Harvesting Energy from Flexible Structures Using Piezoelectric Technology

REPORT (MIN-300)
LAB BASED PROJECT

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1) ABSTRACT

This study investigates energy harvesting through piezoelectric materials utilizing flag flutter, a phenomenon where flags oscillate in response to fluid flow. By embedding piezoelectric elements within flags, mechanical stress induced by fluttering motion can generate electrical energy through the piezoelectric effect. Experimental research focuses on optimizing piezoelectric element placement, configuration, and material properties to enhance energy conversion efficiency. Additionally, this study investigates energy harvesting through piezoelectric materials utilizing flag flutter, a phenomenon where flags oscillate in response to fluid flow. By embedding piezoelectric elements within flags, mechanical stress induced by fluttering motion can generate electrical energy through the piezoelectric effect. Experimental research focuses on optimizing piezoelectric element placement, configuration, and material properties to enhance energy conversion efficiency. Additionally, the impact of flag geometry, dimensions is analysed. A Prototype is developed to validate the feasibility and effectiveness of flag-based piezoelectric energy harvesting systems. Results indicate the potential of flag flutter as a promising source of mechanical energy for sustainable power generation. The study contributes valuable insights into design considerations and optimization strategies for maximizing energy conversion efficiency in such systems. Pact of flag geometry, dimensions is analysed. A Prototype is developed to validate the feasibility and effectiveness of flag-based piezoelectric energy harvesting systems. Results indicate the potential of flag flutter as a promising source of mechanical energy for sustainable power generation. The study contributes valuable insights into design considerations and optimization strategies for maximizing energy conversion efficiency in such systems.

2) INTRODUCTION

The world is at a critical juncture in its quest for sustainable energy solutions. With finite fossil fuel reserves and growing concerns over environmental degradation, there is an urgent need to harness alternative sources of power. Piezoelectricity, a phenomenon rooted in the ability of certain materials to generate an electric charge in response to mechanical stress, offers a promising avenue for sustainable energy generation.

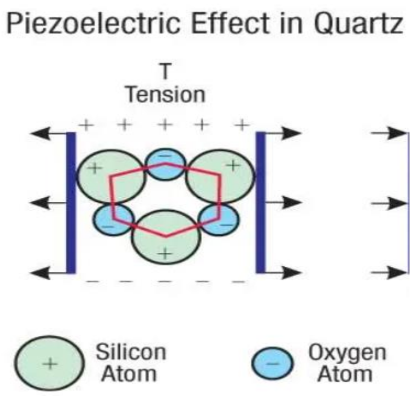
In this study, we embark on a journey to develop a prototype that capitalizes on the piezoelectric effect embedded within flexible materials. Our objective is to create a robust system capable of generating significant voltage output from mechanical deformations. The envisioned prototype holds promise as a scalable solution for fulfilling small-scale energy needs in various applications, ranging from wearable electronics to structural monitoring systems.

Key to the success of our endeavour is the careful selection and characterization of flexible materials with inherent piezoelectric properties. By systematically exploring a diverse array of materials, including but not limited to polymers, composites, and textiles, we aim to identify the most efficient candidates for energy conversion. Through rigorous experimentation and analysis, we seek to elucidate the influence of material composition, structure, and mechanical properties on the performance of piezoelectric generators.

3) LITERATURE REVIEW

I) Piezoelectric Material

Piezoelectric materials are a class of materials that can generate an electric charge in response to mechanical stress (the direct piezoelectric effect) or deform in response to an applied electric field (the inverse piezoelectric effect). This unique property makes them valuable for various applications in sensors, actuators, energy harvesting, and more.



When it is subjected to mechanical stress, such as compression or bending, these crystal structure deforms, causing a displacement of positive and negative charges within the material. This displacement results in the accumulation of electric charge on the material's surface, generating an electric potential across it. This potential difference can then drive an electric current when the material is connected to a circuit.

1.Ref. peizo

Some common piezoelectric materials include:

Quartz: Quartz is one of the most well-known natural piezoelectric materials. It's commonly used in oscillators, sensors, and timing devices due to its stable piezoelectric properties.

2.Ref. piezoelectric-material

Lead Zirconate Titanate (PZT): PZT is a synthetic ceramic material widely used in industrial and consumer applications due to its high piezoelectric coefficients and versatility. It's used in sensors, actuators, ultrasound transducers, and energy harvesters.

