EPJ Web of Conferences **343**, 04007 (2025) https://doi.org/10.1051/epjconf/202534304007
AIMACE-2025

Analysis of spiral cantilever structures for hybrid vibration energy harvesters

Nevin Augustine[1]*, *S.Meenatchi* Sundaram[1], *Gabor* Berti Ternyak [2], *Reshma S*[3], *and Veena* Mathew[4]

[1]Department of Instrumentation and Control Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal, Karnataka, India- 576104.
[2]Faculty of Electrical Engineering and Information Technology, Technische Universität Wien, 1040 Vienna, Austria
[3]Department of Mechanical and Industrial Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal, Karnataka, India- 576104.
[4]Department of Electrical and Electronics Engineering, Mar Athanasius College of Engineering-Kothamangalam, APJ Abdul Kalam Technological University, Kerala- India 686666

Abstract. The recent advancement of low power electronic circuits has boosted the importance of vibration energy as a viable source to power such devices. Vibration energy can be harvested using piezoelectric, electromagnetic, or triboelectric transductions. Piezoelectric energy harvesters typically use micro-scale cantilevered beams, but their fundamental frequency often exceeds the range of most mechanical vibrations. While increasing beam length can reduce the frequency, it may lead to impractical designs. Multi-cantilever beam systems offer an alternative by addressing these limitations while maintaining efficiency. This study explores the significance of various orthogonal spiral cantilevers as prominent structures for the design of a hybrid vibration energy harvesting using the piezoelectric-electromagnetic technique. As piezoelectric requires higher stress density, electromagnetic transduction requires a greater displacement to enhance the power output, the analysis is performed for the natural frequency, stress distribution and surface displacement of various beam structures, ensuring stable and efficient energy harvesting. All the structures are simulated in COMSOL Multiphysics and excited with a vibration force of 1g acceleration. Among the analyses on spiral cantilevers, orthogonal spiral cantilevers have shown the best response. The natural frequency of the structures has shown a decreasing trend which varied from 31Hz for structures with the number of beams (n) = 2 to 15.3Hz for structures with n=6. With a displacement of 0.307cms and maximum Von Mises stress of $3.83 \times 10^6 N/m^2$ orthogonal spiral structure with n=5, has proved to be the ideal candidate for VEH in this study. This study serves as the preliminary analysis for the use of spiral structures as prominent structures for developing VEHs, overcoming traditional limitations, and providing a robust solution for harvesting ambient vibrations.

*Corresponding author: nevin.augustine@manipal.edu

1 Introduction

Energy harvesting or energy scavenging is the conversion of the energy available in the surroundings (e.g., thermal and wind energy, solar power, salinity gradients, and kinetic energy into electricity. Solar panels, wind turbines, hydroelectric power etc. are major contributors of higher scale energy. Kinetic energy is yet another source, the research on exploring the possibility of conversion is booming nowadays. In many of the conditions in which available light or thermal energy is insufficient, considering other sources for power generation is imperative. Though the amount of power generated by such sources is less, with the advent of self-powered microdevices in engineering applications over the past decade, research for alternative sources of energy has gained momentum. A few examples of such applications are portable electronics, structural health monitoring, environmental monitoring etc. Harvesting power from ambient mechanical vibrations available is a very promising alternative for such applications. Harvesting vibration energy for powering such devices is the focus of the proposed work. [1-6] The energy harvested from vibration can be either used as a substitute for other sources or in conjunction with the available sources for powering remote devices.

Most of the VEH's are using cantilever structures as the substrate to transfer vibrations from the source to the device. Traditional cantilever structures, while effective, have limitations in energy harvesting due to their relatively narrow bandwidth and inefficiency at lower frequencies. Modified cantilever structures like spiral beams provide enhanced performance by addressing these limitations. These advanced designs help in improving energy capture by increasing flexibility, tuning resonance frequencies, and offering multi-directional response to vibrations. This makes them capable of harvesting energy for powering low-powered devices in medicine, military equipment, and wireless communications. Especially, in the field of medicine where devices such as pacemakers are used quite widely, it is essential to find a way to replace the batteries so that it would not lead to unnecessary surgery for the patient in the long run. Energy harvesters are replacing batteries with very low-powered electronic devices, either by using only piezoelectric or electromagnetic vibration energy harvesters or hybrid ones, which combine both mechanisms and are gaining global attention due to their inexhaustible nature and better efficiency. Almost all the energy harvesters which have been designed earlier have shown great results, however at the same time they have faced problems such as bulk volume and higher frequency.

