

High force compression mode to Shear mode piezoelectric energy harvesting

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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 and 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.

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 [1,2] from high drag or friction) or ambient energy that is harvestable such as light, heat and kinetic [3,4]. Energy harvesters are gaining traction in electronic devices such as sensors in structural health monitoring [5,6], wearable electronics, and mobile phones or Internet of Thing (IOT) devices [7,8]. 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 [9–12]. With lower energy consuming electronic devices, some energy harvesting systems that where once seen as un-feasible because of the low power output are now verging on capable [13–15]. 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. [16]

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 [17–19]. The challenge is the adding of a structural mechanism for load distribution 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.

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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 et al. [20] demonstrated the use of Belleville washers (Fig. 1-A) for absorbing much high forces combine with a piezoelectrical system and a mass, with the system achieving 1–2 J. Further experiments in cymbal transducers have led to the novel shapes such as the wagon wheel [21], from the fist conception of rectangular structured bridges [22], and the earlier conception of the cymbal by Fernfindez and Dogan [23]. The curvature structures mentioned distributes the force on a piezoceramic elements face between compression and shear mode, activating the d33 & d15. [24–27].

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 (Fig. 1-B), [28] which also shows the characteristics of radial expansion and shearing. Implemented by Zhu [29], 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 [30–33] (disc spring - Fig. 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 elements 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.

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, that is more powerful and compact for end use in a high force energy harvesting structure.

2. Methodology

2.1. Voltage & electrical energy

2.1.1. Piezo compression equations

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

$$V = -(g_{33}hT) = -\left(g_{33}h\frac{F}{A}\right) \quad (1)$$

V =Voltage, g_{33} =Piezoelectric Voltage Constant (Vm/N), h =Thickness (m), T =Force applied/area (m^2), F =Force (N), A =Area (m^2).

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

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

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

2.1.2. Piezo shear equations

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

$$g_{15} = \frac{d_{15}}{\epsilon_{11}^T} \# \quad (3)$$

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)

$$V = -(g_{15}hT) = -\left(g_{15}h\frac{F}{A}\right) \quad (4)$$

V =Voltage, g_{15} =Piezoelectric Voltage Constant (Shear strain) (Vm/N), h =Thickness (m), T =Force applied/area (m^2), F =Force (N), A =Area (m^2)

$$E = \frac{1}{2}(C_0V^2)(1 - k_p^2) \quad (5)$$

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

$$\epsilon_{11}^T = \frac{\epsilon_{11}^T}{\epsilon_0} \cdot \epsilon_0 \# \quad (6)$$

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

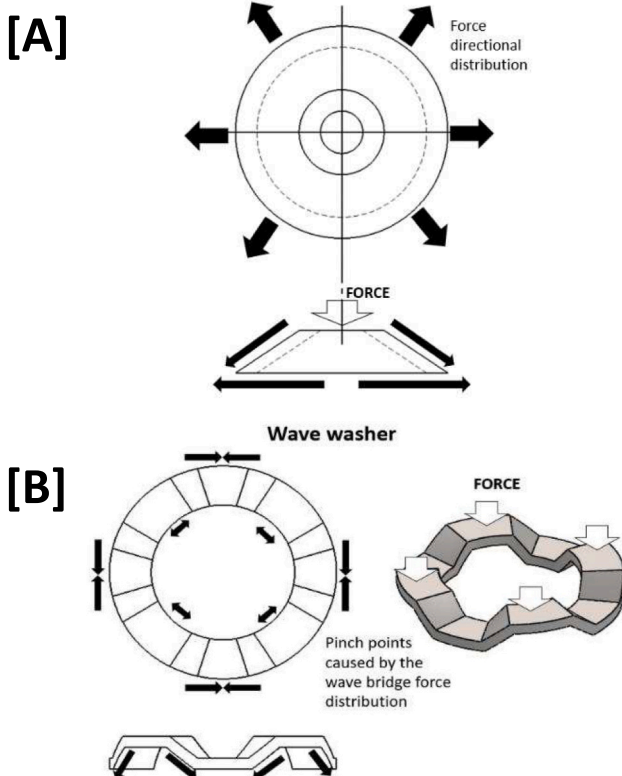


Fig. 1. - Belleville Disc Spring[A] & Wave/Crinkle Washer[B].