II) Physics behind fluttering

The three non-dimensional parameters that govern the stability of the flapping flag are the structure-to-fluid mass ratio (μ), the Reynolds number (Re), and the non-dimensional bending rigidity (KB). These parameters play a crucial role in determining the stability and response of the flapping flag, with the mass ratio, Reynolds number, and bending rigidity influencing the structural restoring force, flow-induced tension, and the overall dynamics of the system

The tension in the flag affects the realization of flapping instability by becoming very significant during active flapping, limiting the flapping amplitude. The dynamically induced tension is a stabilizing effect, while the centrifugal force is a destabilizing effect of the Kelvin–Helmholtz instability. Both of these effects are scaled by the total inertia, which is the sum of the structural mass and added mass. Additionally, the added mass, which is advected with the flow velocity, influences the system differently from the structural mass and brings about the flapping instability. However, this instability cannot be realized on a massless body. Therefore, the tension in the flag plays a crucial role in determining the stability and response of the flapping dynamics.

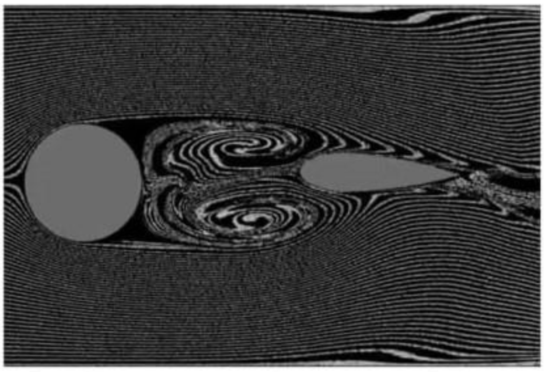
Parameters which will affect the flapping of flag Ref1 (YUE, 22 May 2007)

$$u = \frac{\rho_s h}{\rho_f L} \; , Re = \frac{V*L}{v} \; , \; k_B = \frac{EI}{\rho_f V^2 L^3}$$

where ρ_s is density of solid
ρ_f is density of fluid,
Re is Reynold no.
EI is Bending Rigidity
v is Kinematic viscocity
k_B is a non- dimensional constant
V is flow velocity

3.Ref.stability and drag of a flexible sheet under in-plane tension in uniform flow 4.Ref1:B. Connell and D. Yue

Effect of bluff body:



When a flag flutters, it's essentially undergoing a complex interplay of aerodynamic forces. Adding a bluff body, such as a pole or mast, can significantly affect this fluttering motion. Here's how:

1. **Change in Flow Patterns**: The bluff body interrupts the flow of air around the flag. This alteration in airflow can lead to changes in the fluttering pattern. The presence of the bluff body can create vortices or eddies, affecting the stability and motion of the flag.
2. **Amplification of Fluttering**: In some cases, the bluff body can amplify the fluttering motion of the flag. The irregular flow caused by the bluff body can induce more chaotic movements in the flag.
3. **Stabilization**: Conversely, depending on the size, shape, and position of the bluff body, it may stabilize the fluttering motion. By altering the airflow in a controlled manner, the bluff body can mitigate excessive fluttering, leading to a more consistent

Effect of wake on flag flutter stability:

When considering the effect of wake on the stability of flutter in a flag, it is important to understand the dynamic interaction between the flag, the flow of air around it, and the wake created by the flag's movement. Flutter in a flag refers to the oscillatory motion of the flag as it interacts with the air flow.

Key points about the effect of wake on the stability of flutter in a flag:

- Wake Formation:

As a flag flutters, it creates a wake behind it, which consists of turbulent air and vortices. The wake is influenced by the flag's shape, size, material, and speed of movement. The wake interacts with the flag as it moves through the air, affecting its motion and stability.

This interaction can create a feedback loop, where the flag's motion influences the wake, and the wake in turn influences the flag's motion. As the flag moves, it can shed vortices (swirling flows of air) from its edges, which contribute to the wake. This phenomenon is known as Vortex shedding. The regular shedding of vortices can lead to periodic forces acting on the flag, which can either amplify or dampen flutter.

- Influence on Flag Motion:

The wake can also the affect the flag motion through the aerodynamic forces acting on the flag, such as lift and drag, which can influence its flutter behaviour. Depending on the nature of the wake and its interaction with the flag, the flag's flutter can become more stable or unstable. This interaction between the flag and its wake can result in flow-induced vibrations, which may contribute to flutter instability.

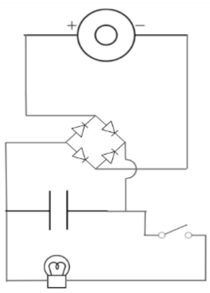
These vibrations can vary in frequency and amplitude, depending on the flag's material properties and the flow conditions.

