Experimental Investigation of Active Flapping for Energy Harvesting: A Comparative Analysis between Circular and C-type Cylinders

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ISLAMABAD

APRIL, 2024

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A thesis submitted in partial fulfillment of the requirements for the degree of

MS Mechanical Engineering

Thesis Supervisor:

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APRIL, 2024

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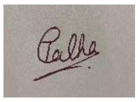

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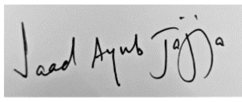

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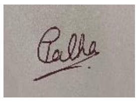

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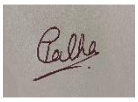

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Dedicated to my great parents and beloved siblings, whose unwavering cooperation and support helped me achieve this amazing feat

ACKNOWLEDGMENTS

I am grateful to my God, Allah Subhana-Watala, for guiding me at every turn and for putting fresh ideas into my head to help me with this effort. Without Your invaluable assistance and direction, I truly could not have accomplished anything. You desired that anybody assists me with my thesis, whether it is my parents or anyone else, thus You alone are deserving of all the gratitude.

I have the utmost gratitude for my cherished parents, who reared me from the time I was unable to walk and supported me in every aspect of my life.

Additionally, I want to thank Dr. Emad Ud Din, my thesis supervisor, for all of his assistance. It's reasonable to say that without his help and encouragement, I could not have accomplished this. With that, I want to express my gratitude to Mr. Wajid Khan, my Master's fellow, for all of his help and collaboration. He always had the answer when I got stuck on something. My thesis would not have been finished if it weren't for his assistance. I am grateful for his understanding and direction during the entire thesis.

In closing, I just wanted to say thank you to everyone who helped me out with my research.

ABSTRACT

The demand for renewable energy resources is increasing day by day. The most efficient sources of energy include hydroelectricity and nuclear power plants. The focus is to develop a sustainable system with minimum cost investment. This study evaluates the generation of electricity through active flapping of the piezoelectric flag that generates electricity through turbulence in the moving fluid. This research compares electricity generation when a circular/solid and C-shaped cylinder is placed at 90 degrees to the moving fluid. The study experiments with different gap widths and velocities of the moving fluid to find the ideal setup. The gap width between the cylinders and the flapping flag varies between $2.0D \leq Dx \leq 4.0D$. Also, the moving fluid velocity varies from $0.136m/s \leq v \leq 0.3m/s$. The experiment shows that a C-type cylinder gives more power than a circular cylinder. The study strengthens the development of renewable energy applications by offering comprehensive details on the best configuration for piezoelectric-based energy harvesters in fluid flow parameters.

Key Words: Energy Harvesting, Piezoelectric Flapping Flag, Flapping Frequency, Flapping Amplitude, Circular and 120^0-Cut Cylinders

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CHAPTER 1: INTRODUCTION

1.1 Background

An increasing number of renewable performers sometimes referred to as energy harvesting products, are being utilized for harvesting renewable energy from the environment. Such systems are objective to be sustainable and helpful and have advanced greatly in recent times including wireless networks of sensors. These can be retrieved by various transduction methods, including piezoelectric, electromagnetic, and electrostatic. Among them, pressure and vibration operating energy harvesters are highly sought-after and researched because of their portability, efficiency, substantial energy, and potential for reducing their workforce. Our goal is to swap out traditional energy sources with sustainable alternatives considering growing worries about resource depletion and the adverse consequences on the environment and the well-being of mankind.

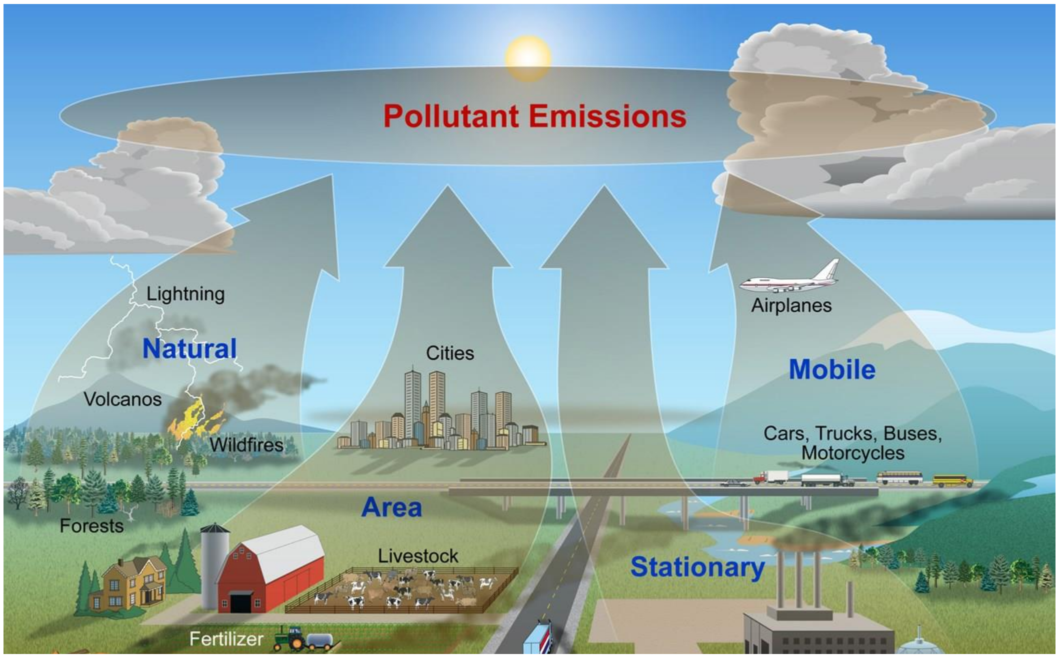


Figure 1: Various sources of Earth pollution[1]

