. The pendulum imparts its energy via physically impacting a piezo beam, or a magnetic interaction between two magnets attached the piezo beam and the pendulum. At low frequency, the magnetic design variation can reach a power output can reach 7 μ W, and degradation was observed of the beam due to overstressing of the piezo element. The physical plucking variant had issues with the stiffness of the piezo beam producing lower frequencies after plucking.

Harvesting rotational energy using a piezo element does come with difficulties as a mechanism is required to exert force on the element to produce the electricity. Single body devices boast the benefits of low complexity and have no rotating parts, whereas multibody systems require a freely rotating part and an off-balance eccentric mass component such as a pendulum mass, which leaves open and redundant space in the system. For this reason, this research will investigate a single body rotational spring mass system.

Springs used in rotating systems are known as torsion springs. There are many different types of spring, most commonly a wire-form design which can be seen in a prototype by Lin [125]. Another version of a torsion spring is a main spring, found in geared watches and clocks and were used before batteries became more efficient and mass produced. This torsional main spring version has been utilised by Graves in an energy harvester storing energy produced by a swinging pendulum and releasing the energy to a motor/generator [126].

This research looks at the shrinking of a torsional spring for an energy harvesting system to be fitted into a cylindrical container suitable for future device integration, harnessing the rotational energy and changes in acceleration received by the device and converting structural stresses directly into shearing on the piezo surface. This new spring design aims at removing complex mechanical gearing systems and can be scaled down more easily requiring only the piezo transducer, a spring and a mass.

6.2 Methodology

In this research, a rotational spring-mass system will be designed in a Multiphysics simulation using COMSOL and then verified using an experimental validation. The total force experienced by the system and the energy absorbed in a spring can be calculated using the following equations:

Rotational Energy Equations

Equation 6-1

$$E_{Rotational} = \frac{1}{2}I\omega^2$$

Equation 6-2

$$I = mr^2$$

Equation 6-3

$$\tau = I\alpha = I \times \frac{\omega_2 - \omega_1}{t_2 - t_1}$$

Equation 6-4

$$k = \frac{\tau}{\theta}$$

Equation 6-5

$$\tau = F \times r$$

Equation 6-6

$$U_{Tortional\ Potential} = \frac{1}{2}k\theta^2$$

$E_{Rotational}$ = Rotational Energy (J), I = Inertia ($kg.m^2$), m = mass (kg), r = radius (m), α = Angular acceleration (rad/s^2), k = ω = Angular velocity (rad/s), τ = Torque (Nm), θ = Angle (Rad), $U_{Tortional\ Potential}$ = Potential energy from torsion (J)

The design of the spiral spring is a like that of a mainspring used in mechanical watches, but combined with a flat spring with similarities designed by Aldawood [127] for a spring assisted energy harvester. The spiral spring is built with three arms, as previous research has demonstrated this number insures stability and balance. To create the simulation, the system needed to be measured, weighed and then designed using 3D modelling.

6.2.1 Simulation

The simulation mimics opposing torque applied to the spring by the mass which acts as a dampener to the system rotation. This method of simulation is a simplification to observe the spring characteristics when coupled to the piezo disc face. The simulation also neglects gravity of the mass and focuses on the shear force created due to coiling and uncoiling arms of the spring.

The mass was left out of the simulation and the torque resistance force on the spring was calculated to a maximum of 3.769 N at the speed of 4000 RPM, the experimental velocity dictated by the maximum velocity of the motor & controller used. This force was localised on the inner shaft of the Spiral Spring (Figure 6-1), mirrored in the experimental set-up where the connection bolt fitting that locks the spring to the mass is located. The experimental set up is designed with a steel mass dampener weighing 0.3 kg. The motor max velocity had a maximum of 4000 rpm (418.9 rad/s) set by the controller, with the programable acceleration and deceleration set to 0.5 seconds with an acceleration switch delay of a second.

Figure 6-2 shows the piezo disc and steel disc underneath the spring, with a small

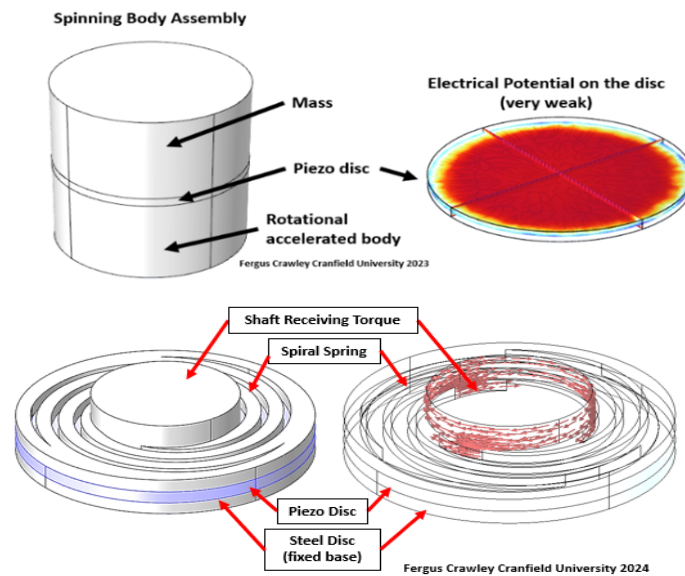


Figure 6-1 - Simulated torsion of a mass on a piezo & torsion of a spiral spring

0.1mm space separating the inner spring shaft to the outer ring shaft (allowing the spiral spring arms to bend freely). In the simulation the force is applied over a one second period using a sine function, the equation:

Equation 6-7

$$F = 3.769 \times \sin(\pi \times t)^{0.7}$$

This equation is adjusted to make the sine wave have an increased or decreased reaction time by adding a square or square root function $((\sin(\pi \times t))^2$ or $\sqrt{\sin(\pi \times t)}$ to the sine function.

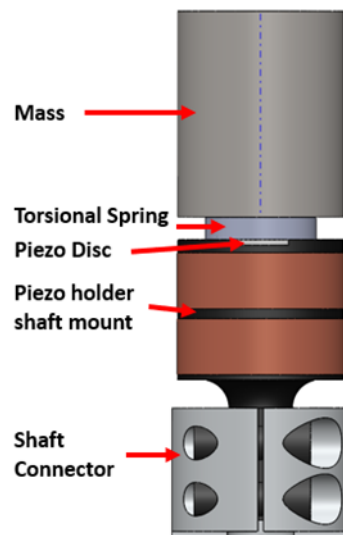


Figure 6-2 Torsional Spring-Mass Piezo assembly attached to a motor shaft

The simulation was designed so that the experiment would theoretically produce clearer voltage results from the capacitor, and this was achieved by lowering the capacitor size to 47pF. Changing the design in the simulation was faster and more easily tuneable, allowing a broader range of results. The motor acceleration characteristics also needed to be implemented into the simulation, this was done by modifying a sine wave as seen in Figure 6-3 to better reflect the acceleration and deceleration of the body.

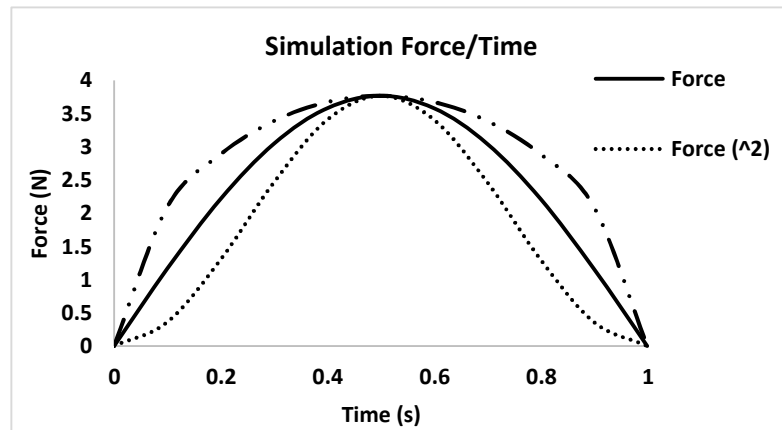


Figure 6-3 Half sine-wave Force input

6.2.2 Experimental

A mass spring system containing a piezo disc, torsional spring (Figure 6-5) and a steel mass is accelerated using an AC motor (Figure 6-4). The spring acts as a dampener storing energy and deforms the spring structure connected to piezo disc, doing work on the surface of the piezo disc in the form of radial expansion or compression,