Tao Dong et al. [1] proposed a MEMS-based spiral piezoelectric harvester. Using FEM simulations, the design's intrinsic properties are studied, demonstrating its sensitivity to vibrations. Analytical models predicted power output in the tens of mW range under a 5g acceleration. Mohd Fauzi Rahman et al. [2] developed a hybrid harvester combining piezoelectric and electromagnetic mechanisms. Their design produced 2.3 mW (piezoelectric, 60 kΩ) and 3.5 mW (electromagnetic, 40 Ω) under 15 Hz and 1g acceleration, showcasing the advantages of dual-transduction systems. Wen Liu et al. [3] discusses about a cantilever structure used as spiral geometry in which they have used copper and silicon as proof mass. The proof mass chosen reduces the natural frequency significantly enabling it to be used in low frequency applications. Tikani et al. [4] optimized a spiral-shaped piezoelectric energy harvester using the Taguchi method, enabling improved design robustness and enhanced output performance. Their study demonstrated that optimized geometric parameters yield closely spaced resonant frequencies, expanding the operational bandwidth and validating the effectiveness of statistical optimization techniques. Tao Li and Pooi See Lee [5] provided an extensive review of advancements in piezoelectric energy harvesting, covering developments in materials, structural designs, and application-specific integration. Their work highlights how innovations in geometry and material engineering collectively enhance the efficiency and applicability of modern harvesters. Miah A. H. Halim

et al. [6] designed and experimentally validated a human-limb-driven electromagnetic harvester employing frequency up-conversion. Their system efficiently converted low-frequency biomechanical motion into higher-frequency oscillations suitable for electromagnetic induction, demonstrating strong potential for wearable energy-harvesting applications. Udvardi et al. [7] developed a spiral-shaped piezoelectric MEMS cantilever array for fully implantable hearing systems. Operating in the 300–400 Hz range, the array produced voltage outputs of 3–10 mV, meeting the requirements for miniaturized biomedical devices. Santos, Hobeck, and Inman [8] conducted theoretical and experimental studies on orthogonal spiral structures, validating lumped-parameter predictions of natural frequencies and confirming the design's suitability for compact, low-frequency energy harvesters. Bai et al. [9] introduced a multi-modal spiral cantilever with magnetic coupling, generating multiple resonant peaks between 15–70 Hz and enabling wideband vibration energy harvesting. Santos, Hobeck, and Inman [10] also developed an analytical model for orthogonal spiral structures, offering predictive relationships between geometry and dynamic behaviour that aid in design and optimization. Challa, Prasad, and Fisher [11] presented a coupled piezoelectric–electromagnetic hybrid harvesting technique that utilizes damping matching to enhance total power output. Their dual-transduction approach demonstrated significantly improved energy extraction efficiency compared to single-mode systems, highlighting the advantages of combining piezoelectric and electromagnetic mechanisms in hybrid harvesters. Thus, multi-transduction mechanisms use both piezoelectric and electromagnetic conversions, to ensure maximum piezoelectric output by matching the lengths of the piezoelectric layer and the substrate, optimizing the stress distribution for enhanced energy conversion. Additionally, a magnet which serves as proof mass moves through a copper coil wound around during vibrations that generate power by electromagnetic induction as well. This makes the harvester hybrid.

This work reports the analysis of spiral cantilever structures for hybrid vibration energy harvester (VEH) designs with both piezoelectric as well as electromagnetic energy harvesting mechanisms that can provide more energy output with smaller volume and lower frequency. The primary requirement is to get an optimal cantilever structure with minimum natural frequency, greater displacement and stress profile when excited with random vibration. The work discusses the analysis of various orthogonal spiral structures to be used as a potential structure for the VEH design.

2 Simulation studies on spiral cantilever structures for VEHs

To evaluate the performance of orthogonal and double orthogonal spiral structures for the proposed VEH, simulation studies are conducted using COMSOL Multiphysics. The goal of the research is to find out the natural frequency of the structures, obtain the stress distribution at the surface of the structures and know the displacement profile at the tip or the free end when the structures are excited with random vibrations. As vibrations are simulated with body load in COMSOL, a body load of 1g constant acceleration is given for the frequency response analysis. By analysing the natural frequency of the structures together with the stress and displacement profiles, the study aims to optimize the design for maximum energy harvesting efficiency while ensuring structural integrity.

2.1 Single Cantilever Beam

Cantilever beams are ideal for vibration energy harvesting due to their ability to convert mechanical vibrations into electrical energy through transducers like piezoelectric, electromagnetic, or electrostatic mechanisms. When exposed to vibrations, the beam oscillates, generating strain that can be efficiently converted into electrical output, especially

at resonance where maximum displacement occurs. Cantilever beams are generated in COMSOL and the eigenfrequency analysis, von Mises stress analysis, and frequency response are obtained. Fig. 1 shows the Von Mises stress distribution of the model generated in a cross-section of 10cmx0.8cm with a thickness of 1mm at a frequency of 65Hz when exited with a body load of 1g acceleration. The thickness of the structure is fixed at 1mm for fabrication studies in future, where fabrication can be done in standard aluminium sheets of 1mm thickness. The simulation studies are carried out with varied widths of the cantilever beam varying from 5 mm to 20 mm. The objective of the study is to get a better dimension to increase the tip displacement and the maximum stress in the domain, with a minimal natural frequency of vibration for using the beams for vibration energy harvesting applications.