Renewable energy is pushing boundaries to provide novel solutions and discovering new methods to make more efficient electronics. Though micro-sensors and other devices that use very little power to run have been powered by scientists, researchers, and engineers, more research and development is still required to find effective methods in this wide sector[2]. We are aware that several uses in the engineering and medical sciences call for further innovation in the field of energy harvesting, as the sensors and equipment in question require microwatts of electricity to function. Multiple harvesting systems can be integrated simultaneously for improved and optimum outcomes to create or extract more out of the existing design devices[3, 4]. The globe is currently shifting toward more practical, diverse, and independent power sources as they are more long-lasting, durable, and sustainable. These methods and investigations will reduce these systems' maintenance and operating expenses while being ecologically benign.

1.2 Energy contribution of sources:

Our globe is powered by a wide range of sources that are utilized by the energy industry. Fossil fuels, such as coal, oil, and natural gas, have long been the main sources of heat, transportation, and electrical production. But the effects they have on the environment, like resource depletion and greenhouse gas emissions, have prompted a move toward renewable alternatives[5]. Whereas solar energy uses photovoltaic cells or solar thermal systems to gather sunlight, wind energy uses the power of air currents. Hydropower makes use of the force generated by flowing water, whereas geothermal energy draws heat from the Earth's interior[6]. Because it is made of organic stuff, biomass offers another renewable resource. By lowering dependency on limited fossil fuels and minimizing environmental damage, these sources provide greener, sustainable alternatives that will promote a more resilient and equitable energy future. The new objectives for the evolution of the energy business are to use low-carbon fossil fuels, embrace sustainable sources, and implement innovative & efficient power-producing systems. Figure 2 illustrates the amount of energy used worldwide, with fossil fuels accounting for 86% of it. Furthermore, we can observe that renewable and sustainable energy sources like solar, wind, and hydro share a very small amount.

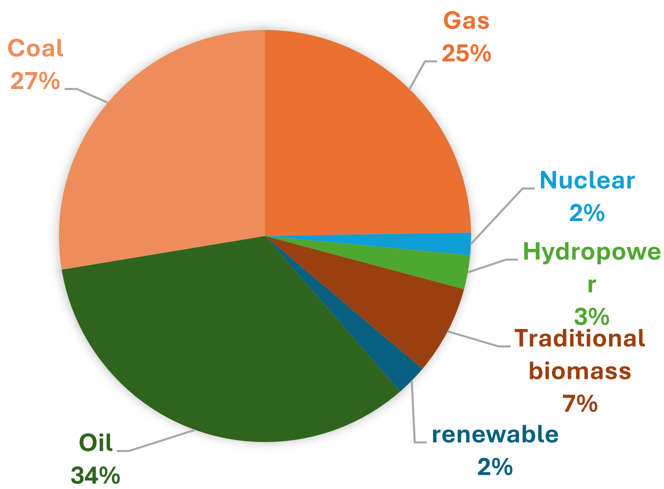


Figure 2: World energy consumption by source [7]

1.3 Thesis objective:

This thesis is developed around the topic of "experimental investigation of active flapping for energy harvesting: a comparative analysis between circular and C-type cylinders". The primary aim of the thesis was to enhance the system's efficiency and examine the mounting pivot mechanism that attaches the flag to the cylinder from behind.

Questions that are included in our research:

1. How much energy is harvested in case of active flapping?
2. What is the effect of fluid velocity and distance of the flapping flag on the A/L ratio of circular and 120-degree cut cylinders?
3. What is the pivoted cantilever mechanism's effect on the flag's amplitude and frequency and its correlation with vortex formation?
4. What are the values of A/L ratios and flapping frequencies for the head and tail of circular and 120-degree cut cylinders?

CHAPTER 2: HARVESTING OF ENERGY

2.1 Conversion of energy and its types:

"The overall amount of energy in the system remains constant for any type of energy conversion from one state to another," according to the first law of thermodynamics. A lesser output than intake indicates that energy has been wasted or transformed into a different form. There are many different types of energy, and each one is essential to keeping our planet running.