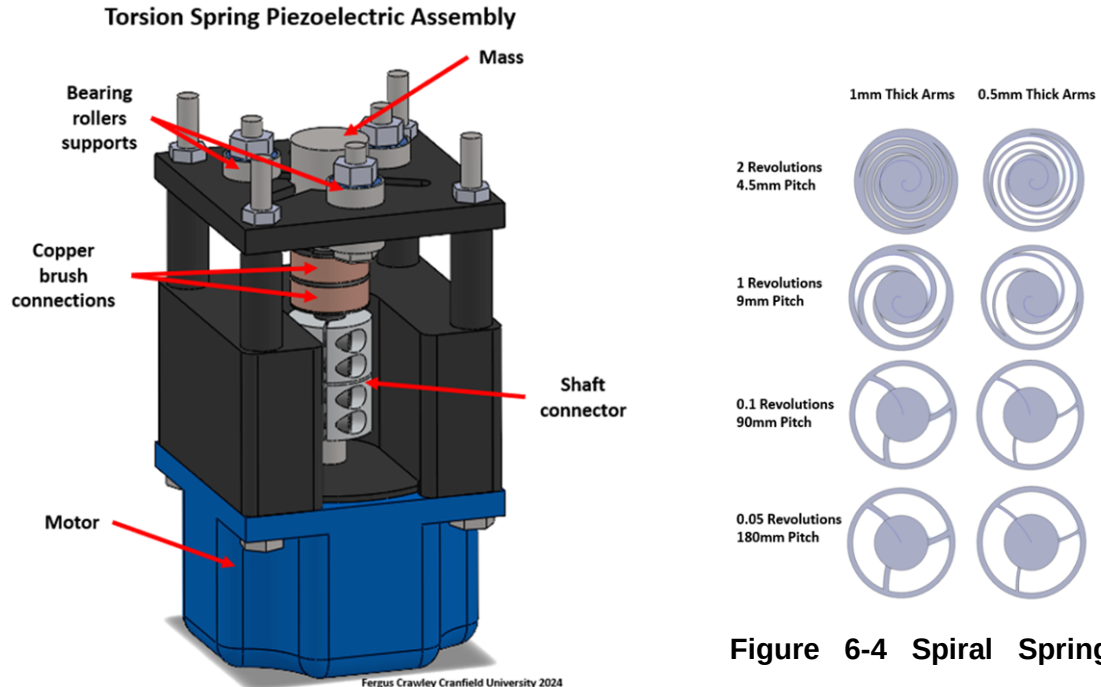


Figure 6-5 Torsional Spring-Mass Piezoelectric Experimental Assembly

Figure 6-4 Spiral Spring Designs, revolutions & arm thicknesses

effectively shearing the surface.

The maximum torque theoretically produced by the mass and the maximum velocity of the motor and can be calculated using formula (6-3) and then turned into a force using formula (6-5), the maximum theoretical force the mass can exert on the torque spring is 3,769 N. This force once transmitted to the spring is turned into radial expansion or compression depending on the orientation of the spiral torque spring, either constricting on itself, or expanding. The motor is pulsed on to reach maximum speed and then turned off, and the oscilloscope is connected to the capacitor while it is charged and slowly discharges. Attached to the top of the mass is a magnet, which is used to trip a Hall effect sensor connected used to measure RPM.

Manufacturing of the spiral spring posed a challenge due to the size and nature of the part. Conventional machining can be used, but usually requires specialist equipment for sub-millimetre cutting, with laser cutting there is also a minimum thickness and cut limit. Metal 3D printing methods such as SLS (Selective Laser Sintering) and FDM (Fused Deposition Modelling) are limited to a minimum of 1mm thickness by most manufacturers and comes with the issue of part warping, shrinkage, and porosity. The method of manufacture used was FDM printing with 17-PH stainless steel using BASF filament and a post processing service, the green printed parts were produced in-house. Using metal 3d filament, the printer could only create successful parts down to 0.5mm spiral arms before issues with warping and poor finishing began. The designs can be seen in Figure 6-5. Sets of 3 springs each were produced of 1 mm and 0.5 mm springs were produced and then post processed to create fully steel components, as seen in figure 6-6, the success rate was the average of 2 working springs.

The nozzle size of 0.4 mm prohibits the printing size of 0.1mm arm structures making the smaller spring design impossible to manufacture this way as shown in the slicing software image showing the absence of a print path (figure 6-6 – top image) for the arms. Once treated and sintered, imperfections, such as layer delamination and gaps cause part failure with many of the spiral spring green parts (those containing 20% plastic) failing. The successful parts can be seen in figure 6-6.

The final parts possess superior strength to plastic and could be used in the experiment. Some parts did have noticeable warping preventing them having a flat face to bond to the piezo element. 3D printing metals does also have an impact on the stiffness of the structure compared to machined steel, the printed spirals showed minimal flex, with the 1 & 2 revolution springs being the most flexible. Factors not considered in the experimental set-up which were seen during the experiments included added energy from friction in the brushes, motor vibrations that could be harnessed by the piezoelectric disc, the electromagnetic noise created by the motor during operation and wobble of the mass at the high rpm due to being only a fraction off-centre, the bearing supports were there to prevent the off-centre wobble, but it was noticed that one bearing was being moved more than the other two, indicating an imbalance.

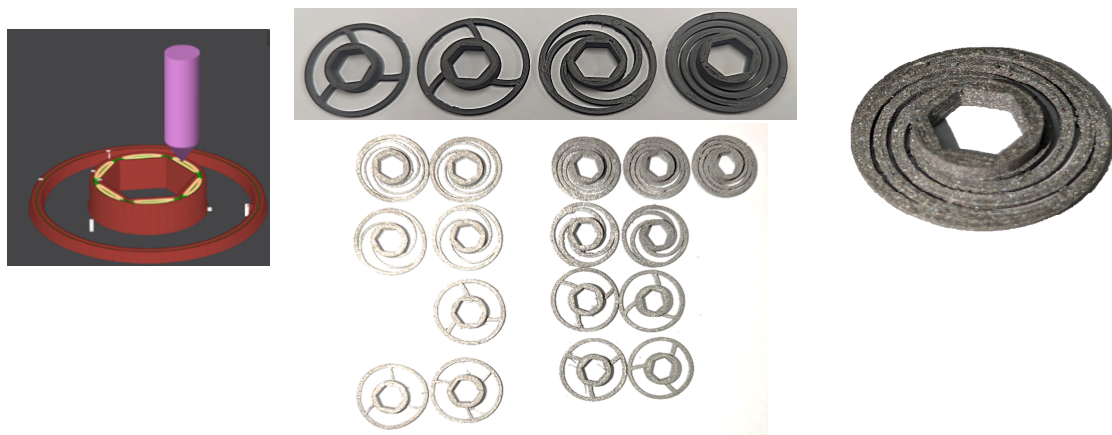


Figure 6-6 Metal 3D printed Spiral Springs

6.3 Results

Simulated Rotational Energy Harvesting

The simulation was carried out to apply torque to the spiral spring and understand how this type of shear spring structure will deform and apply work in the form of shear force on the disc surface. The lengths of the arms are shown in Table 1.

The structural results shown in Figure 6-7 demonstrate that force is being absorbed by the spring structure and further results show minor deformation of the arms under load absorbing and storing the energy as a spring. The second area where force is being concentrated is in the outer ring of the spring where the arms connect. Exaggerating the deformation by scaling the results shows that the outer ring would

eventually buckle inwards under high loads (Figure 6-8). This inward travel translated through the piezo disc is a mechanism of shear. Other high stress concentrations as shown as a red area (Figure 6-7 & 6-8) are the result of the material stretching on the outer surface of the arm, again localised at central arm connections closest to the where the force is being exerted and because of the twisting angle. Stresses exerted into the spring structure will store energy but do not necessarily get transferred to the piezo disc structure to convert to electricity.

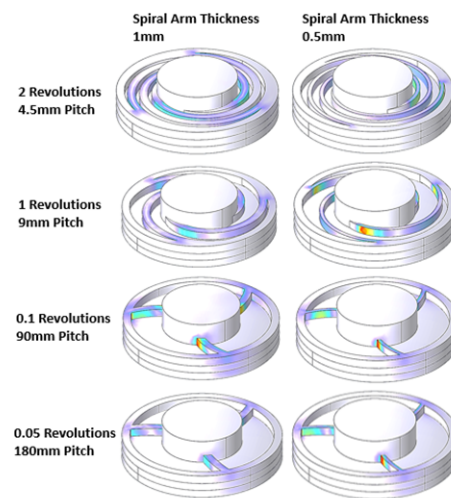


Figure 6-8 Simulated Spiral Springs experiencing torsion

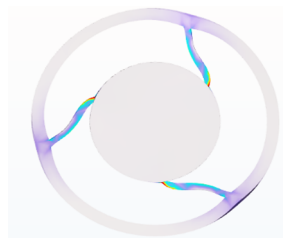


**Figure 6-7 0.5mm Spiral Spring (scaling exaggerated)
Deformation of outer ring**

The total charges collected in the capacitor (Figure 6-9) show that this rotational spring-mass piezo design can be used to produce electricity using a torque spring. The voltages represent energy which can be calculated using the equation:

Equation 6-8

$$Energy_{cap} = \frac{1}{2} CV^2$$

With $Energy_{cap}$ = energy stored in a Capacitor (J), C = Capacitance (Farad) and V = Voltage.

The graphs show that the thinner springs with the shortest spiral arms, 0.5mm arm thickness & 0.05 revolution, produced the highest voltage of 0.57V. The least energy being produced was by the 1 revolution spring in both thicknesses with lowest voltage of 0.025V. This

The 1 revolution spiral spring performed better than expected in both the simulation and the experiments. And the reason for this is not clear in the data or the design. The reasons for absorbing more energy could be because of the spiral design arm lengths and natural frequency of the spring.

The shape of the curves in Figure 6-10 changes with the thickness of the arms, with a steeper gradient with shorter lengths of the spring arms, transmitting the energy more directly from the mass to the piezoelectric disc. The shorter arms can absorb less energy and deform less, resulting in more energy transferred to the outer ring, and decreasing stored spring energy.