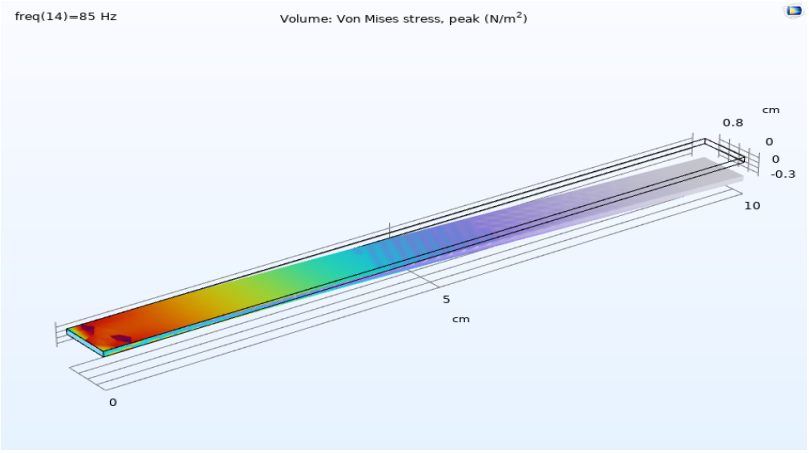

Fig.1 Von Mises stress distribution of cantilever beam with w=0.8mm at 65Hz VEH, simulation studies are conducted using COMSOL Multiphysics.

2.2 Orthogonal Cantilever Structure

Orthogonal spiral-shaped cantilevers are advanced design variations used to enhance performance in vibration-based applications, particularly in energy harvesting and sensing. These cantilevers feature a spiral geometry arranged in orthogonal planes, which allows for greater flexibility and multi-directional sensitivity to vibrations.

Orthogonal spiral-shaped cantilever beams are generated in COMSOL and the eigenfrequency analysis, von Mises stress analysis, and frequency response are obtained. One end of the structure is fixed, and the rest is free to vibrate. Fig.2 shows the Von Mises stress distribution at the natural frequencies of the orthogonal spiral structures analysed when excited with a body load of 1g acceleration. All models are analysed in a cross-section of 10cmx10cm with a thickness of 1mm. The width of all beams is 8mm as from the data obtained from a single cantilever beam, 8mm has given the best performance. The thickness of the structure is fixed at 1mm for fabrication studies in future. The number of turns (n) of the spiral structure is taken as a parameter, and it varies from n=2 to n=6.

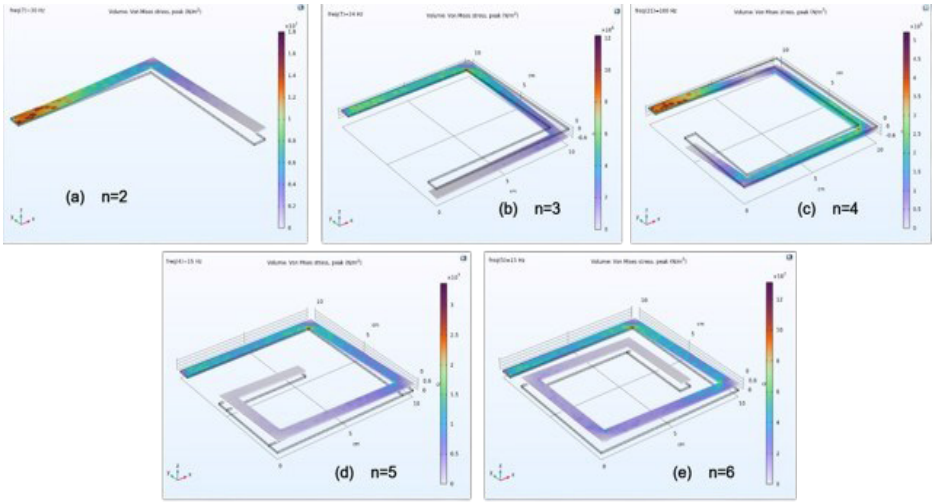

Fig.2. Von Mises stress distribution of various orthogonal spiral beams at their natural frequencies.

2.3 Double Orthogonal Cantilever Structure

Double orthogonal spiral-shaped cantilever structures are advanced designs used to enhance vibration energy harvesting and sensing applications. These structures feature two interconnected spiral beams arranged orthogonally, allowing them to capture vibrations from multiple directions. Double orthogonal spiral-shaped cantilever beams are analysed in COMSOL and the eigenfrequency analysis, von Mises stress analysis, and frequency response are obtained. Two ends to the structures are fixed and the rest is free to vibrate. Fig.3 shows the Von Mises stress distribution at the natural frequencies of the orthogonal spiral structures analysed when exited with a body load of 1g acceleration. All models are analysed in a cross-section of 10cmx10cm with a thickness of 1mm. The width of all beams is 8mm from the data obtained from a single cantilever beam, 8mm has given the best performance. The thickness of the structure is fixed at 1mm for fabrication studies in future. The number of turns (n) of the spiral structure is taken as a parameter, and it varies from n=2 to n=6.