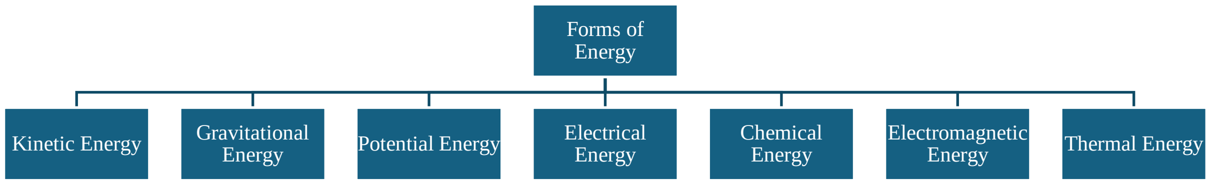


Figure 3: Various forms of energy

Transportation and machinery are powered by mechanical energy, which is obtained from motion or position. Particle motion within our dwellings generates thermal energy, which powers industrial operations[8]. Wires carry electrical energy, which powers our gadgets and lights up our cities. Our bodies run on chemical energy stored in bonds, which also drives chemical processes. Nuclear energy is produced by atomic processes and is used to power spaceships and produce electricity. Waves carry sound energy, which enables speech and music. Life on Earth is supported by solar energy, which also drives solar technology[9]. It is crucial to comprehend and utilize these many energy sources to satisfy our demands sustainably and to promote technological innovation.

2.1.1 Kinetic energy:

Motion energy is known as kinetic energy. Kinetic energy is continuously transformed and used to carry out tasks, from the motion of cars on highways to the flow of rivers and the spinning of wind turbines[10].

2.1.2 Potential energy:

Stored energy with the capacity to perform work is known as potential energy. This energy is connected to the state or location of an object. A lifted weight, a stretched spring, or water contained behind a dam, for example, all have potential energy that may be released and transformed into other types of energy[11].

2.1.3 Electrical energy:

Modern life is powered by electrical energy, which travels via cables to power machines, light up our houses, and charge our gadgets. It is produced when electrons flow through conductive materials and may be transformed into a variety of other energy types, including heat, light, and mechanical motion[12].

2.1.4 Chemical energy:

Molecule bonds contain chemical energy, which is released during chemical reactions. It supplies the energy required for metabolism and cellular functioning, powering biological processes inside living things. In addition, batteries and other energy storage devices, as well as fossil fuels like coal, oil, and natural gas, are sources of chemical energy[13].

2.1.5 Thermal energy:

The internal energy that a system has as a result of its particles moving about is called thermal energy, or heat energy. It is a property of all matter and is transmitted by radiation, convection, and conduction. Everything from steam turbines in power plants to the preparation of meals is powered by thermal energy[14].

2.1.6 Electromagnetic energy:

A wide range of energy is included in the term "electromagnetic energy," including visible light, X-rays, microwaves, radio waves, infrared radiation, ultraviolet radiation, and gamma radiation[15]. These energy types, which travel in waves, are used in many industrial operations, heating, medical procedures, and communication.

2.2 Renewable energy sources(Large scale):

Reliance on finite fossil fuels is decreased, degradation of the environment is reduced, and naturally regenerating resources are harnessed via the use of renewable energy, marking a revolutionary move towards sustainable power sources. In contrast to traditional energy sources like coal and oil, renewable energy comes from plentiful and never-ending resources including biomass, sunshine, wind, and water. Adopting renewable energy technology helps to address the urgent problem of climate change while simultaneously promoting energy independence, job development, economic growth, and social fairness by decentralizing energy production[16, 17]. Renewable energy provides promise for a greener future as countries throughout the world work to shift to a cleaner and more resilient energy paradigm.

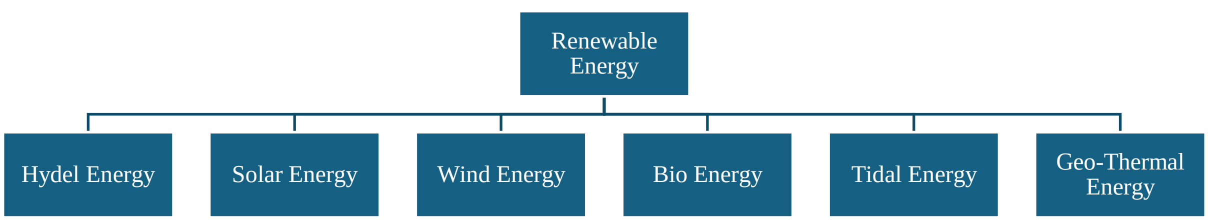


Figure 4: Renewable energy resources

2.2.1 Hydel energy:

Utilizing the gravitational force of falling or flowing water, hydroelectric power, or hydel energy, produces electricity. Large-scale dams and reservoirs produce dependable and dispatchable electricity, but careful design and management are required due to worries about habitat damage and community uprooting.

2.2.2 Solar energy:

Sunlight is the source of solar energy, which is one of the most plentiful and accessible renewable resources. Direct solar energy conversion into electrical power is provided by photovoltaic cells, which may power everything from large-scale solar farms to personal dwellings[18]. Technology breakthroughs and falling costs have made solar energy more affordable and accessible, which has fueled wider adoption and aided in global energy transition initiatives.

2.2.3 Wind energy:

Using wind turbines, wind energy captures the kinetic energy of flowing air masses. Wind farms, both onshore and offshore, harness the energy of the wind to create electricity that can be incorporated into the current electrical systems[19]. Technological improvements have made it possible for larger and more efficient turbines to produce huge amounts of renewable electricity, which has led to tremendous growth in the wind energy sector.