Table 6-1 - Spiral Spring revolutions and calculated arm length

Revolutions	Pitch (mm)	Arm Length (mm) (Inside Arc)
2	4.5	39.30
1	9	19.96
0.1	90	4.46
0.05	180	4.12

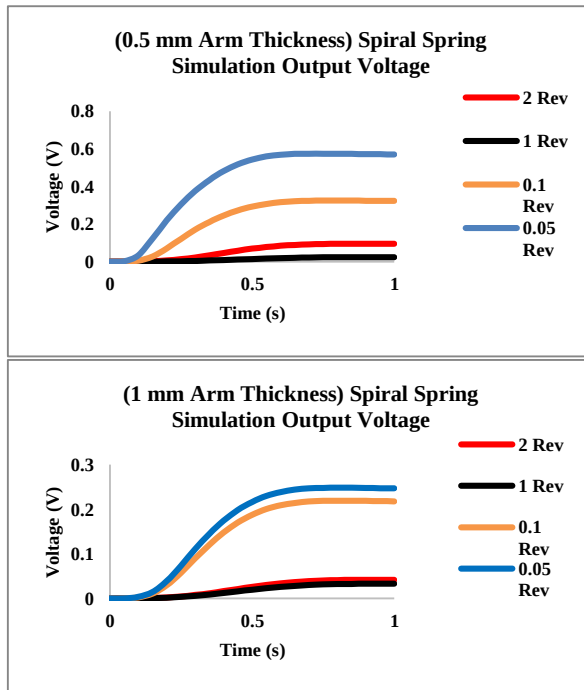
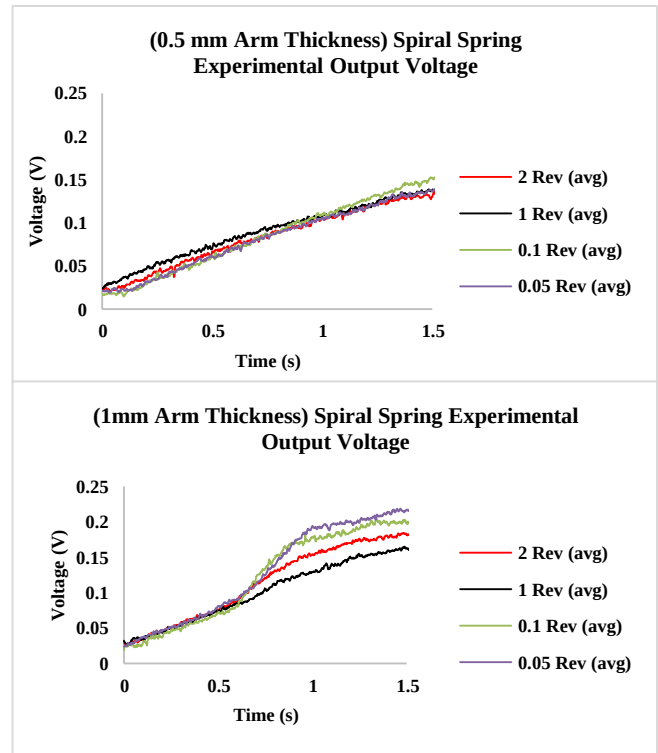


Figure 6-9 Simulated Spiral Spring Rotational Energy Harvester Results

Figure 6-10 Experimental Spiral Spring Energy Harvester Results

The results figures 6-9 & 6-10 are different due to reaction time of the motor increasing the time of the acceleration profile and there is visibly more noise in the experimental results. The thinner armed springs performed as expected in the experiments compared to the simulated results as the thicker discs produced higher voltages, demonstrating increased energy storage in from the torsion.

Experimental results

There are differences in the experimental results and the simulations due to the limitations of the simulation software and the difficulties of creating perfect conditions in an experiment. 0.5mm spring thicknesses were the smallest springs manufacturable using 3D printing, which was an immediate limitation. The motor was one limitation, ramping up and down the speed of the motor was limited to the control system reaction time, which could not match exactly that of the simulations. A larger capacitor (10 μ F) was needed also, as there was magnetic interference caused by the motor spinning coupled with the wire movement, created large interference. Data capture also

included delays in experiment recording which required filtering of the data collected. The motor at high RPM created vibrations throughout the entire assembly, and the Piezo can sense and absorb these vibrations, adding more energy to the experimental results. The brush system used to connect the piezo disc to the capacitor circuit created friction and potentially heat at the high velocity and this could lead to extra charge in the piezo circuitry, which would not be seen in a final device, as the electronics would be mounted to the rotating components.

The experimental results in Figure 6- 9 show that in both spring types of manufactured spring (1mm & 0,5mm arm thickness), demonstrated a trend in gradient but with differences to the simulations. The 2 revolution springs show a definite increase in energy loss as expected with more energy being diverted to spring energy storage. This can be realised in the results of the system without a spring (figure 6-11), with an overall voltage of springless system having a voltage of 0.25 V as there is no spring to absorb the torque and thus delay energy generation.

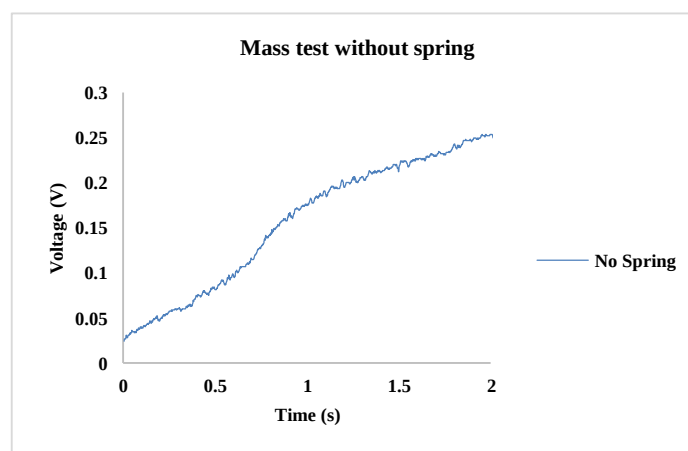


Figure 6-11 Mass Test (No Spring)

The 0.5mm thickness spring results show larger change in voltages than the 1mm results. The energy output of the 0.5mm springs show a higher drop in voltage, which shows the spring has dampened the transfer between the mass and the piezo disc as seen in in Figure 6-9 comparing to 6-11, a drop of 0.1 V.

In the 1mm thick Spiral Spring Experiment, the spiral spring - piezo electric generator had a higher voltage of 0.21 V which is only a 0.04 V difference from the springless system indicating less transmission to the spring. The 0.05-revolution and 0.1-revolution spring energy performances in the 1mm results showing a steep incline after 0.5 seconds, the sharper incline in the charging gradient can be attributed to increased stiffness of the spring itself recovering faster than the longer armed springs.

The 1 revolution spring, as predicted by the simulation was an outlier in performance, more visible in the 1mm thickness results in Figure 6-9, suggesting that this arm length is suitable for this system as it could have unintentionally been at a resonant frequency.

A defined difference between the simulation results and the experimental results is the first 0.5 seconds of acceleration. The experimental results show very little energy and difference in voltages in any of the spring variations, until after around 0.5 seconds (motor deceleration), where the energy levels then show the greatest deviations which is more apparent in 1mm thickness results. This spike in energy may be where the spring is imparting stored kinetic energy back to the system, with the shorter springs

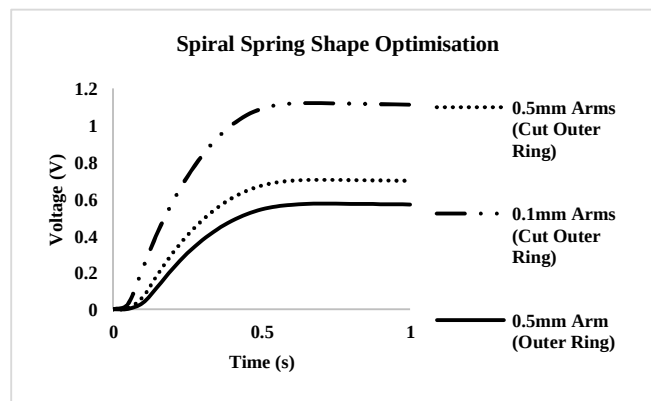


Figure 6-12 Spiral Spring Optimisation Results

showing a much faster reaction time to the sudden deceleration. In the simulation results, this spike cannot be seen, and this may be the result of the set-up of the simulation that uses a torque force input and cannot re-create the spring storing energy storage and then transferring it back to the system. When the spring exerts force back to the system, there is potentially a reversal of the force expanding the arms into the outer ring which is also not shown in the simulation. A change to the input

force equations to add negative force direction and damping could further improve the simulations results to experimental results.

Feature optimisation

To improve the energy generation, observations from the results such as the bulking of the outer ring indicates there is stored energy in the structure. Simulating the segmented version (Figure 6-11) of the outer ring of the spiral spring produced an immediate energy increase of up to 0.7 V on direct transmission to the piezo disc.

Decreasing the outer ring thickness and tapering the width of the arms towards the outer edge led to increased energy transfer to the spring, indicating that a better spring-piezo interface with more freedom to deform with thinner arms would be more beneficial for energy output. Decreasing the thickness of the arms to 0.1mm further improved the simulated energy output to 1.1V (Figure 6-12).

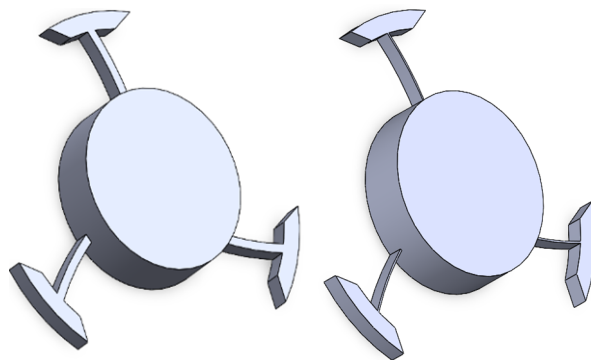


Figure 6-13 Spiral Spring without outer ring and thinner arms (right)

To achieve more accurate experimental results, the 3D printed spiral springs would need to be machined more accurately. The ideal metal for a spring would be a hardened tool steel that can be machined to a small thickness. Metal 3D printing has benefits of rapid manufacture and ability to produce complex structures, but the tolerances and warping still pose an issue.