5.Ref-Liaosha Tang, Michael P. Paı¨doussis

4) Methodology:

I) Description of prototype

Basic Circuit Design:

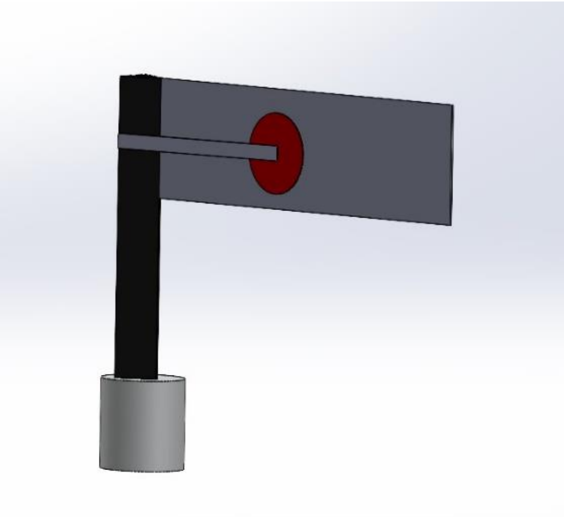


Piezoelectric Buzzer Specifications:

Resonance Frequency: 4.6Khz +/- 0.5Khzv
Resonance Impedance: 200 Ohms
Piezoelectric Buzzer Diameter: 27mm
Piezoelectric Buzzer Material: Lead Zirconate Titanate

Full wave Rectifier
Switch

Capacitor used of 100µF
Diode used of BA/57 M/C



SolidWorks model of Flag pole Setup:

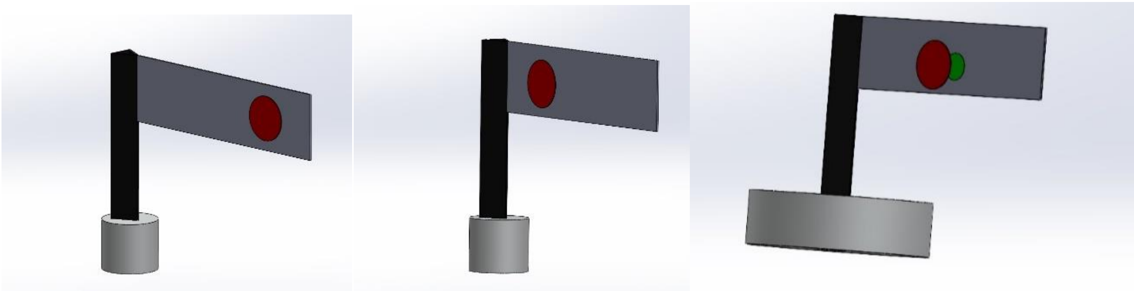
Shape of prototype-Prototype consists of rectangular shape flag, flag pole, piezoelectric buzzer and base.

Dimensions of flag- 15cm length*4cm width

Flag Pole Height: 20cm
Triangular cross section of base 1cm and height 1cm

Flag Pole Base:

Shape: Cylinder
Dimension: Height = 6cm
Diameter = 8cm



Flag pole Setup at different position of piezoelectric Buzzer

II) Procedure:

- In initial phase, we focused on developing a suitable rectifier and energy storage circuit to process the AC voltage generated by piezoelectric materials for our intended application. This involved the strategic use of diodes, rectifiers, and capacitors to rectify and condition the voltage output.
- Following experimentation with diodes and rectifiers to correct and enhance the current flow from various piezoelectric elements, we determined that rectifiers were more effective for our intended purpose. Additionally, we incorporated diodes to prevent reverse flow of charge from the battery to the setup, ensuring efficient energy management.
- Moving forward, we explored different configurations for connecting piezoelectric materials, including parallel and series arrangements. Through our testing, we found that the series connection yielded superior results, as it generated a higher potential due to the cumulative effect of the individual elements.
- We initiated our investigation on flag dynamics, meticulously recording results for different geometric profiles, dimensions, and arrangements of piezoelectric buzzers. Our aim was to discern the most optimal combination that would maximize energy harvesting efficiency.
- We have taken different material so that we can see relationship between flexural rigidity and fluttering. More fluttering will lead to more stresses on flag and this ultimately increases voltage generation by the set-up.
- Materials that we have taken are:

Material	Polypropylene	Resin Coated Paper with layers of polypropylene	Polyethylene Terephthalate
Density	0.9 gm/cm^3	-	1.38 gm/cm^3
Tensile strength	(25-35) MPa	(20-50) MPa	(55-75) MPa
Flexural Modulus	(1000-1500) MPa	(1400-2000)MPa	(2500-4000) MPa