2.2.4 Bioenergy:

Bioenergy is the process of creating heat, electricity, or biofuels from organic resources including wood, garbage, and agricultural leftovers. In addition to being directly burnt for energy production, biomass may also be processed into biofuels like ethanol and biodiesel and utilized in anaerobic digestion to create biogas. To maintain sustainability and avoid detrimental environmental effects like deforestation and competition with food production, proper management is necessary.

2.2.5 Tidal energy:

Utilizing the kinetic energy of ocean tides, tidal energy produces electricity. The ebb and flow of the tides are used by tidal power plants to power turbines and generate renewable energy. Although it provides a steady and reliable energy source, tidal energy can only be applied geographically in coastal areas with large tidal ranges.

2.2.6 Geothermal energy:

Using steam or hot water reservoirs, geothermal energy harnesses the heat that exists inside the Earth to produce power or offer direct heating and cooling. High geothermal activity regions can host geothermal power plants, which provide a dependable, low-carbon energy source with little effect on the environment[20].

2.3 Renewable energy sources(small scale):

To achieve the global aim of employing sustainable sources for power production, energy collection using small-scale devices is essential. Wearable electronics, wireless sensors, and other tiny, autonomous devices are powered by the small amount of electricity that is taken, transformed, and stored from external sources[21].

Low current-consuming devices, like certain kinetic energy-using wristwatches (automatic watches), are powered by arm motions, which are a kind of energy harvester and generate minuscule quantities of current. Solar radiation is used by semiconductor-based photovoltaics (PV) technology to produce DC power[22]. Thermoelectric generators (tegs) also exploit the potential heat gradient connecting two materials. The tiny wind turbines convert wind energy into electricity to power the low-current gadgets. A nominal voltage is produced when a piezo crystal is mechanically forced. An electrical current is produced by vibration in electromagnetic induction.

2.3.1 Radiation energy:

The research given here supports the theory that electricity might be transferred from any place by using radio transmitters that are already in use. In the past, extracting any useful energy from radiation required a large collecting area or proximity to the source of radiation transmission[23]. However, if optical rectenna (antenna) devices were developed to capture the sun's abundant radiation energy, this constraint may be addressed.

However appropriate authorities worldwide have set a restriction on the highest wattage that may be sent. Radio-frequency identification (RFID) systems that are passive may function without an external power source and are now widely available[24].

2.3.2 Fluid flow energy:

A variety of turbines and non-turbine generators may be used to capture the potential and kinetic energy carried by fluid flow. Aerial wind energy systems (AWES) and wind turbines of a new generation are designed to actively search for and capture wind energy for use in industrial settings[25]. To capture wind energy on a smaller scale, Zephyr Energy has developed a wind-beam microgenerator, which may be used to replenish batteries and power devices. The University of Bern researchers have created a new blood flow-driven pacemaker by encapsulating the pounding heart's kinetic energy inside a spring[26].

Latif U. et al. of NUST University investigated the effects of angle, gap, and speed on the power gathered by a piezoelectric flag and vortex-induced vibrations using a bluff body as a water-energy harvester[27]. In structural health monitoring systems, microelectromechanical sensors are very useful. Instead of using chemical batteries, piezoelectric harvester eels (flags) may be used to disperse these sensors across several sites.

2.3.3 Photovoltaic energy:

Compared to outdated wire-based or fully battery-stored sensor systems, photovoltaic harvesting wireless technology offers a plethora of benefits and is an endless power source with few negative environmental effects. Amorphous silicon-based indoor photovoltaic harvesting devices, including solar calculators, are widely used. One example of a new generation of photovoltaic (PV) technologies that have emerged after years of study is dye-sensitized solar cells (DSSCs).

2.3.4 Piezoelectric energy:

Pierre and Jacques Curie proposed the concept of piezoelectricity in 1880[28]. The ability to transfer mechanical energy, such as motion, weight, vibration, and temperature changes, into electrical power is made possible by the discovery of the piezoelectric effect. This is because the milliwatt-level power produced by piezoelectric devices is just too low to be of any value in a system. Still, it works well for little gadgets like self-winding or automated wristwatches. The use of the piezoelectric effect is a cutting-edge technological development that has attracted a lot of attention in recent years. Many commercial applications such as vibration energy harvesting and sensor supply appear between 2000 and 2005. Further research has shown that piezoelectric technology can convert mechanical energy from human motion into electrical energy. A more thoughtful design process is needed to maximize the practical and enjoyable aspects of these energy-gathering assets. Researchers have been investigating methods to use human leg and arm movement, implant impacts, and blood pressure to address the need for small electricity-provided implanted or wearable sensors[29]. Three-dimensional NGs may be built and then deployed in regions with available force or pressure changes, like a shoe pad, an underskin layer for airplanes, or close to a vibration source, such as an automobile engine, using a layer-by-layer building method[30]. A micro-belt may be worn to transform breathed air into useful energy. Internal resonance and a piezoelectric cantilever may be used to build an omnidirectional energy harvester that gathers resonant energy from vibrations caused by human motion, which can originate from any direction. One way to harness and use pedestrian "people energy" is to place piezo components on sidewalks. They may also be used to gather "walking energy" when worn appropriately. In 2005, MIT researchers created the first micro-scaled piezo-based energy harvester made of PZT[31]. A team of researchers showed the simultaneous conversion of light from the sun and raindrops into energy using a triboelectric system and solar panels[32].