Shear force activation of the piezo ceramic disc in this experiment relied on shear tape. The tape worked to hold the spring firmly in place, but further non-conductive bonding in future experiments could produce higher energy levels and prevent transduction loss through slipping at the interface.

The design of this energy harvester also has a potential to be expanded to a hybrid energy harvester, like the hybrid energy harvester created by Seol that added a triboelectric effect for linear electromagnetic oscillator [52]. Changing the mass for magnets and adding outer coils [35] or creating a rotational sliding system [49] for rotating triboelectric energy generation could also further boost the power output but would require additional electrical conditioning components for mismatched voltages produced by the different technologies.

6.4 Conclusion

In this paper a simulation and experimental analysis was performed on a novel design for a rotational piezoelectric energy harvester. The spiral spring-mass piezoelectric energy harvester demonstrated by this research is meant to for compact electronics in high acceleration environments. The experimental results were limited by the manufacturing quality of complex and miniature metal springs in which the designs and material properties in the simulation would not perfectly match, but the results do show parallel similarities and trends.

- The Torsional Spiral Spring design is based around a linear spring mass system, but instead aims to convert rotational energy into shear mode activation in a piezo element. Spring structural characteristics were explored to improve energy generation:
- The experiments produced larger energy outputs than the simulations generating over 0.2V of electricity stored in a larger 10 μ F capacitor (figure 6-9). With the energy stored in the spring estimated at a maximum of 0.1 V which is then transmitted back into the system after the initial rotational acceleration.

Discrepancies in the experimental and simulations were due to the motor used which created electromagnetic interference, the use of brushes for monitoring charge collection as this created friction, spring fabrication to make more accurate designs and bonding between components, as this could have led to less transduction between the mass spring and to piezo surface. The system did have complexities in construction, and it can be estimated that scaling down this design would further increase manufacturing and bonding complexities which could defeat the object to create a power dense system that is mass producible and low cost.

Future work could further refine this design to produce a structure that can combine the characteristics of the spiral rotational energy harvesting with a linear energy harvesting structure allowing for an energy harvester suitable for multiple environments and load types. Optimisation has shown thinner arms, less revolutions and a strong surface bond improve the energy production in the initial acceleration, but increasing the spring revolutions increases the energy stored by the torsional spring and adds time delay and would create further oscillations to the energy harvester and potentially improve energy production over a duration. Frequency testing would also be beneficial to match system resonant frequencies and prevent overly damping structures that would contribute to energy loss.

This system has a potential in the defence industry in types of ammunition that require power such as fused warheads as it uses a piezoelectric rotational harvesting device that can create electrical energy needed to power electronics. The system can harness rotational energy from large rotational energy sources such as the rotation created by barrelling used by projectiles for stabilisation. The design is compact and does not have much empty volume, unlike other technologies (electromagnetic) and has many avenues to increase power density such as using piezo material with a higher energy generating density (piezo crystals), increasing the mass density by using a heavier metal such as lead and creating a thinner spring with the same spring rate using stronger spring materials. Other industries that utilise rotational energy harvesters in mm-scale volumes are watches and smart phone technologies. The torque spring rotational device could be tuned to these scenarios, but the spring stiffnesses would need to be decreased to align with human motion and smaller forces.

Energy Scavenging Piezoelectric LED system for Small Arms Ammunition Tracers

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Un-Published

Statement of Contributions of joint authorship

Fergus Crawley conducted all simulations, experiments and writing for this manuscript. Fergus also created all figures and graphical data. Zhenhua Luo proof-read and assisted with improving the manuscripts details and structure.

Abstract

Tracer ammunition is a type of ammunition that is used by military forces to physically see the flight path of a bullet by the shooter. Seeing a bullet's flight path is needed by the shooter to understand the bullet trajectory and signal to others where the bullet is going, this is necessary tactically and for better aim. Current tracer technology is in the form of a fuel and oxidiser pellet that is ignited on bullet firing, and this burns a compound that has a bright flame, but fuel oxidiser has drawbacks such as material toxicity, material supply and the burning effect is trajectory altering. Moving to a system that uses a Piezo element to convert parts of shock to electrical energy and an LED is one approach to removing issues of the fuel-oxidiser tracers. This work simulates a novel integrated piezoelectric mass-spring system with an electrical output above 3V, capable of illuminating an LED for a theoretical distance of 1.75m.

Keywords: Tracer, Energy harvester, Piezoelectric, Piezo, COMSOL, Rectification, LED

6.5 Introduction to Piezo energy Harvesting

A pyrotechnic tracer is a type of ammunition used to create a visible projectile path. The tracer purpose is for the user to visibly see the path, make corrections to the target, and give others a visible path to concentrate fire. There are several types of tracers based on use such as visible and infrared, this is determined by the use and technology viewing the tracer flight path [128].

The materials used for tracers are barium and strontium peroxides oxidisers, magnesium carbonate and calcium resinate fuel. The method of activation is by the propellant explosion that ignites the open end of the tracer and starts the reaction of the pyrotechnic tracer. Because of the materials used and functionality, there has been growing call to replace the materials and even the method at which light is created due to; environmental concerns of toxicity [129], use with newer technology (night vision) [130], supply coordination and the sustainability of raw materials.

A method of avoiding toxic chemicals is the addition of an energy harvesting system that can replace the fuel and oxidiser in the tracer slug, which would harvest kinetic energy from the initial propellant explosion and power on a small electronic circuit for the required duration of flight. There are previous experiments that have attempted this feat using different mechanical to electrical components which are electromagnetic converter system [131] and piezoceramic [132], [133] systems. Electromagnetic converter systems are known for their good performances when there is a rotation of the magnetic field, and there are types of linear systems that can be designed such as an inertia or setback generator or a simple magnetic oscillator using a spring to capture vibrations. Willemin demonstrated the setback generator with a mechanical oscillation mechanism capable of harnessing energy from high accelerations of up to 22,700Gs and producing 140 mJ of usable electricity at a package volume of 117cm³ [41]. Issues surrounding electromagnetic energy harvesters are found when scaling down electromagnetic components such as the magnets and coils and there are other design hurdles such as creating counter rotating bodies and creating enough extension for a magnetic field to fluctuate, all these issues can lead to diminished power returns and low energy density [134].

Piezoelectric materials show potential when experiencing high shock and have already been used for this type of experiment by J. Rastegar [16], [17], who explored the Piezo Spring-Mass energy harvester design using a combination of disc springs and machined springs. The Ø20mm by 45mm (119.3cm³) prototype device was able to achieve a 1.03 Joules of energy stored by the spring with 30-50% electrical conversion at accelerations of up to 45,000Gs, which is 309 – 515 mJ of electrical energy.

The prototypes designed by Rastegar, Willemin are similar in the way they use a spring to capture energy and transfer it to the electrical conversion mechanism (piezoelectric or electromagnetic) by harmonic vibrations. The energy stored therefore is dictated by the spring design, deflection, and the spring rate: K (N/mm).

Equation 0-1

$$E = \frac{1}{2} K d^2$$

E = Stored Kinetic Energy (J), K = spring constant (N/m), d = extension or compression (m)

The springs used in these prototypes are a double helical and a machined spring (mass spring element) with Belleville washers for pre-tensioning. The spring rates of the machined spring mass by J. Rastegar was 168 kN/m (163 N/mm) and experimental double helix spring by J. Willemin was able to achieve 430 kN/m (430N/mm).

Hooke's Law:

Equation 0-2

$$F = -Ks$$

F = force (N), K = spring constant (N/m), s = extension or compression (m).

To increase the energy stored in the mass spring system, a method would be to increase the spring stiffness while decreasing the size of the spring to also allow for a bigger mass. At high forces, increasing spring stiffness is a challenge with such a small area for deformation (spring extension), is challenging. Newer spring designs such as the wave spring could be used to in this case for space saving and enhanced energy storage. Zhu has demonstrated a wave spring [123] in the application of energy

harvesting for this exact reason, to bring down the overall height of the spring by 50% but keep the same displacement and load capability.

The Piezoceramic itself will expand radially under compression due to the Poisson's ratio (ν) and any shear force applied will increase this, the limits of the compressive and radial expansions are defined by the young's modulus (Elastic Constants) Y_{E33} & Y_{E11} . This can be found using the YM formula.

Equation 0-3

$$PZT\ 5A: \nu = \frac{\text{Lateral Strain (m)}}{\text{Longitudinal Strain (m)}} = 0.34$$

Equation 0-4

$$\text{Lateral } Y_{11}^E = \frac{\sigma_{11}}{\epsilon_{11}}$$

Equation 0-5

$$\text{Longitudinal } Y_{33}^E = \frac{\sigma_{33}}{\epsilon_{33}}$$

6.6 Piezoelectric Energy Harvester

Piezoelectric energy harvesters can be constructed with a spring-mass system to capture vibrations, or in an off-resonant system to harness the initial impact force. The energy difference in the system is created by allowing the mechanical force to oscillate longer and increase the duration of energy being produced. The spring-mass system design must be tuned to the input force and frequency to achieve better results, and to do this the mass and spring can be designed to maximise the available energy.

6.6.1 Basics

The energy available for harvesting originates from the kinetic force produced when a tracer is fired. The kinetic force can be split into two parts which can be based on the mechanism required to harvest the energy. The first is linear acceleration that is created by the expanding gases from ignition of the propellant, and the second is rotational acceleration created by the rifling of the barrel.

