In: 2023 IEEE 22nd International Conference on Micro and Nanotechnology for Power Generation and Energy Conversion Applications (PowerMEMS), 11-14 December 2023, Abu Dhabi, United Arab Emirates
DOI:10.1109/PowerMEMS59329.2023.10417175

HIGH FORCE COMPRESSION MODE TO SHEAR MODE PIEZOELECTRIC ENERGY HARVESTING

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ABSTRACT

This paper evaluates a novel design of a bridge shear-force structure used to transfer large compressive loads into shear loads on the surface of a piezo disc. The wave/crinkle design can increase the overall number of bridges in a concentric orientation to the circumference with the aim of producing multiple shear force pinch points, changing the shear mode extension path along the piezo discs' axial plane, allowing for tunability, and increasing electrical energy output of a Piezoelectric Energy Harvester (PEH).

KEYWORDS

Piezo, Energy Harvesting, Shear, Compression, Spring Washer, Crinkle Washer, Wave spring

INTRODUCTION

Energy harvesters are gaining traction in electronic devices such as sensors in structural health monitoring [1], [2], wearable electronics, and mobile phones or Internet of Thing (IOT) devices [3], [4]. 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 [5]. 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 [6] Nevertheless, 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 energy to electrical energy.

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 [7], [8] from high drag or friction) or ambient energy that is harvestable such as light, heat and kinetic[9], [10]. 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[11].

The mechanism that activates a piezoelectric material is stress and strain on the internal crystalline structure of the piezoelectric element, which results in electrical polarization 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 has significant influence on 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 [12]–[14]. The challenge comes from the adding of a structural mechanism for load distribution which can take a compression force and direct the forces radially into shearing and thus utilizing the higher charge density of piezo electric shear mode d15.

A piezo element can be activated in a 3-Dimentional sense, and the energy produced is characterised by the piezo materials charge constants (d33, d15, d31) and voltage constants (g33, g15, g31). Simply, if a force is applied to a piezo material, depending on the direction of the input

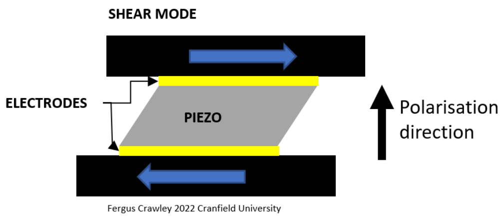

Figure 1; Piezo Shear Mode

force, an electrical field and voltage potential-difference is produced which can be collected by electrodes and stored. Shear force activation (Figure 1) 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. [15] demonstrated the use of Belville washers (Figure 2) for absorbing much high forces combine with a piezoelectrical system and a mass, with the system achieving 1-2 Joules at high force. Further experiments in cymbal transducers have led to the novel shapes such as the wagon wheel [16], from the first conception of rectangular structured bridges [17], and the earlier conception of the cymbal by Fernfindez and Dogan [18]. The curvature structures mentioned distributes the force on a piezoceramic elements face between

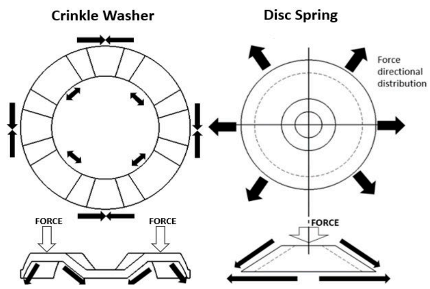

Figure 2; Crinkle Washer & Disc Spring Force Directions compression and shear mode, activating the d33 & d15 [19]. Previous studies using wave springs (reference) have shown that the wave structures are space saving and have a high energy density capacity The crinkle washer which is a simplified version of the wave spring[20], [21] which also shows the characteristics of radial expansion and shearing. (Figure 2) However the crinkle washer is a lesser explored structure compared to that of a cymbal or Belleville disc[22], [23] (disc spring - Figure 2) which have been the focus of much research for shearing piezo elements. Spring discs have seen many variations as mentioned, and the crinkle washer has yet to be tuned and customised to change the amount and distribution of waves in the circumference, even though the force distribution characteristics of crinkle washer can create radial expansion, and pinching when disc springs can only create radial expansion, which could lead to further improved energy conversion.