2.3.5 Smart road energy:

With the limited amount of energy available, energy harvesting plays a vital part in using the environment, such as smart highways, which can generate power. Roadside piezoelectric sheet couplings may transform strain from vehicle pressure into voltage and current.

2.3.6 Smart transportation network energy:

Piezo-based sensors have been included in the advancement and creation of sustainable smart-road technology. There is a critical need for change, such as the implementation of an intelligent road network system that can anticipate and notify passengers about traffic congestion, the reinforcement of buildings susceptible to collapse, and the development of a self-repairing electric grid. This approach will effectively address the problem of traffic congestion in the network. However, to fully harness the capabilities of these technologies, there has been a limitation in terms of funding due to the high cost of these early-developed systems. However, prompt measures such as research and development and substantial investment will undoubtedly expedite its availability in the sector. It is important to note, however, that a significant portion of the technology is still in the developmental phase and will not be accessible for a considerable period.

2.3.7 Photoelectric effect energy:

The phenomenon of generating an electric current or voltage as a result of a temperature differential is referred to as the pyroelectric effect. For an effect to occur, it requires the use of variable temporal inputs. Typically, it experiences reduced power generation in electricity-collecting applications because of low operating frequencies. In contrast to thermoelectric devices, pyroelectrics possess a notable characteristic of withstanding temperatures of 1200°C or higher. This enables the extraction of power from high-temperature sources[33, 34].

2.3.8 Electrostatic- Capacitive energy:

Electrostatic energy harvesters use the concept of variable capacitance in capacitors to extract mechanical energy from motion. The system's mechanical energy is converted into electrical power via the oscillations of the charged plates. This strategy is beneficial for devices that can replenish their power, directly charge batteries, or implement self-charging.

2.3.9 Magnetic induction energy:

As per the principle of magnetic induction, when a magnetic field is disturbed, it leads to the creation of an electromotive force (voltage). Magnetic fields may be disrupted by several types of motion, including vibrations and rotational forces. Cantilever-based mechanisms that include vibrating magnets are susceptible to the vibrations of the system, resulting in the generation of a minimal quantity of power[35]. In 2007, researchers from the University of Southampton created a little gadget and effectively implanted it in remote situations that lacked direct access to any electrical source[36]. This advancement enabled the gadgets to autonomously recharge and establish communication with distant receivers located in inaccessible regions.

A recent research used the notion of energy harvesting using magnetic induction to apply it to a wall design. The authors have shown that the application of stress induces vibrations that lead to changes in the wall patterns of microwires and variations in induction. There are a limited number of magnetic induction power generators that are suitable for industrial applications. The research is now ongoing for sensors that can directly harness structural vibrations from overhead transmission lines or power cables for monitoring purposes.

2.4 Aspirations for the future:

The discovery of innovative polymers with exceptional tensile strength and optimal efficiency is essential for the advancement of energy harvesting technologies. Electroactive polymers (EAPs) are lightweight systems that are believed to be much more economical than those relying on piezoelectric materials, making them the optimal choice. The NiPS Laboratory in Italy is researching methods to capture and use energy derived from ambient noise.

To meet the needs of the future, it is necessary to decrease reliance on batteries or disposable power storage devices, especially in remote settings where traditional power infrastructures are unable to provide a comprehensive answer. An effective approach is to create hybrid versions of existing energy-collecting technology. The use of hybrid systems offers a method to enhance the global reliance on autonomous systems.

CHAPTER 3: LITERATURE REVIEW

Strain measurement instruments, portable electronics, and web-based Things devices have all found utilization for piezoelectric materials in energy harvesting. Effectively implementing small-scale energy harvesting is crucial for powering portable electronic devices such as laptops, nanorobotic devices, self-power supplies, and surveillance devices[37]. For instance, nano-robotic devices are technologically advanced machines that can identify, adjust to, and carry out exceptionally difficult tasks. Nonetheless, it can be problematic to operate these small devices with completely self-sufficient energy sources without decreasing their practical application[38]. The technique of vibration-based harvesting of energy, which transforms vibrational momentum from movement of fluid into useful power, has become more well-known throughout the last two decades in tandem with developments in semiconductor technology and tiny technological advances in sensors. Piezoelectric Vortex Induced Vibration (VIV) is an increasingly prevalent technique for getting electrical energy from the mechanical energy of the moving fluid[39]. Concerning their functionality, performance, and potential as sensor nodes, these piezoelectric energy generators show commitment. Just like the movement of fish in the water or the wings of the birds in the air; the flapping flap follows the same pattern when placed behind the bluff body. This pattern is created by the vortices produced when the bluff body is placed in the moving fluid. Because of fluid flowing patterns and pressure fluctuation, a bluff body's downstream section experiences frequently occurring Eddie shedding which leads to VIV.