Linear energy harvesting mechanisms are easier to construct than a rotational harvester with piezoelectric components and with the tracer system, compactness and system volume is constricted.

Bullets get their energy from the combustion process of the propellant, accelerating it out of the rifle barrel. The rifle barrel is designed with internal twisting grooves that convert some of this energy into rotation, which is for projectile stability in flight. The energy available is dependent on the slug size (slug being the projectile part of a bullet). The calibre sizes considered in this study is the 5.56mm and the 7.62mm munition as these are commonly used by infantry. These munition sizes pose a challenge for an integrated energy harvesting system due to the small volume to build into. For a 5.56mm electronic tracer, the volume available is restricted to under a 5.7mm diameter and below 10mm length. The 7.62mm slug comes in at a larger size of 7.83mm diameter at just over 20mm long. These dimensions do not consider how much of the slug will be free space for the Energy Scavenging Piezoelectric Electronic Tracer System (ESPETS). The slug still must retain weight and wall thickness to still work primarily as a projectile.

The weights of the 5.56mm slug (NATO Standard) is 4 grams and reaches a speed of 948 m/s with the total energy of around 1.9 kJ. The weights of the 7.62mm slug (NATO Standard) is 9.5 grams and reaches a velocity of 850 m/s with a total energy of over 3 kJ [135]. The total energy of the standard munition is different for tracer ammunition due to the difference between the solid slug and one with pyrotechnic material that does not have the same density and mass as the standard solid metal version.

To power an electronic tracer the Piezoelectric Energy Harvester needs to produce at minimum; 36mW-(Low powered LED 1.8V and 20mA). The energy is transferred to the slug from the initial firing, more specifically the propellant exploding. The energy required to power on an LED is dependent on the intensity of light required to be observed from a distance, as well as the viewing angle. Light dissipates following the inverse square law [136]:

Equation 0-6

$$\frac{I_1}{I_2} = \frac{D_2^2}{D_1^2}$$

Intensity in lux (lux=lm/m²) and distance in meters (m).

Keeping the viewing angle tighter is one method of reducing energy dissipation and LED energy requirements. To calculate the intensity of an LED at distance, the luminous flux and viewing angle are required.

Equation 0-7

$$\Phi_V = I_V \cdot \Omega$$

Φ_V = luminous flux in Lumens (lm), I_V = luminous intensity in Candela (cd) and Ω = solid angle of the beam in Steradian (sr).

The solid angle of the beam can be calculated from the angle of the beam.

Equation 0-8

$$\Omega = 2\pi \left(1 - \cos\left(\theta \cdot \frac{\pi}{360}\right)\right)$$

θ = Beam angle in degrees (°).

Equation 0-9

$$Lux = \frac{lm}{sr} @ 1m$$

1 Steradian = 1 m² which can be used to find the light intensity lux value at 1 m distance.

Luminous intensity at distance:

Equation 0-10

$$I_{v(cd)} = E_{v(lx)} \times (d_{(m)})^2$$

Light under 0.1 lux is invisible to the human eye [137], limiting the viewing angle and the beam steradian can reduce the required candela brightness of the LED needed, but the LED still needs to have a high lumens value.

For this study, the internal volumes for the Energy Scavenging Piezoelectric Electronic Tracer System will be focussed on the 7.62mm munition and the package size was kept at 6mm diameter and a 10mm height giving a total volume of 282.7 mm³.

6.6.2 Harvester electronics

The 7.62mm slug has internal volume of diameter 6mm, and a length of maximum 10mm, the number of electronics for rectification of the piezoelectric energy harvester is limited to two circular faces of a PBC with areas of 28.27 mm² equalling a total of 55.54 mm². The thickness of the electronics must also be thin enough to leave space for a spring mass and the piezoelectric components. The simplest components are required to produce usable Direct Current (DC) electricity from the piezoelectric output which is Alternating current (AC). These components are diodes or a full bridge rectifier integrated component (FBR), a capacitor, resistor, and a Light Emitting Diode (LED). A simple system with these components will have losses due to the rectifier diodes (Schottky) where energy is lost through voltage drops and conduction loss [138], [139]. The power loss (W) = $P_{loss}(t)$ in a transient system is determined by the equation:

Equation 0-11

$$P_{loss}(t) = 2V_D(t)I_D(t)$$

Where $V_D(t)$ = forward voltage drops (V) over the diode, and $I_D(t)$ = the forward current (A). When the voltage and current drops under these limits, the diode no longer operates, thus energy is lost. The problem with this type of system is, there is no conditioning other than a resistor. The resistor does slow the rate of discharge from the capacitor to the LED, but the LED will be able to drain the capacitor immediately. The capacitor discharges at an exponential rate. This is calculated using the equations:

Equation 0-12

$$Q = Q_0 e^{-\frac{t}{RC}}$$

Equation 0-13

$$Q_0 = CV$$

Equation 0-14

$$V = V_0 e^{-\frac{t}{RC}}$$

Equation 0-15

$$I = I_0 e^{-\frac{t}{RC}}$$

Equation 0-16

$$RC = CR_{Load}$$

Where Q is charge (C), Q_0 = initial charge in the capacitor (C), C is capacitance (F), RC time until half the capacitor is discharged (s), t is time (s), V_0 is initial voltage (V), I_0 = initial current (A) & R_{Load} = load resistance (Ω).

Using these equations, it is possible to tune the system size and discharge rate, but when the discharge voltage drops below the forward voltage of the LED (load) then the rest of this energy is un-usable and thus wasted, also there will be noticeable light intensity fade as the voltage across the LED decreases. To get around the high energy loss of the capacitor discharge, it is possible to use Pulse Width Modulation (PWM) or a simpler self-oscillating system. To create this effect, different electronic components are required and there are limitations to the size of the electronic circuit board and the various components, one component that does not miniaturise well is an inductor.

A simple circuit is demonstrated on this 20mm system in figure 7-1, is designed to use the energy from the piezo harvester system. The design has two individual circuits, designed for two piezo discs. The largest parts of this circuit are the capacitors, (the male prongs are removed for wires).

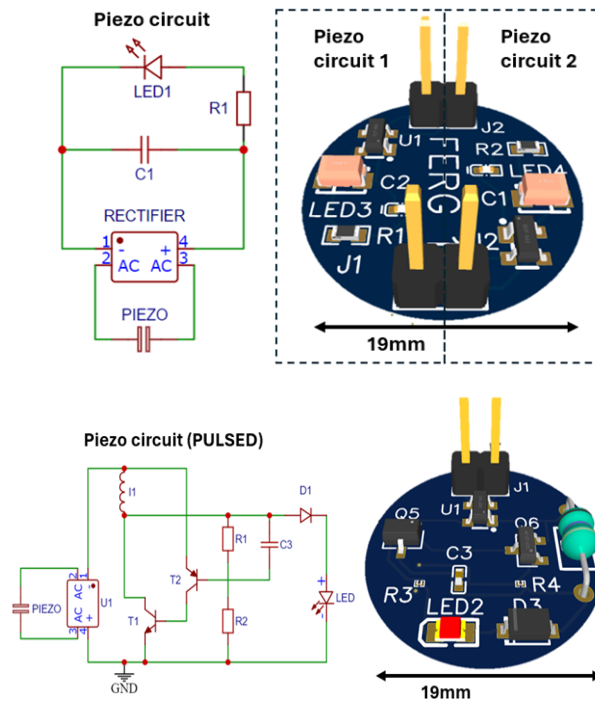


Figure 0-1 20mm LED circuits, Simple Capacitor-Resistor LED circuit (TOP), Self oscillating LED circuit (BOTTOM)

Different approaches to resolve the energy losses have investigated alternatives to the inductor, an example is the Synchronised Switch Harvesting [140] of a Capacitor using switched capacitors to filter or smooth the output of the piezo element. The issue of this type of circuit is the components footprint, with advancements in integrated chip components, there is limited commercial availability of this type of circuit for an AC high voltage created by the piezo discs.

6.6.3 Mechanical-Electric Transduction System Design

Previous research on improving mechanical to electrical generation using shear structures on piezo ceramic discs has shown that linear force can be diverted into

shearing to improve electrical generation [115]. An internal spring mass system inside the 7.62mm slug would require a mass that is determined by the size of the electronics used, the piezo disc size and the springs used. The material for the mass would ideally be high density heavy metal, exerting as much force onto the spring and piezo as possible.

Using a steel mass with the dimension's; height = 6mm, diameter = 6mm, with a density of 7850kg/m³, the mass would be 1.55 grams. The acceleration of a 7.62mm slug is noted around 1,500,000 m/s² creating a force in the range of 2300 N. Using a lead mass with a density of 11400kg/m³ would further increase this force to 3300 Newtons if linear acceleration stayed the same. To understand what energy levels would be available, a simulation was constructed to predict voltages.

6.6.4 Simulation Parameters

Setting up the system in COMSOL Multiphysics, the input force will be simulated to peak at 0.5ms for a 1ms burst using half a sine wave (or 2kHz frequency). The simulated storage capacity is a 4.7 μ F capacitor, connected to the piezo disc's electrodes via rectification diodes. For a better understanding of the spring washer – piezo disc interaction, each piezoelectric output is stored in a separate capacitor.

The simulation struggled to converge at higher loads due to the increase in deformation of the structures, and fully coupled with electro potential physics of the circuit output energy gave back false results and components crossing contact boundaries. To prevent this, the mesh was refined, and the washers were made thicker to increase their strength but decrease flexibility and create only boundary contact.