In this work, both disc spring and crinkle washer were studied by simulation and experiment to understand their mechanisms and performance in converting compression into shear force in piezoelectric disc to develop a high force energy harvesting structure.

METHODOLOGY

Experimental

To create a force input, an Instron 5kN press with programmable force and speed inputs (Figures 3-4) is used to compress a Piezo disc between 2 machined aluminium (Figures 5) 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 3200mm/min and a max load of 5kN set up with 2 flat plates for compression.

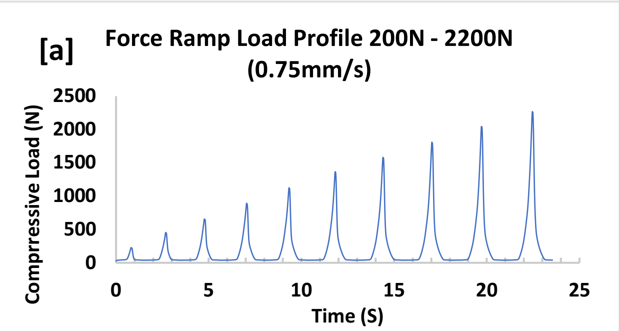

Figure 3; Instron Force Ramp Load Profile

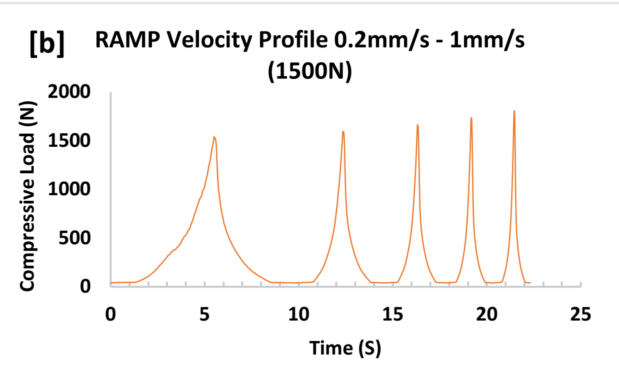

Figure 4; Instron Velocity Ramp Profile

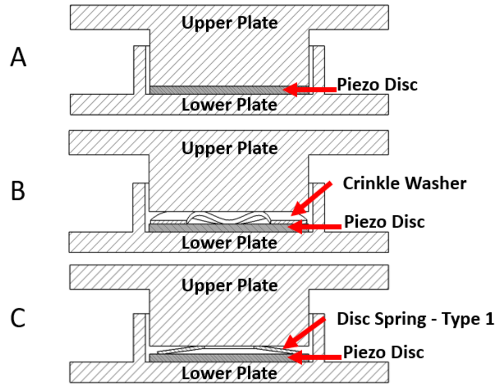

Figure 5; No Washer, Crinkle Washer & Disc Spring in compression plates

The second stage of testing various washer designs on the top piezo face (Figure 5 & 6). 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. 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 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).

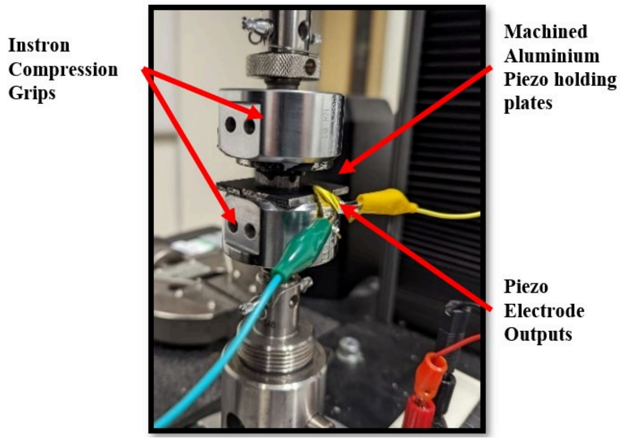

Figure 6; Instron Test Setup

Simulations

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

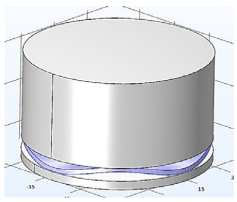

Figure 7; Simulation Setup

profiles from the experiment into the COMSOL Multiphysics (Figure 7).