By mixing a cylinder at the free end, the turbulent forces of a flowing fluid can intensify the periodic deformations of the piezoelectric flag[40]. The differential pressure distribution in the fluid also causes the flapping flag to whirl around, leading to strain on it. The effects of inserting rods at various angles near a circular cylinder were shown by Hu et al., increasing power production and enlarging the unsteady zone. In comparison to a circular cylinder, Usman et al.[27] study of inverted C-shaped bluff bodies that had various cut angles yielded a 66% power boost at a 120° cut angle. To improve efficiency and boost turbulence, Wang et al.[41] fastened Y-shaped foils across a cylindrical body, causing VIV to accelerate with a suggested 60° inclination angle was implemented. The bluff body's redesigned form greatly enhanced its power generation. At a critical velocity, the swirling flag displays flapping and changes into constrain cycle oscillations, which produce large amplitude motions. Broad magnitudes of energy are extracted at a low or stable frequency.

The speed of flow, load resistance, spacing ratio, bluff body shape, and angle are among the flow and geometric factors that are vital to the energy harvester's operation. By varying these variables and creating sets of experiments can develop the optimum system to get maximum energy as output. In this research, two variables varied including the speed of the fluid and the gap of the flapping flag from the cylinder.

CHAPTER 4: ENERGY HARVESTING THROUGH THE FLAPPING FLAG

4.1 The flapping of piezoelectric flag:

Underwater, flapping flags that utilize piezoelectric technology have proven to be highly advantageous for energy harvesting. This is because they have the unique capability to convert mechanical motion into electrical energy. When the flag moves due to fluid flow, electrical charges are generated by the deformation of piezoelectric materials embedded within it. These charges can be harnessed and stored, offering a sustainable source of power for a range of underwater applications.

Operating in environments where traditional energy sources may be limited or impractical, piezoelectric flapping flags offer a significant advantage for energy harvesting underwater. Unlike batteries or fuel-based generators, piezoelectric energy harvesting is ideal for long-duration deployments in remote or harsh underwater environments due to its independence from external fuel sources.

In addition, energy can be harvested from flapping flags using piezoelectric technology, providing a solution that is both sustainable and environmentally friendly. By utilizing the inherent movement of the flag in response to fluid flow, researchers can significantly reduce the environmental consequences linked to conventional energy extraction techniques. In addition, the flexibility and lightweight nature of piezoelectric materials enables the creation of energy harvesting systems that can be seamlessly integrated into underwater structures, thereby improving their efficiency and practicality.

4.2 Energy harvesting through piezoelectricity(operating principle):

As shown in Fig. 5, the piezoelectric effect is the basis for how a piezoelectric energy harvester operates. It can function as an energy harvester and a sensor. The phenomenon by which some materials may produce an electric charge or distort in response to an electric charge or mechanical stress is known as the piezoelectric effect. Electrically neutral molecules arise when no mechanical tension is applied. This is because the centers of each molecule's positive and negative charges coincide, canceling out the exterior effects of the charges, as seen in Figure 6(a).

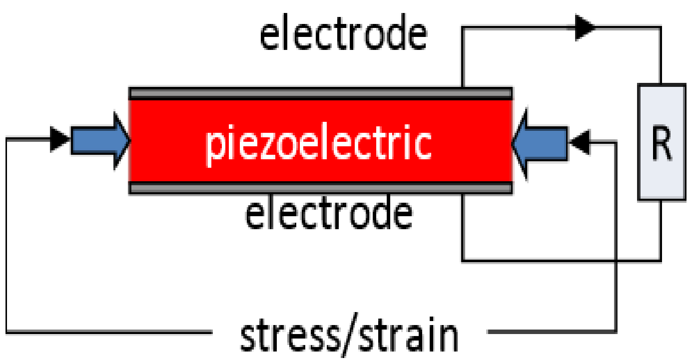


Figure 5: Piezoelectric converter of energy[37]

As seen by Fig. 6(b), underweight, the centers' distances change and the gap between the molecule's positive and negative charges separates them, creating a tiny dipole. Above the surface, polarization charge is induced, and facing poles are mutually canceled. polarization as a consequence produces a charged field that converts mechanical energy into electrical energy.

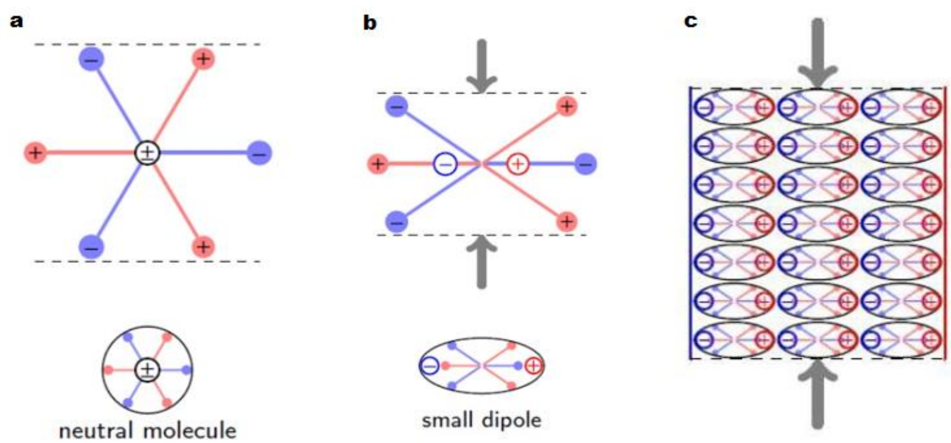


Figure 6: Conversion process of piezoelectric[42]