6.6.5 Hyperbolic Paraboloid Crinkle Washer

The simulation is set up as two piezo discs with a spring design sandwiched between them. The piezo discs have steel backing discs to prevent bending, and the force is applied vertically downwards in the Z axis, with the bottom face fixed. The Hyperbolic Paraboloid Crinkle Washer is a single component but exhibits similar design features to disc springs. Once the simulation is completed, and the voltages stored in the capacitor are known, the next stage is to size the resistor using the equations 7-9, and this will indicate the length of time and the distance the LED will be activated using the simple circuit.

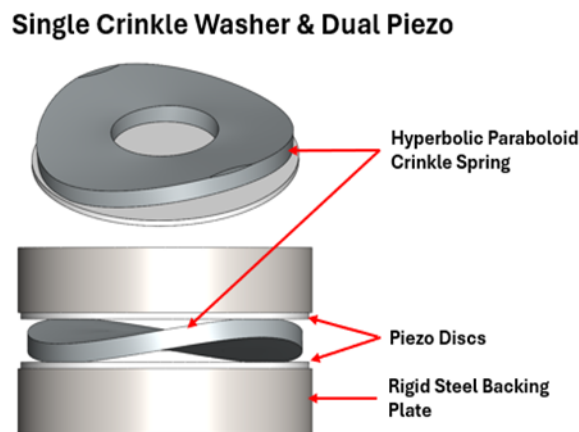


Figure 0-2 Double Piezo Hyperbolic Paraboloid Crinkle Washer

6.7 Results

The simulations were run at different loads to establish the most stable thickness to prevent inverted meshes, while also balancing the computational time. The overall voltage was recorded, and the design was iterated to improve the overall electrical power outputted from the initial peak of the force wave at 2300N. These simulations only represent the power produced under a single peak force input, and not further resulting oscillations. Larger backing plates were used to reduce bending deformation.

The initial design with two piezo discs (Figure 7-3) with a thickness of 0.8mm and a height of 1mm completely flattened at 1200N. The rectified and stored electrical energy was recorded at 566.13 mV over a 10uF Capacitor. This voltage was not sufficient to power the electrical system. The spring washer also buckled and created limited shearing to the piezo discs, as the height and resultant curve of the structure was minimal.

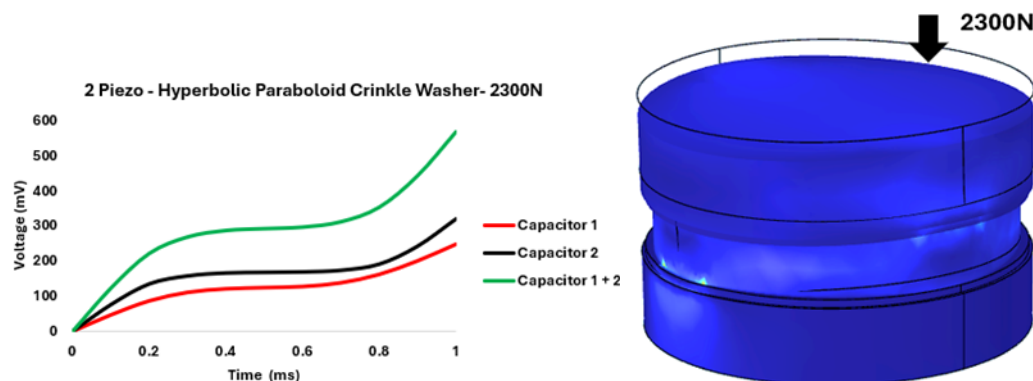


Figure 0-3 Initial Hyperbolic Paraboloid Crinkle Washer Energy Output (TOP), System deformation (BOTTOM)

To maximise the electrical energy from the spring, the design was changed to absorb a higher force. To improve the voltage output, two approaches were used, increasing the number of piezo elements to four, and decreasing the capacitor size to 4.7uF. The next iteration (Figure 7-4) was 1mm thick design with an increased height of 1.5mm, using more of the shear spreading. This resulted in an energy output of 2252mV, which could turn on a micro-1.8V LED requiring lower voltage, typically seen on PCB boards. The stress distribution in this iteration however showed less deformation, and reduced shearing indicating that it was too thick. Also, stress can be seen forming (light blue) in the space between the two perpendicular contact points.

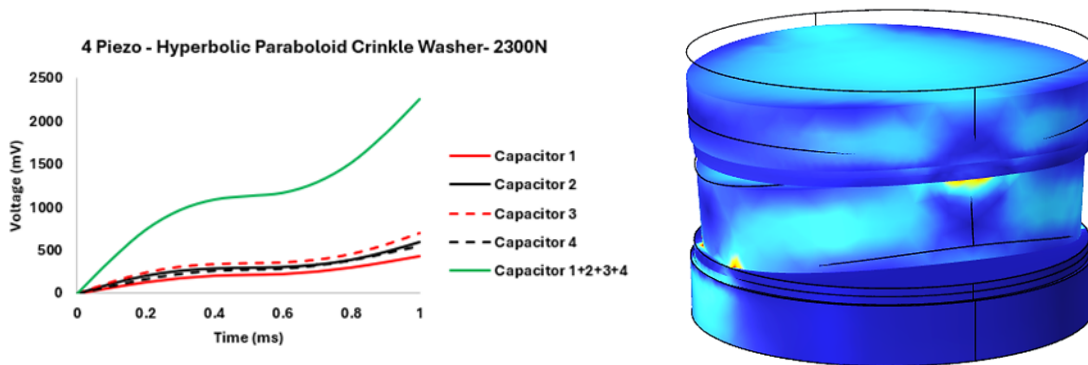


Figure 0-4 4 Piezo - second iteration Hyperbolic Paraboloid Crinkle Washer Energy Output (TOP), System deformation (BOTTOM)

The next iteration, (Figure 7-5) reduced the stress of the spring by decreasing the thickness, increasing the height, and increasing the shear flexing further by removing material from areas that were concentrating stress. The resulting washer had a thickness of 0.9mm, and a total height of 1.6mm, with radial cuts from stress areas. The resultant voltage output was 3050mV. This voltage is enough to turn on the 3V-LED and this is from the initial force peak.

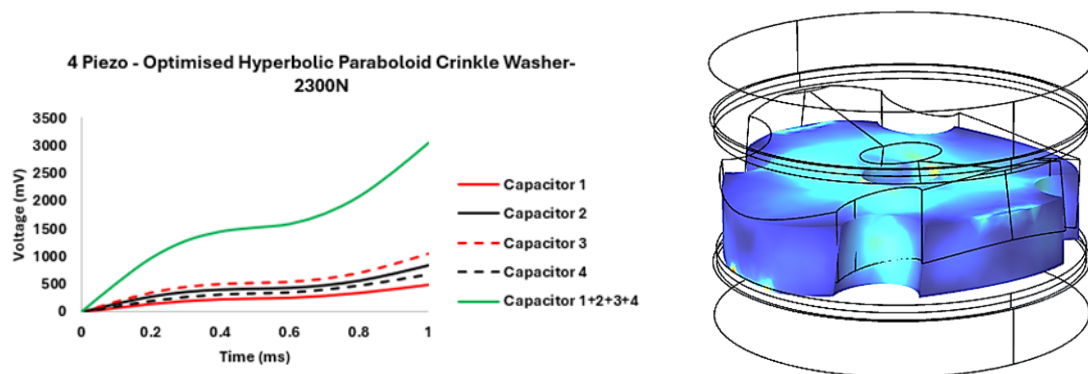


Figure 0-5 third iteration Optimised Hyperbolic Paraboloid Crinkle Washer Energy Output (TOP), System deformation (BOTTOM)

The resultant energy level for the initial force input, (or half an oscillation), is very low, but using equations 12-16, this energy could power a 1.8V LED at 20mA using a 150 Ω resistor (*with both voltage and current decaying) for around 0.7ms. As the slug is traveling at 749 m/s, this gives a visible distance of around 0.52 m. The initial power output derived from the results is 60 mW with a volume of 282.74 mm³, giving the device a theoretical power density of 212 mW/cm³.

6.8 Proposed Design

The final design of the piezoelectric energy harvesting electronic tracer (Figure 7-7) incorporates washers at both ends of the mass. These washers absorb the initial force of 2300N and subsequently release it into the opposite spring, creating an oscillating system that starts at a frequency of 2 kHz. The system's energy output increases with the number of oscillations, thereby extending the duration the LED remains lit.

As previously discussed, the available volume is limited, so reducing the size of the

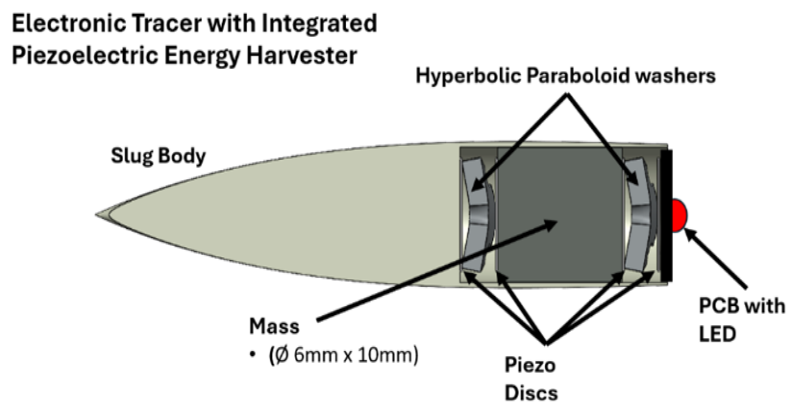


Figure 0-6 7.62 Slug with integrated Piezoelectric energy harvester.

components is essential. This can be achieved by substituting the spring washers' material with stronger alloys, which would allow for a greater number of piezo discs, resulting in higher voltage and energy output. Similarly, using a denser metal for the mass could increase the force generated or reduce the volume required to achieve the same force.