2.1.3. Power equations with matched circuit resistance

$$P_{max} = \left(\frac{V}{Z_1 + R_L} \right)^2 \cdot R_L \quad (7)$$

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).

2.1.4. Simulation

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

3. 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 used is a 5965 with a max return speed of 3200 mm/min and a max load of 5kN set up with 2 flat plates for compression (Appendix).

3.1. 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.

3.1.1. 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 0.4 mm thickness, (the crinkle washer used was 0.55 mm 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,

3.1.2. 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.

3.1.3. Instron variable force & acceleration inputs

The first Instron experiment, (Variable force), uses a RAMP profile (Fig. 2-C) that incrementally compresses the piezo from a pre-compression of 40 N in steps of 200 N, up to 2200 N at a velocity of 0.75 mm/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) (Fig. 2-D), incrementally increases the velocity by 0.2 mm/s from 0.2 mm/s – 1 mm/s. Ramping the velocity does introduce a change in force caused by the Instron feedback system limitations. Above 1 mm/s, the system could not stay within 20% of the 1500 N.

4. Results

4.1. Theoretical results

The theoretical calculations (Figs. 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.

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.

4.2. Simulated force ramp simulation

The simulation was set up to use the Instron load profile (Fig. 3 - H). A function plot: Interpolation and importing the Force/Time data. The Piezo material used in the simulations was PZT 5 A as it is of similar

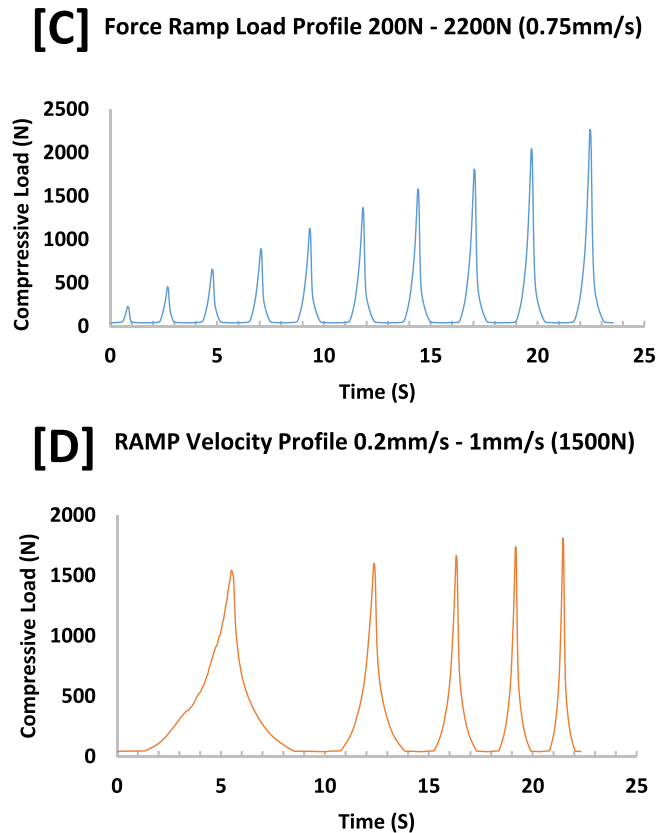


Fig. 2. - Instron Force Ramp Load Profile[C] & Instron Velocity Ramp Load Profile[D].