4.3 Investigating Piezoelectric Flags' Passive and Active Flapping Underwater

Underwater flapping movements in piezoelectric flags provide fascinating new insights into fluid-structure interactions and their potential applications in biomimetics, propulsion, and energy harvesting. These movements may be roughly divided into two categories:

1. Passive flapping
2. Active flapping

Passive flapping happens when one end of the flag is secured, allowing the other end to move unrestrictedly in response to water vortices. This motion, when harnessed, can result in fascinating dynamics and endless creative opportunities, especially in the field of biomimetic design and the extraction of energy. On the other hand, active flapping allows for unrestricted movement of both ends of the flag, resulting in increased motion and the possibility of generating more energy. With their increased freedom of motion, active flapping flags are perfect for applications that demand precise control or enhanced propulsion. Their agile and responsive behavior ensures optimal performance.

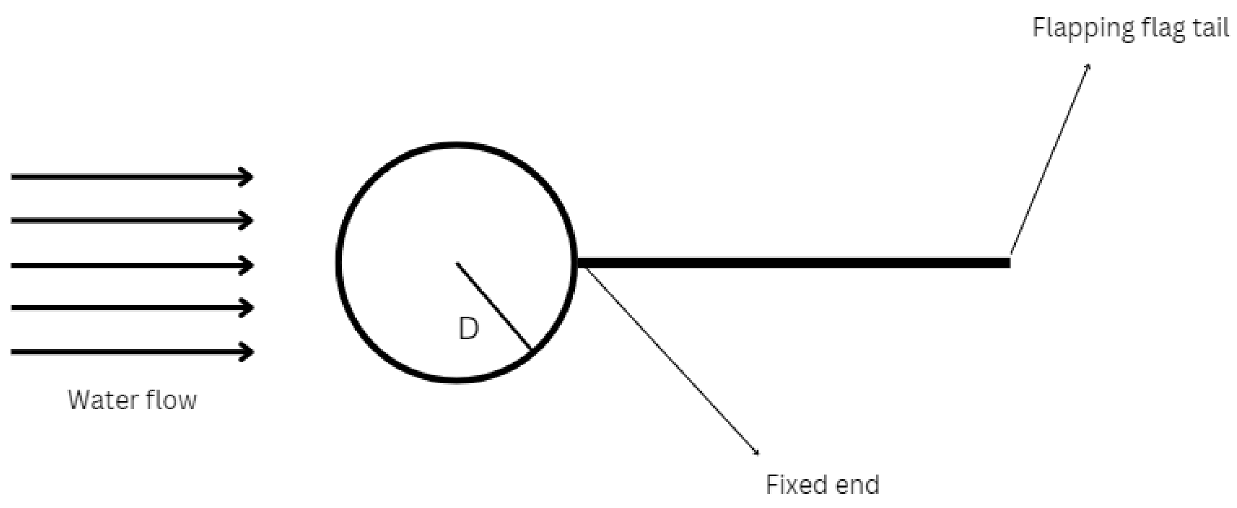


Figure 7: Schematic for passive flapping

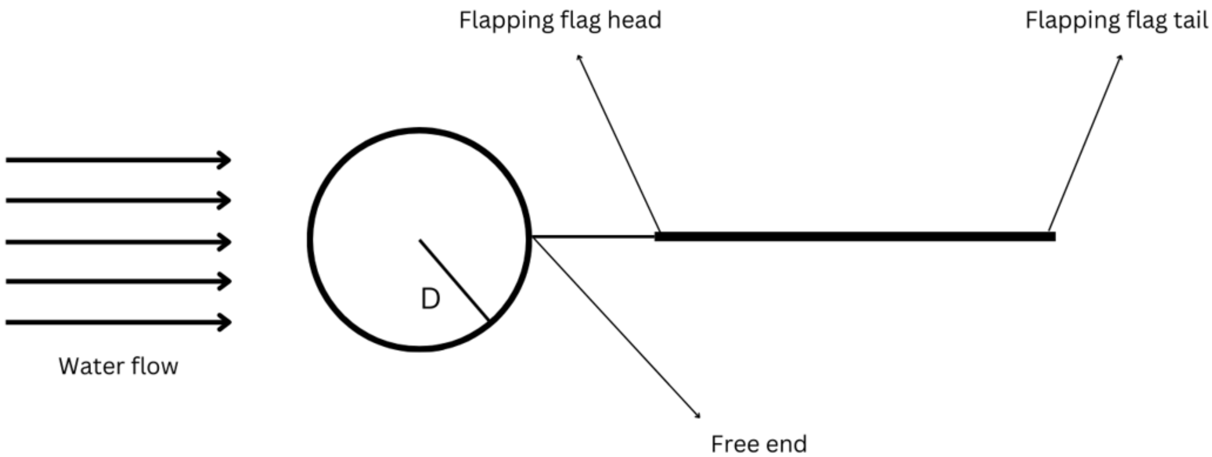


Figure 8: Schematic for active flapping

In general, every approach has its unique advantages and opportunities for innovation, including efficient energy harvesting and autonomous underwater navigation. Through a deep understanding of passive and active flapping, researchers can explore exciting opportunities in the fields of underwater robotics, renewable energy technologies, and environmental monitoring.