The circuitry for this system can be kept simple by using only AC rectification diodes, resistors, an LED, and a capacitor. This configuration would cause the LED to gradually dim as the voltage and current drop below the required levels. However, the system's performance could be enhanced by incorporating a simple self-oscillating circuit to regulate the electrical discharge. The challenge with this approach lies in the need for a large inductor component.

One potential solution to this issue is to have the mass serve a dual purpose. By using a steel or ferrite mass wrapped in coils, the mass could function as an inductor, eliminating the need for a separate inductor on the PCB alongside the other electronics.

6.9 Summary & Limitations

This research explored the feasibility of integrating a piezoelectric energy harvester into a bullet slug to power an LED, aiming to replace traditional pyrotechnic tracers with an electronic alternative. One of the primary challenges in developing an electronic tracer is sourcing electrical energy. Given the diverse environments in which these tracers operate, it would be advantageous to harness the kinetic energy generated by the propellant explosion. The simulations presented in this study propose a design that could potentially generate 3V of electricity, stored in a capacitor, to power an LED over a limited distance. The system utilizes a novel washer that activates piezo discs in shear mode on two faces, aiming to enhance compactness and energy density. Simulation results suggest that the system could generate enough energy to illuminate an LED for a short distance, though further research is needed to fully understand the energy produced through system resonance.

However, the study is limited by its reliance on simulations, which cannot fully replicate real-world challenges such as cracking, material weaknesses, and imbalances that could significantly alter experimental outcomes. Additionally, factors like system rotation, rapid temperature changes, and environmental conditions, which could affect metal expansion and the pyroelectric properties of piezoceramic materials like PZT, were not considered. The simulation also faced issues with high deformation levels, leading to a lack of convergence. The design of the Hyperbolic Paraboloid Crinkle Washer was limited to specific iterations, as adding complexity would reduce manufacturability and make the design less practical.

The LED's viewing distance is significantly influenced by ambient light conditions. As light dissipates with distance (as described by Equation 1), visibility diminishes rapidly, especially when combined with the voltage decay in the capacitor. The optimal conditions for LED visibility occur in low-light environments, such as at night or in dark settings. To mitigate rapid voltage decay and improve the LED's performance, the circuit shown in Figure 7-1 (bottom image) can be used. This circuit pulses the LED at a high frequency, conserving energy and extending both the brightness and effective viewing distance of the LED tracer. But this circuit is dependent on space on the circuit board and the size of the inductor component, which a work around concept has been presented in the proposed design section.

6.10 Conclusion

In conclusion, while the research demonstrates the potential of using a piezoelectric energy harvester to power an LED in a bullet slug, replacing traditional pyrotechnic tracers, it also highlights significant challenges. The system shows promise in generating sufficient energy for a limited time of 0.7ms after half an oscillation which would be an approximate distance of 0.52 m.

From this study it has found that:

- Hyperbolic Paraboloid Washers are the combination of crinkle washers and disc springs and can be used effectively to store high forces. They can also be used to activate piezoelectric discs on both shearing faces and are potentially space saving compared to the alternative springs.
- Piezoelectric energy harvesters are theoretically capable of not only fitting inside a 7.62 tracer, but capable of harvesting enough energy to light an LED.

The complexity of the washer design and the practical limitations in manufacturability also pose obstacles to the implementation of this technology. Further investigation and refinement are needed to address these challenges and fully realize the potential of this innovative approach.

7 General Discussions & Limitations

In recent years, electronic components have become smaller and more energy-efficient, leading to the development of compact, self-powered devices. As power sources have also shrunk in size while maintaining power density, and with advancements in wireless communication, small-form electronics have seen significant growth across various sectors, including medical, aerospace, industrial, leisure, and consumer products.

The decreasing energy demand for electronics, driven by more efficient components, has created favourable conditions for functional electronics with energy-harvesting sub-systems to potentially replace traditional applications. This research focused on replacing pyrotechnic materials, traditionally used to generate light, with an LED circuit powered by kinetic energy harvesting.

Shifting away from highly toxic, combustible materials that are in limited supply offers numerous advantages. An electronic tracer not only reduces environmental pollution but also benefits from the global mass production of its components, mitigating supply chain bottlenecks. Additionally, the versatility of an electronic tracer system is enhanced; if sufficient power is generated by the energy harvester, the functionality is constrained only by the available package volume.

The research began with a review in Chapter 2, exploring technologies that could serve as viable alternatives for generating sufficient electrical energy without the need for battery storage. Cost and complexity were also considered crucial factors in determining the suitability of these devices. The review primarily focused on millimetre-scale devices that had been successfully prototyped and demonstrated to produce electricity. This focus inherently limited the scope of referenced concepts, as larger and smaller-scale energy harvesting systems were excluded. These excluded systems typically require specialized manufacturing knowledge, which would have broadened the research scope excessively—for instance, techniques like photolithography and chemical etching used in silicon and nanostructure fabrication. Hard piezoceramic materials were identified as particularly suitable due to their ability to withstand compression and shockwaves, their Curie temperatures of up to 300°C,

their relative affordability, and their potential for integration into an energy harvesting system with minimal components.

After selecting a piezoelectric energy harvesting system for converting kinetic forces into electricity, it became necessary to delve into the physics and existing system designs to optimize electrical output. As detailed in Chapters 3 and 4, certain structural designs, such as the cymbal transducer, Belleville Spring, and disc spring, have demonstrated success in enhancing electrical generation by converting linear forces into shear forces. However, further optimization of these structures, as explored in Chapter 3, revealed that there was still room to improve electrical power output. Another design, the crinkle washer, was also identified during the research for its shearing capability, which could further enhance electrical power generation, as discussed in Chapter 5. Iterative designs in Chapter 5 showed the potential to create a double-sided shearing structure superior to currently available designs. A hyperbolic parabolic geometry emerged as a promising concept, sharing similarities with the mirrored disc spring design. The benefits of this geometry include fewer individual components, increased shearing, and the ability to incorporate wave patterns for stability and frequency tuning.

Chapter 6 explored the rotational dynamics of a bullet, which is created by the rifled barrel's spiral grooves. Rotation provides gyroscopic stability, ensuring the bullet's point remains oriented correctly. Harvesting energy from inside the bullet would be beneficial, as adding external features could increase drag, compromise rotation, and destabilize the bullet's flight—detrimental to an electrical tracer intended to replicate standard munitions characteristics. A spiral torsion spring was designed for this purpose, fitting compactly inside the bullet and removing only a small force. While the torsion spring design showed potential as a rotational spring-mass system, scaling it down for munitions such as the 5.56mm and 7.62mm poses a challenge, requiring sub-1mm machining to create the spiral arms.

Simulations in this research were conducted using COMSOL Multiphysics, chosen for its ability to couple structural and electrical physics, allowing for the observation of structural deformation alongside analysis of the electric potential generated by the piezoelectric material. While the software was relatively straightforward to use,

successful simulation required meticulous attention to every aspect of the physical system, necessitating a deep understanding of the system's intricacies.

However, several variables could lead to discrepancies between simulation and experimental results. For example, experimental issues such as piezo ceramics cracking or boundary adhesion problems—where the simulation could maintain connections that might fail in real-world conditions—could affect outcomes. In simulations, structures were modelled as defect-free, with perfect form, density, and smooth surfaces, but these structures are likely to have imperfections that could impact their performance.

Continued refinement of these structures led to the development of novel spring designs, which were then applied in Chapter 7 to conceptualize and demonstrate the complete electrical tracer system as a fully assembled component, with results that conclude a system capable of lighting the LED system for 0.7 ms and 0.52 m at half an oscillation. However, due to limitations in time, safety, and resources, the prototype could not be evaluated in real-world conditions. Without field deployment, it remains impossible to fully assess the design's limitations. The electronic layouts were successfully demonstrated, showing that the necessary electronics could be constructed to fit within the small size of a 7.62mm slug. However, the research could not determine whether the electronic components would withstand the proposed forces, particularly those with liquid elements, such as electrolytic capacitors, and components sensitive to temperature, which might require further revision.

The novel systems presented in this research could be further improved through various modifications. For instance, while the springs in the simulations were consistently designed using structural steel, enhancing material stiffness could positively impact the system by reducing the size and thickness needed, thereby creating additional volume for increasing the mass and force or electrical system. This aspect was not explored, as the required materials were not available in the COMSOL Multiphysics library. Further physical testing of redesigned structures was hampered by the high costs of prototyping, with methods such as stamping and forming requiring expensive customized Molds. Metal 3D printing offered a more accessible manufacturing method, but the technology currently lacks the precision and uniformity needed, with many 3D-printed metal parts failing after the sintering stage and

successful parts often exhibiting rough surfaces, warped constructions, and lost characteristics.

The next chapter concludes this PhD thesis, summarizing the research and offering recommendations for future work to further develop the concepts derived.

8 Conclusion & Recommendations

8.1 Summary

This research has been conducted to explore and develop an energy harvesting system that can be integrated into a high linear force and rotational package suitable for the use in projectiles such as tracer ammunition, replacing the previous technology that is pyrotechnics. Focusing on the design of the mechanical transduction system converting kinetic energy into electrical energy to be used by an LED circuit to produce viable light. The aims and objectives have been achieved in the following sections:

Objective 1:

A detailed literature review (Chapter 2), has evaluated previous technologies, understanding the fundamental working principles of the core energy harvesting technologies. The review was created to give an overview of the energy densities and the limitations of implementing these technologies when scaling down to smaller work volumes.