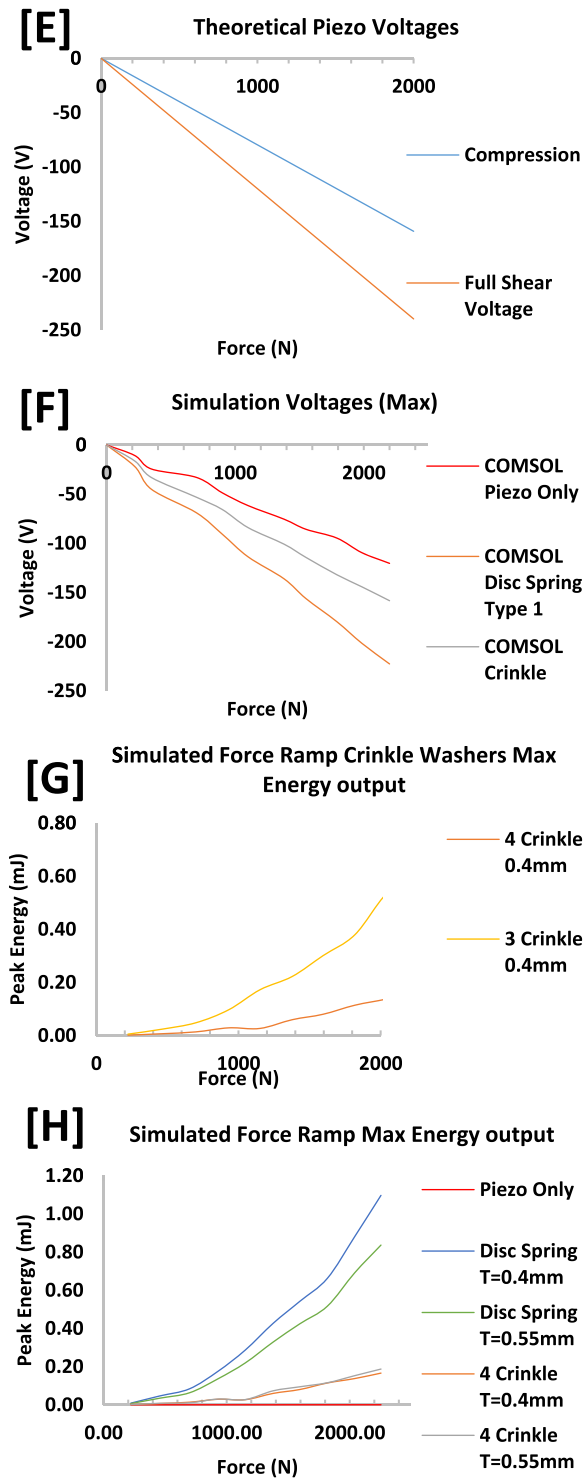


Fig. 3. - Theoretical Piezo Voltages[E], Simulated Voltages (stationary)[F], Simulated Force Ramp Energy Outputs (stationary)[G], Simulated Crinkle Washer Energy Output (Thickness and wave changes) [H].

Table 1 - D
Characteristics PZT 5 A & PIC255.

	PZT 5 A	PZT PIC255
D33 [C/N]	3.74×10^{-10}	4×10^{-10}
D31 [C/N]	-1.71×10^{-10}	-1.81×10^{-10}
D15 [C/N]	5.84×10^{-10}	5.5×10^{-10}

characteristics (Table 1). The voltage characteristics under no load correspond with the results from the experimental tests and close to the hand calculations. The 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 [34]. The simulation pictures have been stopped at 21.4 s 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 (Fig. 3- G) 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 0.17 mJ to 0.61 mJ.

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 d33 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 (Fig. 4 —I).

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 d15 (Fig. 4-J).

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 (Fig. 4-K).