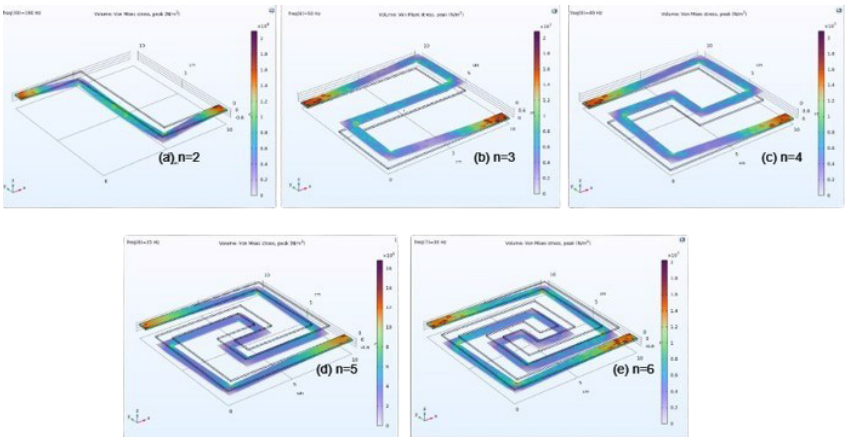

Fig.3 Von Mises stress distribution of various double orthogonal spiral beams at their natural frequencies.

3 Results

This study aimed to explore and compare the structural performance of different cantilever designs for vibration energy harvesting applications under random vibration excitation. Simple cantilever beams, orthogonal spiral beams, and double orthogonal spiral beams are analysed using COMSOL Multiphysics. A structure is best suited for harnessing low-frequency vibrations if the structure's natural frequency matches the excitation frequency. Thus, a low natural frequency is preferred for vibration energy harvesting structures. As mechanical energy of the vibrations can be converted to electrical energy either by piezoelectric or electromagnetic transduction techniques, the stress distribution on the structure should be maximum, which could give a higher piezoelectric output, together with a greater tip displacement, which can give a greater electromagnetic output.

3.1 Natural Frequency Distribution

For harnessing vibration energy from ambient vibrations like human motion, vehicular movement, vibration of electronic devices, waves in the ocean etc., the harvester must possess a lower natural frequency, which would enable maximum vibration transfer from the source to the structure. At resonance, the energy harvester achieves maximum amplitude, resulting in higher energy output. The natural frequencies of the analysed structures revealed significant variation based on the geometry. Fig.4 shows the consolidated distribution of natural frequencies of the different structures analysed. The simple cantilever beam exhibited the highest natural frequency, indicating a higher stiffness. In contrast, the orthogonal spiral and double orthogonal spiral beams showed progressively lower natural frequencies, making them more suited for harvesting energy from low-frequency ambient vibrations. Among these orthogonal spiral structures have a lesser distribution of natural frequency compared to single beam and double orthogonal beam, making it the best structure in the comparative analysis.

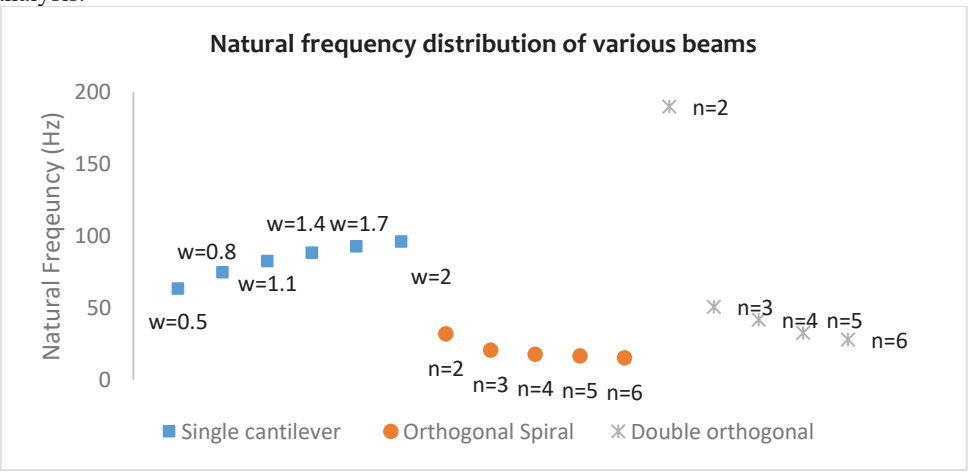

Fig.4 Distribution of natural frequencies of the different structures analysed.

For single cantilever beams, the natural frequency increases with beam width (w), ranging from approximately 63.38 Hz to 96.14 Hz as w increases from 0.5 to 2.0. In contrast, orthogonal spiral structures exhibit a marked reduction in natural frequency with an increasing number of turns (n), stabilizing below 20 Hz for higher values of n. Structure with n=6 has shown the minimum natural frequency of 15.34 Hz in the overall study conducted. These lower frequencies highlight their suitability for low-frequency vibration energy

harvesting. The natural frequencies of the double orthogonal spiral structures are little higher than that of single orthogonal structures, which decreases by small amounts when n increases. The lowest natural frequency was recorded as 28.08Hz for n=6. From this analysis the inference can be derived as orthogonal spiral structures show the minimum natural frequency which makes them prominent structures for vibration energy harvesting applications.