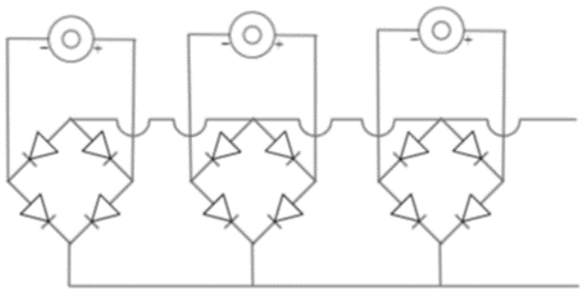
6.Ref properties data

- To see the effect of flag shape on fluttering we have taken two shapes of flag rectangular and triangular. And further data is recorded at different locations of piezo at same wind speed. After recording and analyzing the data conclusion for the best geometry has been made.

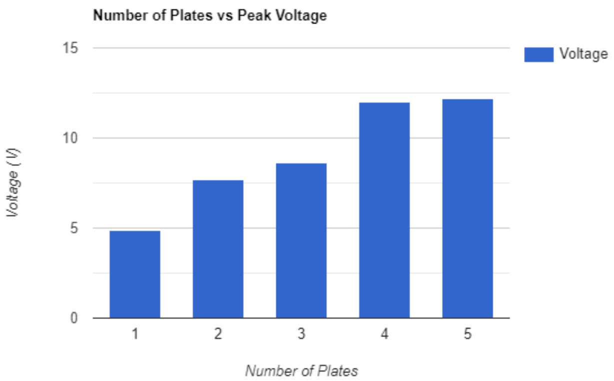
- Data is available of 10m and 50 m height from the site. We have taken average data for 10 years and taken average speed to approximate it so that we can find the average wind speed at 30m height. This is done because the maximum height of buildings in Roorkee is approximately 30m.
- We recorded data for multiple geometry at different wind speeds to understand the optimum conditions on which the flag can flutter at its best.
- Since the potential developed by a single flag was insufficient for our objective of charging the battery, we devised a circuit comprising multiple flags. Through this approach, we successfully attained the necessary voltage level by harnessing the collective output of multiple flags.

5) RESULTS:

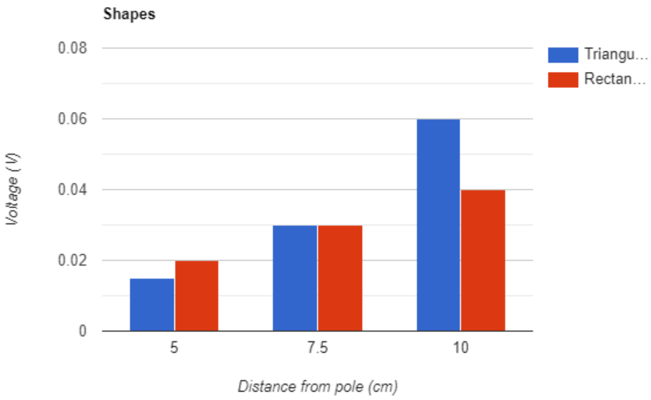
- Circuit that we finalized after trying different combination is with series combination of piezoelectric elements. And afterwards connecting capacitors of different flags in series to achieve required potential difference.



- The capacity of peak voltage generated by multiple piezo can be seen below and it was observed that the generated voltage gets saturated after certain number of piezo. The maximum possible voltage cannot be generated due to hindrance from other piezo. In case of interaction with wind enough stress will not be generated so we cannot utilize maximum capacity of piezo.



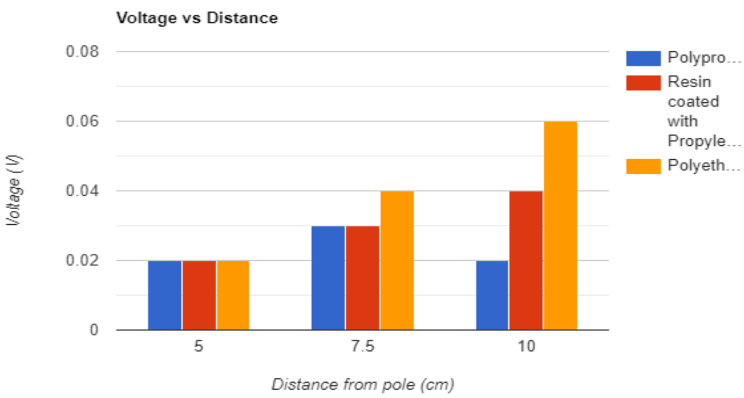
- Among different flag shapes we considered, the most optimum flag shape we found was triangular (when attaching piezoelectric buzzer directly) and with use of supporting strip rectangular flag performed better.