The COMSOL simulation results show that the shear activation does

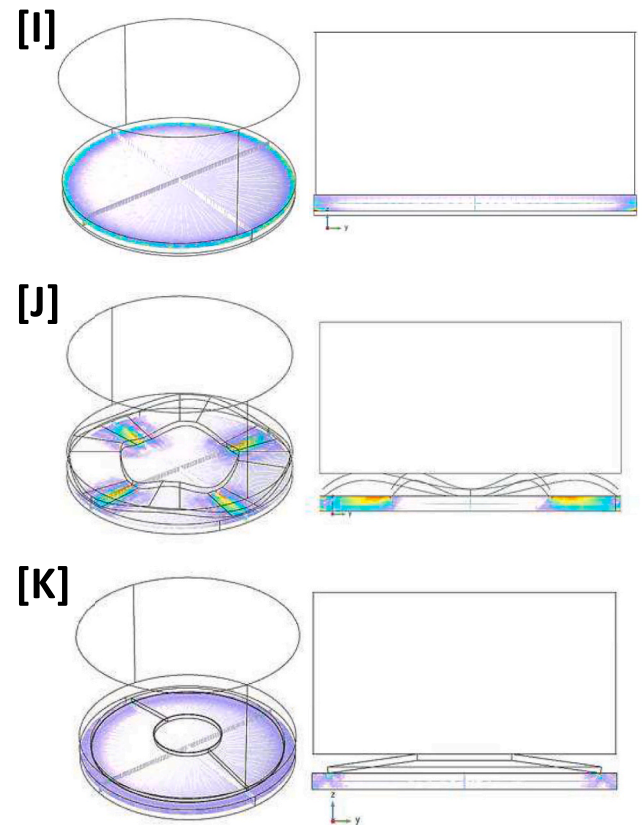


Fig. 4. - Piezo Only Compression[H], Crinkle Compression[I] & Disc Spring Compression[J].

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 0.9 mJ energy (only 15% of the disc spring systems energy) at 2200 N. 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.

4.3. Simulated velocity ramp

The immediate results from the change in velocity of impact (Fig. 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.

4.4. Experimental validation of simulated results

4.4.1. 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 2).

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

The crinkle washer has a more gradual force/displacement in comparison the disc spring which has a much smaller extension (Fig. 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.

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.

4.5. Experimental force ramp experiment

The first set of tests focused on the change in force at a fixed velocity. These tests were carried out between 200 N - 2200 N and velocity of 0.75 mm/s, the speed and force range chosen was simply to get results

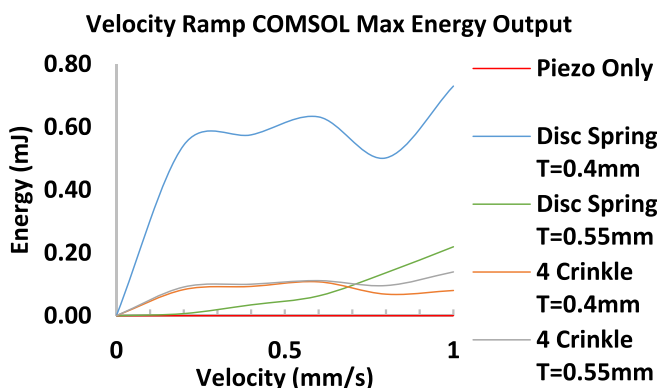


Fig. 5. - Simulated Energy Outputs.

Table 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

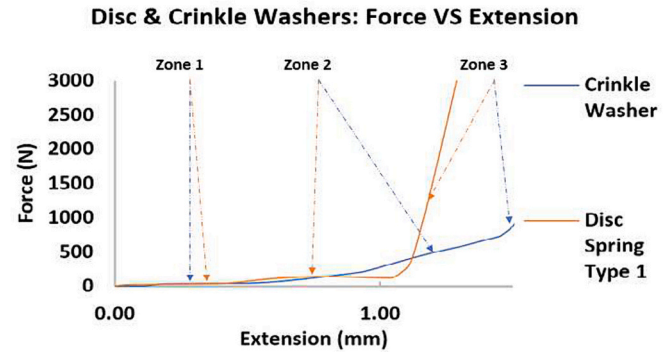


Fig. 6. - Instron Load Profiles for both washer types.

while staying in the working limits of the Instron and maintaining accuracy (Fig. 7).