3.2 Maximum Von Mises Stress

Piezoelectric strips for VEH's must be placed on cantilever structures where stress is maximum. The von mises stress analysis in COMOSL gives insights on the regions on the beam where stress is maximum when excited by a load. The regions can be identified using this for incorporating Piezo elements at a later stage of the harvester design. Since higher stress leads to greater deformation in piezoelectric materials, maximizing stress—while remaining within the elastic limits—is key to generating higher electrical output. By carefully designing the structure to localize stress without exceeding the material's allowable limits, both durability and energy conversion efficiency can be improved, ensuring effective utilization of ambient vibrations without risking structural failure. Von Mises stress Vs frequency plot of the different single cantilever beams, orthogonal spiral structures and double orthogonal spiral structures are shown in Figs.5,6 and 7 respectively. Fig.8 shows the consolidated distribution of maximum Von Mises stress of the different structures analysed. The orthogonal and double orthogonal spiral beams exhibited higher stress concentrations compared to the simple cantilever beam, particularly in regions crucial for piezoelectric transduction. A double orthogonal spiral structure with n=4 has exhibited a maximum stress value of 3.88 x106N/m2. However orthogonal spiral structure with n=5 has a maximum stress of 3.83 x106 N/m2 which is comparable to that of a double orthogonal structure. However, both these structures have a better stress distribution when compared to simple cantilever structures which suggests their potential for enhanced energy conversion efficiency.

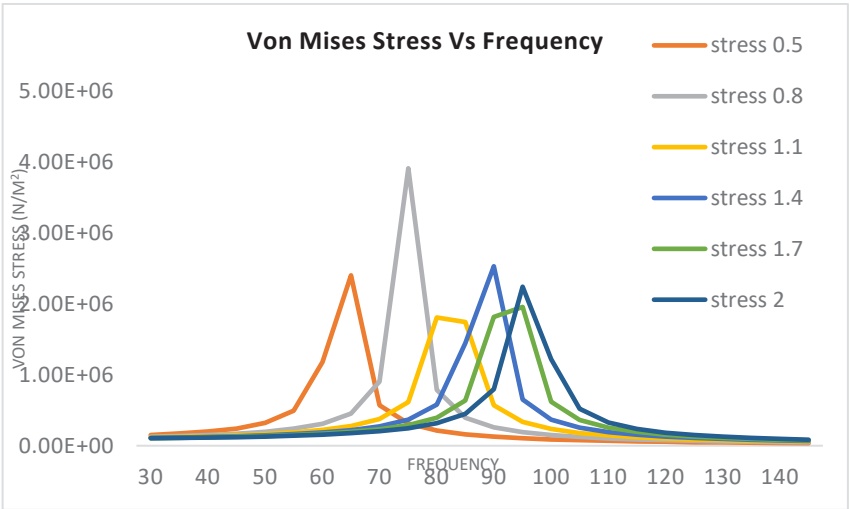

Fig. 5 Von Mises stress Vs frequency of different simple cantilevers analysed.

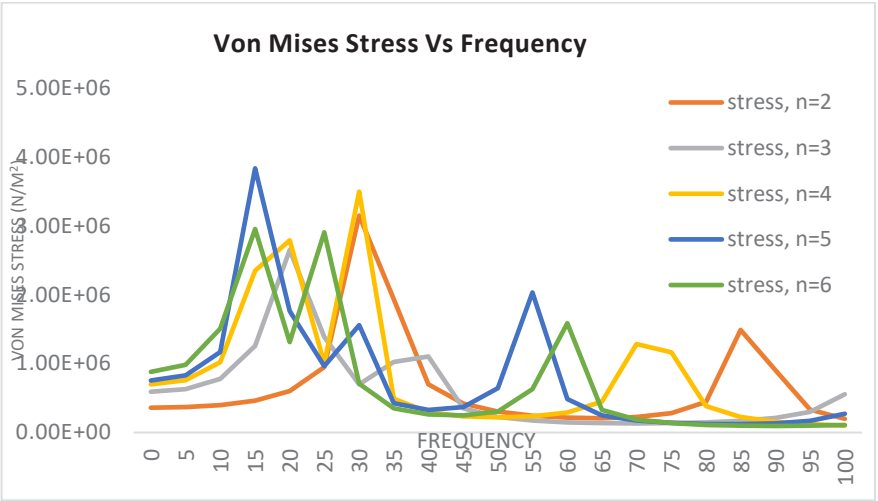

Fig. 6 Von Mises stress Vs frequency of different orthogonal cantilevers analysed.