Results

Simulations

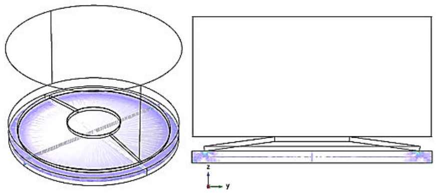

Figure 3; Disc Spring Electric Potential simulation results

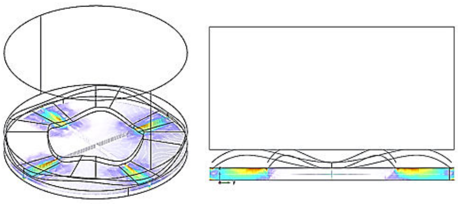

Figure 9; Crinkle Washer Electric Potential simulation results

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The disc spring washer shows a strong indication of electrical potential generated in the horizontal plane (Figure 8) and small areas of electrical potential in the vertical plane with a higher energy output than compression alone. The crinkle washer produced electrical potential in the horizonal plane (Figure 9) where it touches the piezo disc. There is also electrical potential produced in the vertical plane. This indicates that the crinkle washer does convert compression into segments of expansion with shear d15 and compression d33, this is also identified in the increased power output.

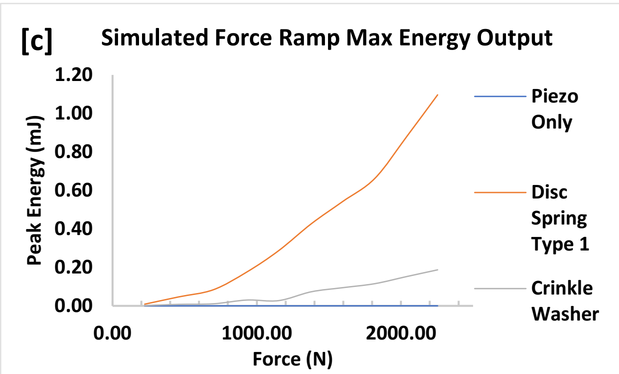

Figure 10; Simulated Force Ramp Energy Outputs

The COMSOL force ramp simulation results (Figure 10) show that the shear activation does increase the voltage and energy over standard compression with the Disc Spring Type 1 having the largest voltage increase. The results (Figures 10) showing large improvements in usable energy produced in comparison of the compression without a structure and the difference in the disc spring and crinkle performance.

The Crinkle Washer has also improved the energy output but not as much as the Disc Spring Type 1. There is a clear effect the Crinkle washer is producing which differs from the Disc Spring in terms of the voltage potentials and field direction, with them being spaced out and perpendicular to each other. The thinner thickness of the disc spring allowing it to deform more easily is a factor that works in its favour, and decreasing the thickness of the crinkle washer and changing the number of waves vastly improved the energy output from 0.2mJ to 0.55mJ (Figure 11).

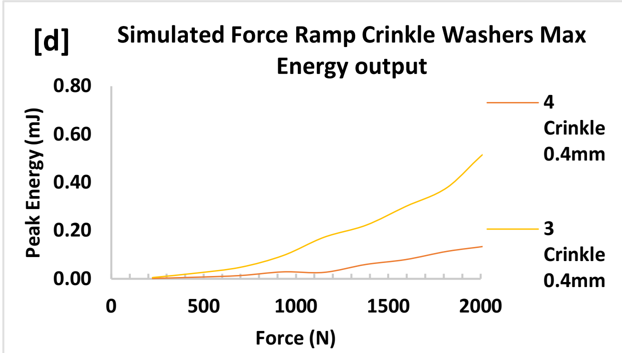

Figure 11; Simulated Force Ramp Energy Outputs (Crinkle washer variations)

For the velocity ramp simulation (Figure 12), the immediate results 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 a side effect of the COMSOL setup, not allowing expansion on the fixed base.