Compared to the theoretical static calculations and simulations, the energy output was much lower. This is because of the many real-world conditions that are not seen in simulation such as mechanical

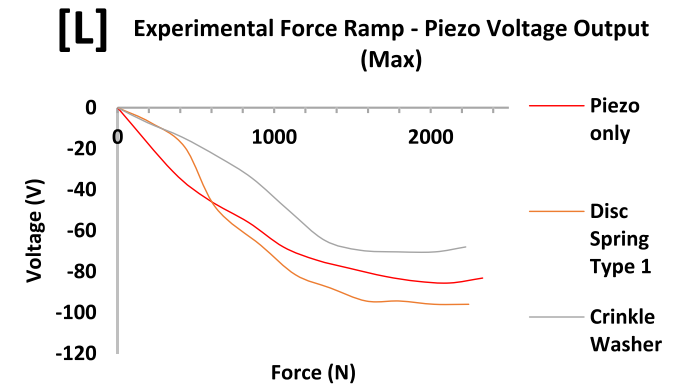
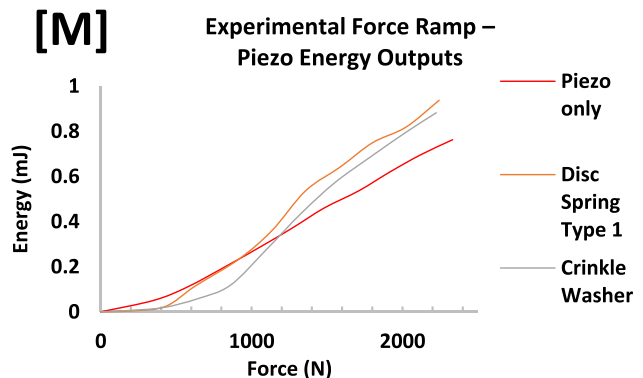


Fig. 7. - Instron Force Ramp Voltage Outputs[L] & Instron Force Ramp Energy Outputs[M].

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.

4.6. Experimental velocity ramp experiment

The variable velocity results (Fig. 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 likely 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.

4.7. Disc spring & crinkle washer piezo disc failures

During the testing, many Piezo Disc samples experienced breakages that caused results to shift, and energy losses in some circumstances. The patterns can be seen (Fig. 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.

5. Discussion

These experiments show that Disc Spring and Crinkle washers can

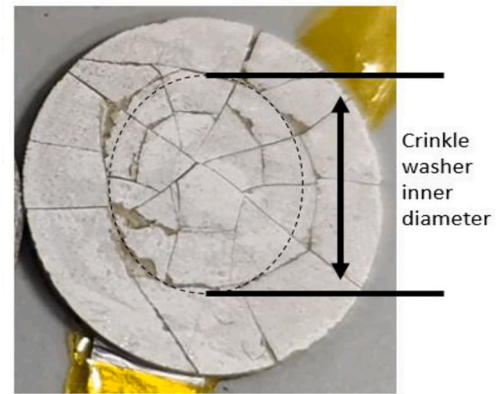


Fig. 9. - PIC255 Piezo Disc Breakages.

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 0.76 mJ (Piezo only) to 0.93 mJ (Disc Spring) from a single hit (Instron Force Ramp) showing a 22% energy increase, with the Crinkle washer achieving 0.88 mJ, a 15% energy increase.

The simulation results showed a maximum of 1.1 mJ from the Disc Spring in the mirrored experimental set up. The Crinkle washer showed a minimal energy of 0.19 mJ 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 (Fig. 3), the maximum energy jumped to 0.61 mJ, 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 0.45 mJ at 1 mm/s compared to the 0.1 mJ from Crinkle Washer which fell under the piezo alone. The simulated Velocity Ramp experiments show a similar trend to the experiments, with the 0.4 mm Disc Spring producing 0.73 mJ at 1 mm/s and the 0.55 mm Crinkle Washer producing 0.13 mJ 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

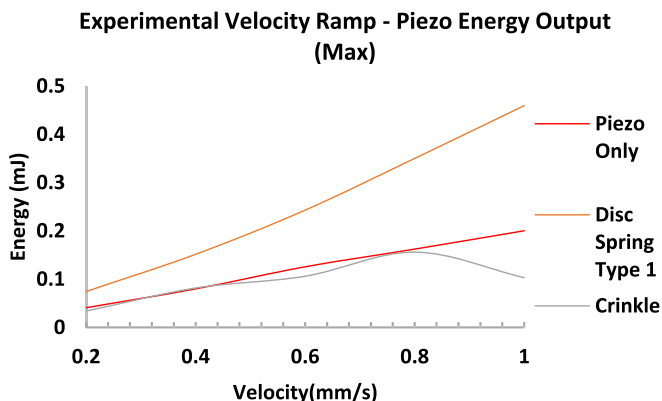


Fig. 8. - Instron Velocity Ramp Energy Outputs.