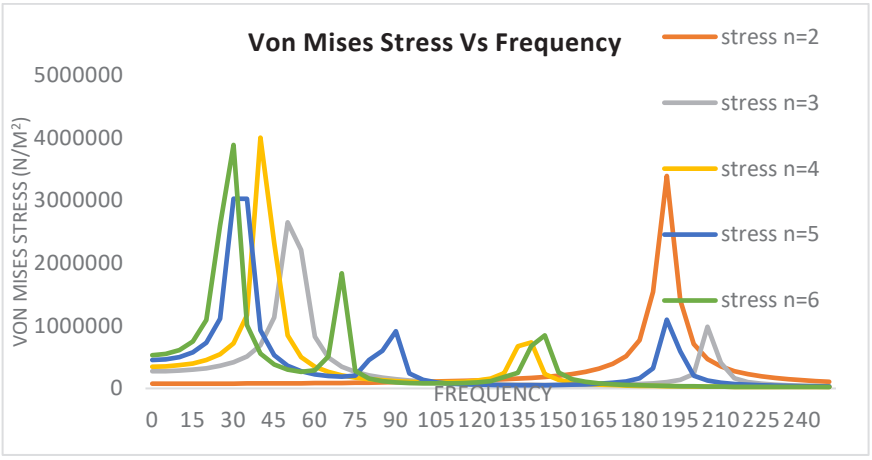

Fig.7 Von Mises stress Vs frequency of different double orthogonal cantilevers analysed.

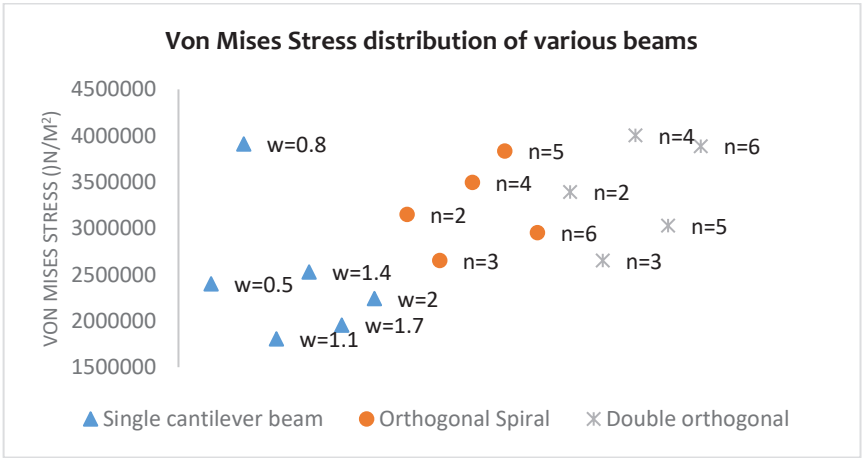

Fig.8 Distribution of maximum Von Mises stress of all the structures analysed.

3.3 Maximum Surface Displacement

Surface displacement analysis is essential in electromagnetic energy harvesting to evaluate the relative motion between the coil and magnet, which directly affects the induced voltage. For increasing the power output through such method, the tip displacement of the structure should be maximised which would in turn increase the rate of magnetic flux.Fig.9.10 and 11 shows the surface displacement versus frequency responses for the single cantilever beams, orthogonal spiral structures, and double orthogonal spiral structures respectively. A consolidated comparison of the maximum surface displacement across all analysed structures is shown in Fug.12. For the single cantilever beam, displacement progressively increases as the width factor (w) increases. At w = 0.8, the displacement remains very low (0.055 cm), indicating strong structural stiffness. The tip displacement is significantly on the higher side for orthogonal structures with an increase in n. Lower values of n (e.g., 2 or 3) yield moderate displacement, whereas the structure with n = 5 exhibits the highest displacement of 0.304 cm. A similar trend is observed in the double orthogonal spiral structures, where displacement continues to rise with increasing design parameters. Thus, the analysis on the surface displacement of the structures shows that both the orthogonal and double orthogonal spiral beams have achieved a greater amount of tip displacement compared to normal cantilever structures. The orthogonal spiral beam achieved the highest displacement, indicating its superior compliance and energy-harvesting potential.

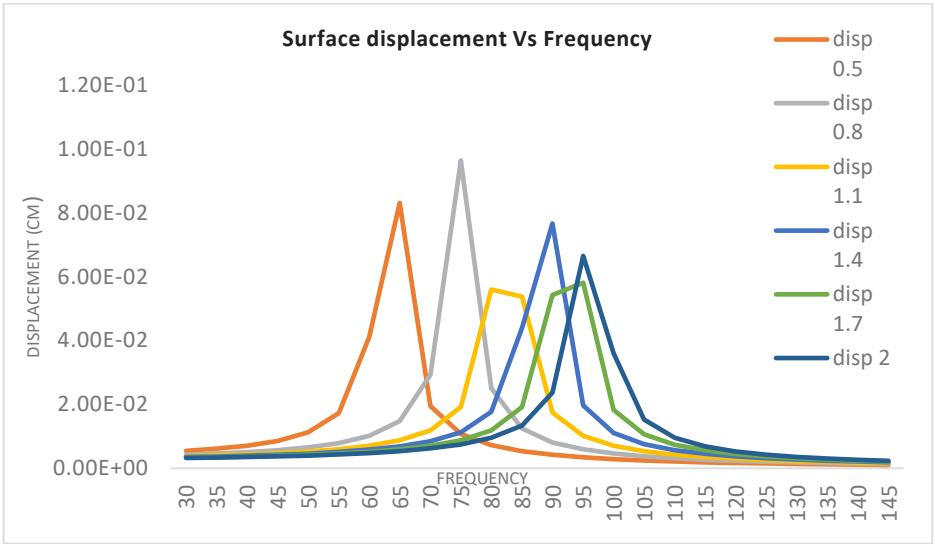

Fig.9 Maximum displacement of top surface Vs frequency of single cantilever beams