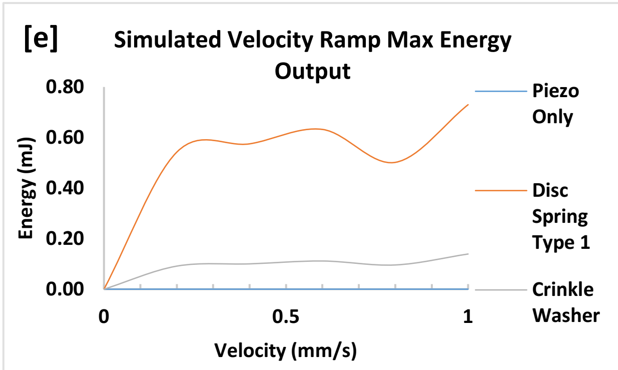

Figure 4; Simulated Velocity Ramp Energy Outputs

Experimental

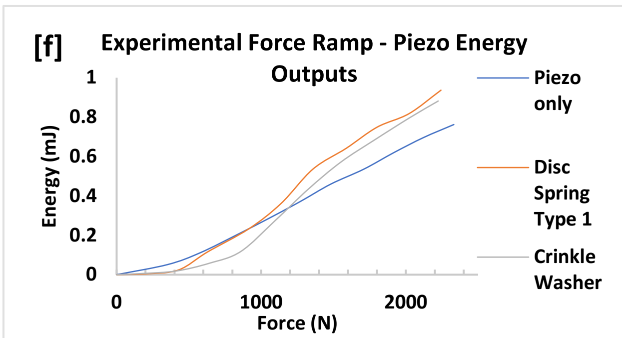

Figure 5; Experimental Force Ramp Energy Outputs

The experimental force ramp experiment energy results (Figure 13) show that the shear structures work in their intended manor and does 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 (a thin layer of silicon), this was not added to the simulations because of increased nodes. The Instron machine itself did not always perfectly repeat each test and time variations did occur due to limited system feedback and sensitivity, especially in the piezo only experiments, which, with no extension, reached the

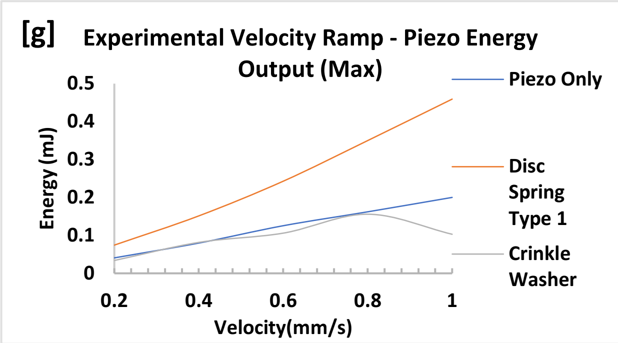

Figure 6; Experimental Velocity Ramp Energy Outputs

high force much faster than the other experiments with washers.

The experimental variable velocity results (figure 14) 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. The experiments produced less energy than the COMSOL simulation, again because of the experimental losses (piezo disc fracture & non-uniform force distribution) 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.

During the testing, many Piezo Disc samples experienced breakages that caused poor results and energy loses in some experiments (figure 15). The patterns can be seen 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.

To counter this in other experiments, smoothing down sharp edges and using adhesive (to prevent loss of grip on

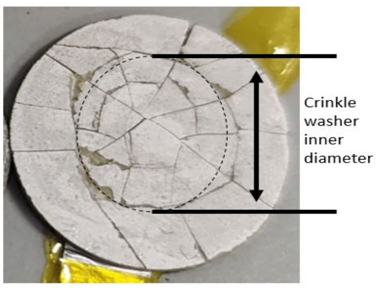

Figure 8; Piezo Disc Failure

the surface) and filling the open central void (Inner radius) would be a step towards preventing this issue. For the outer cracks, radial compression or removing any space between lower case and piezo circumference edges to prevent radial over extension could also be added.