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 Fig. 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) (Fig. 10) which the disc spring cannot achieve as a single washer. Using the results found in this research, it 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.

6. 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.

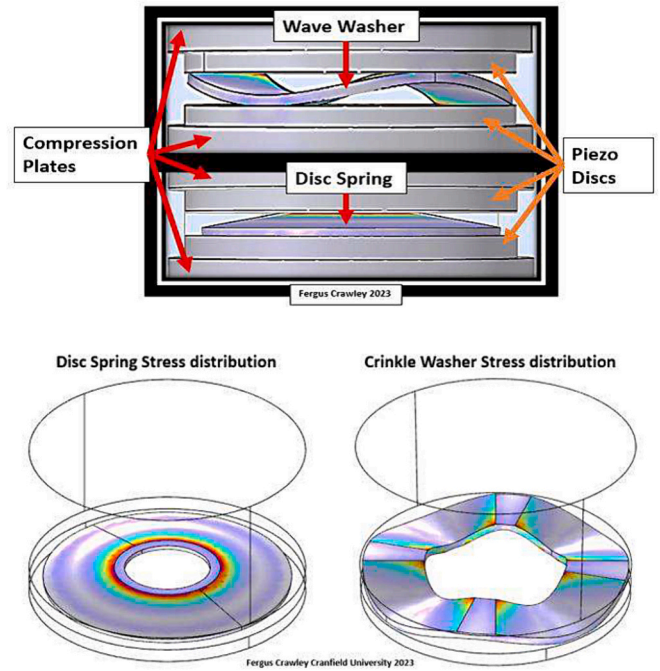


Fig. 10. - Washers in Piezo Stack (dual face), Disc Spring & Crinkle Washer Under Stress.

Declaration of competing interest

Fergus J.E. Crawley reports financial support was provided by Engineering and Physical Sciences Research Council. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary Data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.mne.2024.100245>.

References

- [1] J. Hou, et al., A high-performance mini-generator with average power of 2 W for human motion energy harvesting and wearable electronics applications, *Energy Convers. Manag.* 277 (2023), <https://doi.org/10.1016/j.enconman.2022.116612>. Feb.
- [2] I.C. Das, Md.A. Rahman, S. Dam, Design, simulation & optimization of a MEMS based piezoelectric energy harvester, *Int. J. Sci. Eng. Res.* 12 (07) (2021) 318–329. Jul, <https://doi.org/10.14299/ijser.2021.07.03>.
- [3] C. H. Wong, Z. Dahari, A. Abd Manaf, and M. A. Miskam, "Harvesting raindrop energy with piezoelectrics: A review," *J. Electron. Mater.*, vol. 44, no. 1. Springer Science and Business Media, LLC, pp. 13–21, Jan. 01, 2015. doi: <https://doi.org/10.1007/s11664-014-3443-4>.
- [4] A. Truitt, S.N. Mahmoodi, A review on active wind energy harvesting designs, *Int. J. Precis. Eng. Manuf.* 14 (9) (2013) 1667–1675. Sep, <https://doi.org/10.1007/s12541-013-0226-4>.
- [5] A. Baxy, A. Banerjee, Energy harvesting using the edge-state phenomena, *J. Intell. Mater. Syst. Struct.* 34 (12) (2023) 1–6, <https://doi.org/10.1177/1045389X221142091>.