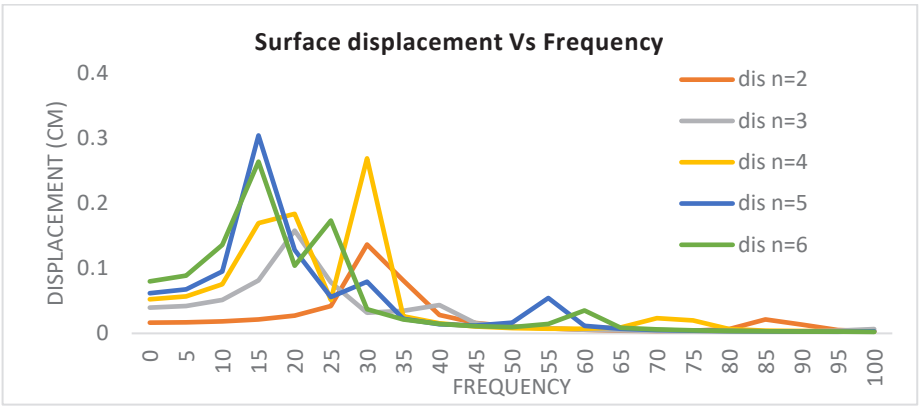

Fig.10 Maximum displacement of top surface Vs frequency of different orthogonal cantilevers analysed

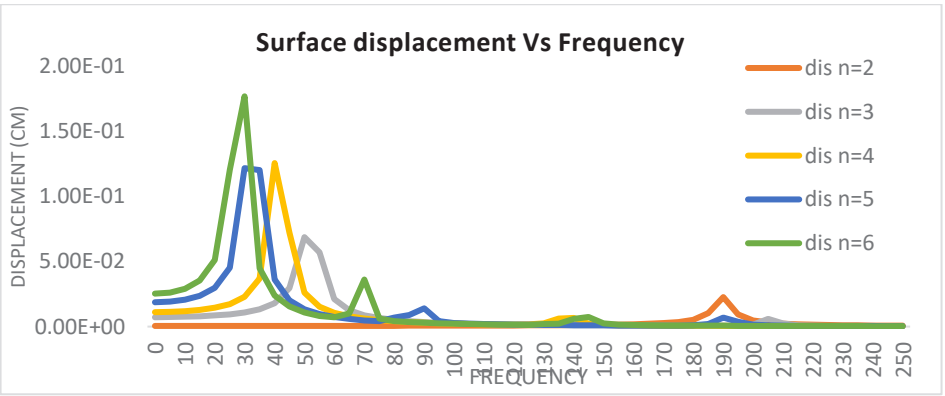

Fig.11 Maximum displacement of top surface Vs frequency of different double orthogonal cantilevers analysed

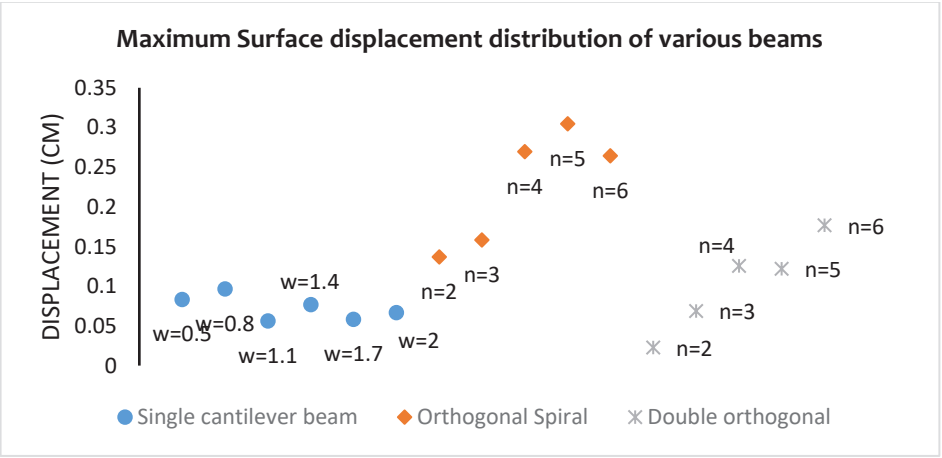

Fig.12 Distribution of maximum surface displacement of all the structures analysed

3.4 Comparative Analysis of Cantilever Structures

The comparative analysis of the performance of the three types of cantilever structures regarding natural frequency, maximum stress distribution and maximum tip displacement is summarized in Table 1. The orthogonal structure with 5 turns showed a very less natural frequency of 16.7Hz compared to the next higher natural frequency of 28.08Hz shown by the double orthogonal spiral structure. When coming to maximum surface stress quantized as Von-Mises stress, Double orthogonal structures have shown a better performance with a stress of 3886900 N/m². The tip displacement is, however, greater for orthogonal structures, showing a far better value of 0.30437 compared to a double orthogonal structure with a displacement of 0.17cm. Thus, comparative analysis shows that orthogonal and double orthogonal structures are a great choice compared to a normal cantilever beam for using them as potential structures for energy harvesting applications.