There is also a very important observation that was realised in the simulations (Figure 16). The disc spring washers are limited to activating on one face at time due to the conical shape with the smaller radius having little electrical effect on the attached surface, this means that to multiply this shearing effect on multiple piezo discs in a stack configuration, another disc spring is required, in comparison, the crinkle washer has an offset line of symmetry (depending on the number of waves) that will activate two faces at the same time. Therefore, in applications with confined and limited space, crinkle washer can achieve higher energy density than disc spring, despite of its lower energy conversion efficiency.

Observations

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 electro potential, whereas areas of expansion did not. A decreased spring deflection of the crinkle washer that could be matched to the maximum expansion limit of the piezo disc could stop this mechanical failure from occurring which was the biggest concern.

The potential benefits of using the wave washer in a piezo electric device instead of the disc spring would come from the similar characteristics of radial expansion to that of the disc spring, with the addition of two faces being activated at once verses the need for two-disc springs to create the same effect.

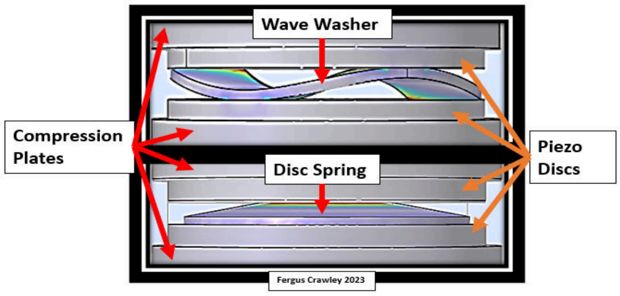

Figure 7; Washers in Piezo Stack

CONCLUSION

The Belville 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 would suggest 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 than the original shape (Figure 11). When designing a stack, decreasing the number and size of the shear structures could increase the power density and decrease the package volume.

Shear structures are an import addition to a piezo element for improving electrical generation when under compression. The Belleville disc is an example of the evolution of the cymbal transducer and the crinkle washer also takes aspects from the original bridge structure, the way that both structures work although being a 90° orientation, could mean that the shapes could further be refined taking the most favourable characteristics of each structure.

AKNOWLEDGEMENTS

This work was supported by Engineering and Physical Science Research Council (EPSRC) funded ICASE project EP/V519509/1.

REFERENCES

[1] A. Baxy and A. Banerjee, "Energy harvesting using the edge-state phenomena," *J Intell Mater Syst Struct*, 2023, doi: 10.1177/1045389X221142091.

[2] 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: 10.1016/j.sna.2016.09.034.

[3] A. Bakytbekov, T. Q. Nguyen, G. Zhang, M. S. Strano, K. N. Salama, and A. Shamim, "Synergistic multi-source ambient RF and thermal energy harvester for green IoT applications," *Energy Reports*, vol. 9, pp. 1875–1885, Dec. 2023, doi: 10.1016/j.egyr.2023.01.027.

[4] A. Bakytbekov, T. Q. Nguyen, C. Huynh, K. N. Salama, and A. Shamim, "Fully printed 3D cube-shaped multiband fractal rectenna for ambient RF energy harvesting," *Nano Energy*, vol. 53, pp. 587–595, Nov. 2018, doi: 10.1016/j.nanoen.2018.09.022.

[5] J. Ghazanfarian, M. M. Mohammadi, and K. Uchino, "Piezoelectric Energy Harvesting: A Systematic Review of Reviews," *Actuators*, vol. 10, no. 12. MDPI, Dec. 01, 2021. doi: 10.3390/ACT10120312.

[6] N. Wu, B. Bao, and Q. Wang, "Review on engineering structural designs for efficient piezoelectric energy harvesting to obtain high power output," *Engineering Structures*, vol. 235. Elsevier Ltd, May 15, 2021. doi: 10.1016/j.engstruct.2021.112068.

[7] 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*, vol. 277, Feb. 2023, doi: 10.1016/j.enconman.2022.116612.

[8] G. De Pasquale, A. Somà, and N. Zampieri, "Design, simulation, and testing of energy harvesters with magnetic suspensions for the generation of electricity from freight train vibrations," *J Comput Nonlinear Dyn*, vol. 7, no. 4, 2012, doi: 10.1115/1.4006920.