- [6] J. Y. Cho *et al.*, "Piezoelectric energy harvesting system with magnetic pendulum movement for self-powered safety sensor of trains," *Sens Actuators A Phys*, vol. 250, pp. 210–218, Oct. 2016, doi: <https://doi.org/10.1016/j.sna.2016.09.034>.
- [7] A. Bakytbekov, T.Q. Nguyen, G. Zhang, M.S. Strano, K.N. Salama, A. Shamim, Synergistic multi-source ambient RF and thermal energy harvester for green IoT applications, *Energy Rep.* 9 (2023) 1875–1885, Dec, <https://doi.org/10.1016/j.egy.2023.01.027>.
- [8] A. Bakytbekov, T.Q. Nguyen, C. Huynh, K.N. Salama, A. Shamim, Fully printed 3D cube-shaped multiband fractal rectenna for ambient RF energy harvesting, *Nano Energy* 53 (2018) 587–595, Nov, <https://doi.org/10.1016/j.nanoen.2018.09.022>.
- [9] J. Ghazanfarian, M.M. Mohammadi, K. Uchino, Piezoelectric energy harvesting: A systematic review of reviews, *Actuators* 10 (12) (2021), <https://doi.org/10.3390/ACT10120312>, MDPI, Dec. 01.
- [10] J.H. Lee, J. Kim, T.Y. Kim, M.S. Al Hossain, S.W. Kim, J.H. Kim, All-in-one energy harvesting and storage devices, *J. Mater. Chem. A* 4 (21) (2016) 7983–7999, <https://doi.org/10.1039/c6ta01229a>, Royal Society of Chemistry.
- [11] Z. Wu, T. Cheng, Z.L. Wang, Self-powered sensors and systems based on nanogenerators, *Sensors (Switzerland)* 20 (10) (2020), <https://doi.org/10.3390/s20102925>, May.
- [12] E. Sazonov, P. Pillay, H. Li, D. Curry, Self-powered sensors for monitoring of highway bridges, *IEEE Sensors J.* 9 (11) (2009) 1422–1429, <https://doi.org/10.1109/JSEN.2009.2019333>.
- [13] N. Wu, B. Bao, Q. Wang, Review on engineering structural designs for efficient piezoelectric energy harvesting to obtain high power output, *Eng. Struct.* 235 (2021), <https://doi.org/10.1016/j.engstruct.2021.112068>, Elsevier Ltd, May 15.
- [14] Energy Scavenging for Mobile and Wireless Electronics [Online]. Available, www.computer.org/pervasive, 2005.
- [15] U. Alvarado, A. Juanicorena, I. Adin, B. Sedano, I. Gutiérrez, J. De Nó, Energy harvesting technologies for low-power electronics, *Trans. Emerg. Telecommun. Technol.* 23 (8) (2012) 728–741, <https://doi.org/10.1002/ett.2529>.
- [16] D. Karmakar, K. Majumdar, M. Pal, P.K. Roy, S. Machavarapu, Energy harvesting from pedestrian movement using piezoelectric material, *Mater Today Proc* 57 (2022) 391–397, <https://doi.org/10.1016/j.matpr.2021.12.250>.
- [17] M. Kuna, Fracture mechanics of piezoelectric materials - where are we right now? *Eng. Fract. Mech.* 77 (2) (2010) 309–326, Jan, <https://doi.org/10.1016/j.engfract.2009.03.016>.
- [18] R.M. McMeeking, Towards a fracture mechanics for brittle piezoelectric and dielectric materials, *Int J Fract* 108 (2001) 25–41, <https://doi.org/10.1023/A:1007652001977>.
- [19] M.E. Voutetaki, N.A. Papadopoulos, G.M. Angeli, C.P. Providakis, Investigation of a new experimental method for damage assessment of RC beams failing in shear using piezoelectric transducers, *Eng. Struct.* 114 (2016) 226–240, May, <https://doi.org/10.1016/j.engstruct.2016.02.014>.
- [20] J. Rastegar, R. Murray, C. Pereira, H.-L. Nguyen, Energy-harvesting power sources for gun-fired munitions, in: *Energy Harvesting and Storage: Materials, Devices, and Applications II*, SPIE, May 2011, p. 803517, <https://doi.org/10.1117/12.883438>.
- [21] O. Ganiłova, A. Awaludin, R. Dong, Hybrid energy harvesting based on cymbal and wagon wheel inspiration, *J. Intell. Mater. Syst. Struct.* 28 (19) (2017) 2872–2884, <https://doi.org/10.1177/1045389X17704066>.