Table 1: Quantitative Comparison of Cantilever Structures

Structure Type	Natural Frequency (Hz)	Maximum Von Mises Stress (N/m²)	Maximum Displacement (cm)
Simple Cantilever Beam (w=0.5)	63.387	2400200	0.083053
Orthogonal Spiral Structure (n=5)	16.7	3834200	0.30437
Double Orthogonal Spiral (n=6)	28.08	3886900	0.17667

4 Conclusion

From the analysis of three different cantilever structures, an orthogonal spiral structure with 5 turns has come out as the best structure, with a minimum natural frequency of 16.7Hz making it the best structure for low-frequency applications. Also, it stands good with the greatest tip displacement near the natural frequency to a value of 0.3047cm compared to the next highest value of 0.17667cm exhibited by a double orthogonal spiral structure. The next structure which is a double orthogonal spiral structure fixed at two ends, showed the best stress distribution with a maximum Von-Mises stress of 3886900 N/m² which makes it the best candidate for the piezoelectric energy transduction mechanism. However, this comes at the price of a slightly greater natural frequency of 28.08 Hz and a lesser displacement when compared to orthogonal structures. The simple cantilever beam has come out as the least performer with a high natural frequency of 63.387Hz, a lesser stress as well as tip displacement. Thus, the analysis shows that orthogonal and double orthogonal structures are far better structures compared to simple cantilever beams for using them as structures for energy harvesting applications.

5 Future scope of work

This study is a limited analysis of three structures with only three parameters considered. However, a parametric analysis would provide a better insight into the performance and pave

the way for optimizing and implementing orthogonal spiral structures for vibration energy harvesting. Also, experimental analysis by fabricating the structure using any aluminium as the material and analysis of the natural frequency, displacement and stress distribution would validate the simulation studies. The integration of hybrid energy harvesting mechanisms, combining piezoelectric and electromagnetic transduction, presents an opportunity to enhance energy output and broaden application domains. Future scope will be integrating these transduction mechanisms and evaluating the power generation efficiency of the device. Further the power generated can be fed to real world applications of powering wearable electronics circuits, micro sensors, micropower grids etc.

References

1. T. Dong, E. Halvorsen, Z. Yang, A Mems-Based Spiral Piezoelectric Energy Harvester, *Proceedings of PowerMEMS 2008+ microEMS 2008*, Sendai, Japan, November 9-12, (2008).
2. M. F. A. Rahman, S. L. Kok, N. M. Ali, R. A. Ham-zah, K. A. A. Aziz, Hybrid Vibration Energy Harvester Based On Piezoelectric and Electromagnetic Transduction Mechanism, *2013 IEEE Conference on CEAT*, (2013).
3. W. Liu, M. Han, X. Sun, H. Zhang, Fabrication of Spiral-Shaped PVDF Cantilever Based Vibration Energy Harvester, *Proceedings of the 9th IEEE International Conference on Nano/Micro Engineered and Molecular Systems* April 13-16, Hawaii, USA, (2014).
4. R. Tikani, L. Torfenezhad, M. Mousavi and S. Ziaei-Rad, Optimization of spiral-shaped piezoelectric energy harvester using Taguchi method, *Journal of Vibration and Control*, 1–8, (2017). https://doi.org/10.1177/1077546317727146
5. T. Li and P. S. Lee, Piezoelectric Energy Harvesting Technology: From Materials, Structures, to Applications, *Small Structures*, 3(3), (2022).
6. M. A. Halim, H. Cho, J. Y. Park, Design and experiment of a human-limb driven, frequency up-converted electromagnetic energy harvester, *Journal of Energy Conversion and Management*, 106, 393–404, (2015).
7. P. Udvardi, J. Radó, A. Straszner, J. Ferencz, Z. Hajnal, S. Soleimani, M. Schneider, U. Schmid, P. Révész, and J. Volk, Spiral-Shaped Piezoelectric MEMS Cantilever Array for Fully Implantable Hearing Systems, *Micromachines*, 8, 265, (2017).
8. A. A. Dos Santos, J. D. Hobeck and D. J. Inman, Orthogonal spiral structures for energy harvesting applications: Theoretical and experimental analysis, *Journal of Intelligent Material Systems and Structures*, 29(9), 1900–1912, (2018).
9. X. Bai, Y. Wen, P. Li, J. Yang, X. Peng, X. Yue, Multi-modal vibra-tion energy harvesting utilizing spiral cantilever with magnetic coupling, *Sensors and Actuators A*, 209, 78-86, (2014).
10. A. A. Santos, J. D. Hobeck, D. J. Inman, Analytical modelling of orthogonal spiral structures, *Smart Mater. Struct.* 25, 115017 (12pp), (2016). https://doi.org/10.1088/0964-1726/25/11/115017
11. V. R. Challa, M. G. Prasad and F. T. Fisher, A coupled piezoelectric–electromagnetic energy harvesting technique for achieving increased power output through damping matching, *Smart Materials and Structures*, 18, 095009, (2009).