- We concluded that up to a certain length of flag, the voltage generation will increase then at a point it will be maximum then it will decrease. And the distance of maximum voltage from the pole will depend on the material and arrangement.

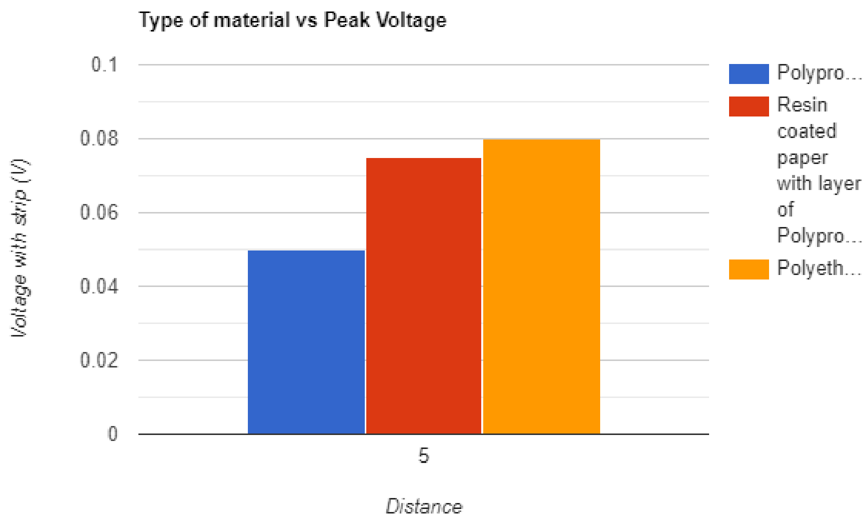
Distance(cm)	Polypropylene (File) (Voltage)	Resin coated paper with layer of Polypropylene(voltage)	Polyethylene Terephthalate (Voltage)
5	0.02	0.02	0.02
7.5	0.03	0.03	0.04
10	0.02	0.04	0.06

- Among the different materials we used in flag material, Polyethylene Terephthalate is the most efficient in voltage generation at higher wind speed and polypropylene at lower wind speeds.



- Since we are using piezoelectric buzzer, we used small circular buzzer between piezo plate and flag surface to concentrate the load at middle of the buzzer.

- Forces developed on the flag can be concentrated on piezo nearest to the flag pole with the use of a strip made of less flexible material.



- Because of many circuit connections on the flag the flexibility of also gets affected to an extent.

6) Conclusion:

Finally, we concluded that the flag with triangular geometry gives highest output voltage at the farthest point but with the use of supporting strip we got even greater potential in rectangular flag (at close distance to flag pole). The voltage generated from a single piezoelectric element proved insufficient for our energy requirements. To address this limitation, we implemented a strategy involving multiple flags integrated with circuitry. By harnessing the combined output from these multiple flags, we successfully achieved the desired voltage level, thereby ensuring adequate power generation for our intended application. During the material selection, among the material we chose the best material we found was Polyethylene Terephthalate for high-speed winds and Polypropylene for low-speed winds.

Further by Introducing a bluff body upstream of the flag fluttering setup can enhance turbulence, consequently amplifying flag flutter and augmenting voltage generation. By strategically placing the bluff body ahead of the flag arrangement, we effectively disrupt the airflow, fostering turbulent conditions that intensify flag motion. This increased fluttering activity translates into higher mechanical stress on the embedded piezoelectric elements, thereby enhancing voltage output. Overall, leveraging the presence of a bluff body as an upstream turbulence inducer represents a promising approach to optimize energy harvesting efficiency from flag flutter.

Also, by Integrating plate piezoelectric elements onto the flag surface significantly enhances stress levels experienced by the piezo material, leading to increased voltage generation. Plate piezo efficiently convert mechanical deformation into electrical energy. By affixing these elements onto the flag, we leverage the dynamic motion during fluttering, amplifying the mechanical strain exerted on the piezoelectric material. This heightened stress facilitates a robust conversion of mechanical energy into electrical voltage, boosting the energy harvesting capability. The strategic deployment of plate piezoelectric elements on the flag surface represents a promising approach to optimize voltage generation, enhancing the efficiency of flag-based energy harvesting systems.

7) Acknowledgement

We thank professor Sushanta Dutta for guiding us throughout this journey and helping us to keep track of what we are doing throughout this project. He provided us necessary facilities for testing and introduced us with good reading materials from which we have enhanced our model.

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