- [22] H. Zhao, L. Qin, and J. Ling, "Test and Analysis of Bridge Transducers for Harvesting Energy from Asphalt Pavement," *International Journal of Transportation Science and Technology*, vol. 4, no. 1, pp. 17–28, 2015, doi: 10.1260/2046-0430.4.1.17.
- [23] J.F. Fernfindez, A. Dogan, J.T. Fielding, K. Uchino, R.E. Newnham, Tailoring the performance of ceramic-metal piezocomposite actuators, 'cymbals, Sensors and Actuators A 65 (1998) 228–237, [https://doi.org/10.1016/S0924-4247\(97\)01668-3](https://doi.org/10.1016/S0924-4247(97)01668-3).
- [24] X. Gao, *et al.*, High output power density of a shear-mode piezoelectric energy harvester based on Pb(In1/2Nb1/2)O3-Pb(Mg1/3Nb2/3)O3-PbTiO3 single crystals, *Appl. Energy* 271, no. April (2020) 115193, <https://doi.org/10.1016/j.apenergy.2020.115193>.
- [25] H.W. Kim, *et al.*, Energy harvesting using a piezoelectric 'cymbal' transducer in dynamic environment, *Japanese Journal of Applied Physics, Part 1: Regular Papers and Short Notes and Review Papers* 43 (9 A) (Sep. 2004) 6178–6183, <https://doi.org/10.1143/JJAP.43.6178>.
- [26] C. Mo, D. Arnold, W.C. Kinsel, W.W. Clark, Modeling and experimental validation of unimorph piezoelectric cymbal design in energy harvesting, *J. Intell. Mater. Syst. Struct.* (May 2013) 828–836, <https://doi.org/10.1177/1045389X12463459>.
- [27] R. Esmaeili, *et al.*, Design, modeling, and analysis of a high performance piezoelectric energy harvester for intelligent tires, *Int. J. Energy Res.* 43 (10) (2019) 5199–5212, Aug, <https://doi.org/10.1002/er.4441>.
- [28] E. Dragoni, A CONTRIBUTION TO WAVE SPRING DESIGN, *J Strain Anal Eng Des* 23 (3) (1988) 145–153, <https://doi.org/10.1243/03093247V233145>.
- [29] D. Zhu, I. Duarte-Rabelo, A. Somov, I. N. Ayala-Garcia, An Electromagnetic In-shoe Energy Harvester Using Wave Springs, *IEEE Industrial Cyber-Physical Systems (ICPS)*, IEEE, pp. 659–663, doi:10.1109/ICPHYS.2018.8390785.
- [30] D. Castagnetti, A Belleville-Spring Based Piezoelectric or Electromagnetic Energy Harvester [Online]. Available, <http://asmedigitalcollection.asme.org/SMASIS/proceedings-pdf/SMASIS2014/46155/V002T07A002/4458407/v002t07a002-smas2014-7424.pdf>, 2014.
- [31] S. Aimmamee, C. Phongsitthisak, Analysis of electrical energy harvesting from piezoelectric integrated shallow conical composite shells in metastable configurations using mixed formulation, *Compos. Struct.* 282 (2022), <https://doi.org/10.1016/j.compstruct.2021.115031>, Feb.
- [32] J. Rastegar, R. Murray, C. Pereira, H.-L. Nguyen, Event sensing and energy-harvesting power sources for gun-fired munitions, in: *Active and Passive Smart Structures and Integrated Systems*, SPIE, 2009, p. 72880Z, <https://doi.org/10.1117/12.815513>, Mar. 2009.
- [33] H. Kim, S. Priya, K. Uchino, Modeling of piezoelectric energy harvesting using cymbal transducers, *Japanese Journal of Applied Physics, Part 1: Regular Papers and Short Notes and Review Papers* 45 (7) (Jul. 2006) 5836–5840, <https://doi.org/10.1143/JJAP.45.5836>.
- [34] H. Shekhani, Impedance Frequency Response of a Piezoelectric Element Using COMSOL [Online]. Available, <https://www.ultrasonicaidvisors.com/impedance-frequency-response-of-a-piezoelectric-element-using-comsol>.



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