[9] C. H. Wong, Z. Dahari, A. Abd Manaf, and M. A. Miskam, "Harvesting raindrop energy with piezoelectrics: A review," *Journal of Electronic Materials*, vol. 44, no. 1. Springer Science and Business Media, LLC, pp. 13–21, Jan. 01, 2015. doi: 10.1007/s11664-014-3443-4.

[10] A. Truitt and S. N. Mahmoodi, "A review on active wind energy harvesting designs," *International Journal of Precision Engineering and Manufacturing*, vol. 14, no. 9, pp. 1667–1675, Sep. 2013, doi: 10.1007/s12541-013-0226-4.

[11] D. Karmakar, K. Majumdar, M. Pal, P. K. Roy, and S. Machavarapu, "Energy harvesting from pedestrian movement using piezoelectric material," *Mater Today Proc*, vol. 57, pp. 391–397, 2022, doi: 10.1016/j.matpr.2021.12.250.

[12] M. Kuna, "Fracture mechanics of piezoelectric materials - Where are we right now?," *Eng Fract Mech*, vol. 77, no. 2, pp. 309–326, Jan. 2010, doi: 10.1016/j.engfracmech.2009.03.016.

[13] R. M. Mcmeeking, "Towards a fracture mechanics for brittle piezoelectric and dielectric materials," 2001.

[14] M. E. Voutetaki, N. A. Papadopoulos, G. M. Angeli, and C. P. Providakis, "Investigation of a new experimental method for damage assessment of RC beams failing in shear using piezoelectric transducers," *Eng Struct*, vol. 114, pp. 226–240, May 2016, doi: 10.1016/j.engstruct.2016.02.014.

[15] J. Rastegar, R. Murray, C. Pereira, and 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. doi: 10.1117/12.883438.

[16] O. Ganilova, A. Awaludin, and R. Dong, "Hybrid energy harvesting based on cymbal and wagon wheel inspiration," *Journal of Intelligent Material Systems and Structures*, vol. 28, no. 19. pp. 2872–2884, 2017. doi: 10.1177/1045389X17704066.

[17] H. Zhao, L. Qin, and J. Ling, "Test and Analysis of Bridge Transducers for Harvesting Energy from Asphalt Pavement," 2015.

[18] J. F. Fernfindez, A. Dogan, J. T. Fielding, K. Uchino, and R. E. Newnham, "Tailoring the performance of ceramic-metal piezocomposite actuators, 'cymbals,'" 1998.

[19] 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*, vol. 271, no. April, p. 115193, 2020, doi: 10.1016/j.apenergy.2020.115193.

[20] D. Zhu, I. Duarte-Rabelo, A. Somov, and I. N. Ayala-Garcia, "An Electromagnetic In-shoe Energy Harvester Using Wave Springs."

[21] "A CONTRIBUTION TO WAVE SPRING DESIGN."

[22] D. Castagnetti, “A BELLEVILLE-SPRING BASED PIEZOELECTRIC OR ELECTROMAGNETIC ENERGY HARVESTER,” 2014. [Online]. Available: http://asmedigitalcollection.asme.org/SMASIS/proceedings-pdf/SMASIS2014/46155/V002T07A002/4458407/v002t07a002-smasis2014-7424.pdf

[23] S. Aimmanee and C. Phongsitthisak, “Analysis of electrical energy harvesting from piezoelectric integrated shallow conical composite shells in metastable configurations using mixed formulation,” *Compos Struct*, vol. 282, Feb. 2022, doi: 10.1016/j.compstruct.2021.115031.

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Crawley, Fergus J. E.

Crawley FJ, Luo Z. (2024) High force compression mode to SHEAR mode piezoelectric energy harvesting. In: 2023 IEEE 22nd International Conference on Micro and Nanotechnology for Power Generation and Energy Conversion Applications (PowerMEMS), 11-14 December 2023, Abu Dhabi, United Arab Emirates

https://doi.org/10.1109/PowerMEMS59329.2023.10417175