Objective 2:

Following on from Chapter 2, the electrical energy requirements to be produced for electrical LED system was understood. The most suitable technology was then chosen to be replicated and improved through research and investigation, including the difference in mechanisms and complexity of harvesting linear and rotational energy.

Objective 3:

Chapters 3 through 7 illustrate the application of design principles, Multiphysics simulations, and structural optimization to previously identified washer structures with shearing properties (disc spring, crinkle washer), which were found to exhibit the highest energy densities for piezoelectric energy harvesting. These chapters detail how modifications to the shearing structure designs and new shapes (hyperbolic paraboloid washer), introduced novel characteristics that significantly improved electrical energy generation capabilities. Additionally, the chapters present validation experiments conducted to test and assess the performance of metal 3D-printed designs featuring complex geometries, providing insights into their practical viability, efficiency and demonstrating their manufacturability.

Objective 4:

Chapter 7 is the final implementation guidelines of the proposed novel-structure energy harvester, combined with the with means of electrical power conditioning and light production. Taking the learnings of the previous chapters to propose a complete energy harvesting and LED circuit schematic for an optimised electronic tracer able to create visible light.

To complete this PhD research's aims and objectives, the project entailed the use of many engineering methods, ranging from technical designs (SOLIDWORKS), finite element analysis of structures under load integrated with electrical physics (COMSOL Multiphysics). The theoretical results showed an improved power density of 212 mW/cm³ (Chapter 7-Results), a higher power density than the piezoelectric prototype created by J. Rastegar of 148.54 mW/cm³ (43% power density increase) with the use of disc spring washers. The main conclusions drawn from this PhD project is that the construction of an electronic tracer with an integrated piezoelectric energy harvester could be in the future a viable replacement for a pyrotechnic tracer. But there would be noticeable differences in the overall characteristics of the electronic and pyrotechnic versions. The scope of this project, to research and design a fully working product in the duration and with the resources available did create limitations.

Key findings of the project:

- The first key finding was the testing and comparison of the use of a two spring-washer shearing structures, the disc spring and the crinkle washer. The crinkle washer, a lesser-known spring structure, successfully worked for shear force spreading of a piezo element.
- The linear force experiments and research showed that the shear structures both effectively improve electrical energy output, with crinkle washers showing shearing capability, but not as efficiently as the disc spring. The observations of the research did however allude to the Crinkle washer's design which was double sided compared to that of the one-sided disc spring structure. These results prompted further exploration in the preceding research.
- Further research attention was given to improving both the disc spring and the crinkle washer. The piezo shearing structures designs were subjected to Multiphysics optimisation and design iterations for linear forces and this

research found methods of increasing the energy transmission and found two new novel structures, Tapered & Optimised Disc Spring (Chapter 4) and a Parabolic Hyperboloid Wave Spring (Chapter 5).

- A third structure in chapter 6 was also designed and conceptualised, highlighting the potential for harvesting rotational energy using torsional springs bonded to piezo disc elements that opens the potential for future combination with linear spring systems and higher power density energy harvesters. This rotational harvester mimicked a linear mass spring system but was translated for rotational motion and utilised new manufacturing methods such as metal 3D printing to verify a physical system.
- The last findings are the limitations of an electrical tracer system when in comparison to the pyrotechnic version. Due to LED brightness capabilities and components required for capacitor discharge control, the system does not fully emulate the combustive materials. Although the premise of using an electrical system has advantages due to the tunability and possibility of increasing the functionality to do more than just power an LED. The volume limit of the system does mean that a finite number of components are able to be compacted into the device, but electronics are always being improved and decreased in size, so more complex electronic systems will potentially become viable.

8.2 Recommendations for future work

This PhD research has focused on developing a piezoelectric energy-harvesting electronic tracer as an alternative to the traditional pyrotechnic tracer. The findings have contributed to the scientific community through published papers. Despite the progress made, several potential avenues remain unexplored, largely due to the extensive range of technologies that could be integrated with this system—far too broad to be fully examined within the constraints of time and resources available for this research.

While other chapters have touched upon some of the limitations encountered during the research, there are additional areas that have not been thoroughly explored. This section seeks to delve deeper into these potential areas for further research.

Expanding on these topics could lead to increased available energy, which would directly enhance the electronic functionality of the tracer.

8.2.1 Optimised structures for the combined physics

Chapters 2-6 focused on analysing the distinct forces acting on a tracer projectile after the propellant is ignited—specifically, the linear acceleration and rotational acceleration. In real-world applications, these forces are experienced simultaneously. Given that each structure was designed to harness only one of these forces, there is clear potential for refinement by integrating the strengths identified in the individual chapters to create a structure capable of harnessing both linear and rotational energy.

The optimized disc spring washer and torsional spring designs already exhibit the simplistic yet effective characteristics of three arms. By introducing radial curvature, sloping on the arms, and a thickness taper from the centre to the edges, a multi-force energy-harvesting structure could be developed. Achieving this would require additional Multiphysics simulations, and constructing such a complex structure would present significant challenges. Assessing this integrated system would also necessitate equipment capable of simultaneously applying both rotational and linear forces.

8.2.2 Hybrid Energy Harvesting Systems

As discussed in Chapter 2, many of the technologies reviewed can complement each other in a hybrid system. For example, the linear electromagnetic and triboelectric spring mass energy harvester (2.4.3) offers a compelling approach. The linear spring systems examined in Chapters 3-5, which involve very small displacements of the mass, could be enhanced by coupling with another technology. Both triboelectric and electromagnetic energy harvesting could be used in parallel. One possible system involves replacing the mass with a magnet and introducing coils, creating a structure like an inertia generator. Alternatively, adding triboelectric materials to the mass face and the inner casing face could enable energy harvesting through Lateral Sliding mode (LS) or Freestanding Layer mode (CFT or SFT) TENG generators.

For the rotational system discussed in Chapter 6, the torsional spiral spring design, which coils and uncoils depending on the number of revolutions, could be adapted for triboelectric energy harvesting. The rotational movement of the mass creates surface

friction, ideal for triboelectric generation. Another approach could involve replacing the mass with a radially magnetized magnet, with coils situated on the inner wall of the casing to harvest energy electromagnetically.

However, integrating an additional technology comes with the trade-off of requiring more complex electronics for power conditioning. This added complexity could be challenging given the limited available volume. Nonetheless, for applications that demand higher energy density, such a hybrid system presents a viable method to achieve it.

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Appendix A

Mechanical Properties	Unit		PRYY+0349	PRYY+0170	PRYY+0354	000014801	PRYY+0189	PRYY+0190	PRYY-0884	PRYY+0853
Resonant frequency (thickness)	kHz		10000	2000	1000	10000	2000	1000	2110	8440
Resonant frequency (radial)	kHz		100	100	100	80	80	80	1135	757
Piezo material			PIC255	PIC255	PIC255	PIC255	PIC255	PIC255	PIC181	PIC181
Electrode			Ag screen-printed	Ag screen-printed	Ag screen-printed	Ag screen-printed	Ag screen-printed	Ag screen-printed	Ag screen-printed	Ag screen-printed
Outer diameter	mm		20	20	20	25	25	25	2	3
Thickness	mm		0.2	1	2	0.2	1	2	1	0.25

		Soft PZT materials					
		Unit	PIC151	PIC255	PIC155	PIC153	PIC152
Physical and dielectric properties							
Density	ρ	g/cm ³	7.80	7.80	7.80	7.60	7.70
Curie temperature	T_c	°C	250	350	345	160	340
Relative permittivity in the polarization direction ⊥ to polarity	$\epsilon_{33}^T / \epsilon_0$		2400	1750	1450	4200	1350
	$\epsilon_{11}^T / \epsilon_0$		1980	1650	1400		
Dielectric loss factor	$\tan \delta$	10 ⁻³	20	20	20	30	15
Electromechanical properties							
Coupling factor	k_p		0.62	0.62	0.62	0.62	0.48
	k_t		0.53	0.47	0.48		
	k_{31}		0.38	0.35	0.35		
	k_{33}		0.69	0.69	0.69		0.58
	k_{15}			0.66			
Piezoelectric charge coefficient	d_{31}		-210	-180	-165		
	d_{33}	10 ⁻¹² C/N	500	400	360	600	300
	d_{15}			550			
Piezoelectric voltage coefficient	g_{31}	10 ⁻³ Vm/N	-11.5	-11.3	-12.9		
	g_{33}		22	25	27	16	25
Acousto-mechanical properties							
Frequency coefficients	N_p		1950	2000	1960	1960	2250
	N_1	Hz · m	1500	1420	1500		
	N_3		1750		1780		
	N_t		1950	2000	1990	1960	1920
Elastic compliance coefficient	S_{11}^E	10 ⁻¹² m ² /N	15.0	16.1	15.6		
	S_{33}^E		19.0	20.7	19.7		
Elastic stiffness coefficient	C_{33}^D	10 ¹⁰ N/m ²	10.0		11.1		
Mechanical quality factor	Q_m		100	80	80	50	100
Temperature stability							
Temperature coefficient of ϵ_{33}^T (in the range -20 °C to +125 °C)	$TK \epsilon_{33}$	10 ⁻³ /K	6	4	6	5	2
Time stability (relative change of the parameter per decade of time in %)							
Relative permittivity	C_ϵ	%		-1.0	-2.0		
Coupling factor	C_K			-1.0	-2.0		