4.4 Passive Flapping: Using the Forces of Nature

When a piezoelectric flag is secured at one end underwater while the other is free to move in reaction to external forces, especially fluid flow vortices, the phenomenon known as passive flapping takes place. This passive reaction to outside stimuli is similar to natural occurrences like fish fins adapting to water currents or submerged plant leaves. When a flag flaps passively, its motion is mostly determined by outside factors, which means it is a reactive process as opposed to an actively directed one.

Vortices are created due to the interaction between the surrounding fluid and the flag, causing the flag to oscillate. The flag's flapping motion is caused by alternate pressure gradients that are created when vortices shed and interact with the flag's surface. Applications for this phenomenon may be found in bio-inspired robots, where passive flapping mechanisms can be used for energy harvesting or underwater propulsion. Engineers can create effective and sustainable underwater systems that can use environmental forces for propulsion or power production by imitating the design principles found in nature.

4.5 Using Active Flapping to Increase Movement and Energy Production

Active flapping, in which the two ends of the piezoelectric flag are free to move underwater, is a more dynamic approach. This design provides greater opportunity for movement and energy generation than passive flapping. The flag's agility and fluid flow responsiveness may be enhanced by researchers by actively controlling its deformation via the use of external actuators or intrinsic material properties like piezoelectricity. Building on this idea, underwater propulsion and manoeuvrability are now possible thanks to the active flapping mechanism. Researchers are able to achieve precise and effective navigation over intricate underwater settings by deliberately manipulating the flag's movements. With the use of this creative method, the flag's flapping patterns may be changed in real-time for best performance under various circumstances.

When a flag flaps actively, it shows that its movement is not just dictated by external forces, but can also be actively controlled and handled. By oscillating both sides of the flag, researchers can design complex flapping patterns that maximise propulsion efficiency and energy-collecting potential. This increased range of motion gives underwater vehicles and robots additional alternatives to navigate challenging terrain with improved precision and agility. Moreover, the active flapping method's versatility goes beyond propulsion. It offers opportunities for cutting-edge uses including undersea exploration, environmental monitoring, and even underwater energy harvesting. Researchers can modify the flag's behaviour to fit certain jobs by precisely controlling its motions, which might transform the possibilities of undersea technology.

The active flapping technique, in short, transforms underwater robotics by offering a flexible and effective way to control and propel. Researchers open the door for a new age of underwater exploration and discovery by using the power of dynamic movement and intelligent design.

4.6Comparative Evaluation and Upcoming Projects

While there are distinct advantages and uses for both passive and active flapping, there are also possibilities and obstacles specific to each strategy. Because of its resilience and simplicity, passive flapping is a good choice for situations when independent control is not necessary. Conversely, active flapping offers more flexibility and adaptability, allowing for exact control over the flag's motion and capacity to capture energy.

Prospective avenues for study might center on enhancing the efficacy of passive and active flapping systems by sophisticated modeling, creation of materials, and control tactics. By merging knowledge from fluid dynamics, materials science, and biology, researchers may keep pushing the frontiers of biomimetics, underwater robots, and sustainable energy harvesting.

CHAPTER 5: EXPERIMENTAL SETUP

5.1 Setup of water tunnel

The study makes use of an enclosed, slow-speed water pathway, as seen in Fig.5 from the Department of Mechanical Engineering at the National University of Sciences and Technology (NUST). The water channel's test segment has square dimensions measuring 2000 mm by 400 mm by 400 mm (L × W × H). The centrifugal pump, which propels the water flow in the channel, has its RPM controlled by a variable frequency drive (VFD) with a frequency range of 1 to 50 Hz. This permits an alteration of the water velocity with an intensity of turbulence of 1%, determined using the PIV process, in the range of 0.1 to 0.5 m/s. A 1.83 m × 0.5 m × 0.0254 m (L × W × H) aluminum honeycomb framework with hexagonal apertures is utilized to provide a uniform flow. Fig.5 completely describes the experimental setup which is being used for this work. The flapping flag is attached to the circular and solid cylinders with such an arrangement that allows both the head and the tail of the flapping flag to oscillate freely, which makes it an active flapping experiment. This arrangement of active flapping is described in the following Fig. 6.

Figure 9: Experimental setup of flow lab

5.2 Arrangements of the camera, DAQ, and flapping flag

A high-resolution camera for recording the video of the flapping flag from the bottom of the tunnel, a flexible flag, a breadboard with an appropriate resistor for the circuit's load, and a Data Acquisition (DAQ) apparatus—which demonstrates an instantaneous voltage produced in the flexible flag because of disturbance—are the experimental tools used in this work. A digital oscilloscope (UTD-2052CL) is utilized for examining the voltages generated and obtained under very similar conditions to verify the degree of precision of the DAQ apparatus. The findings are found to be almost identical. The PVDF flag is 0.072 m lengthwise and 0.016 m broad, but because sticky tape and epoxy gel are used to shield the connections and to attach the end of the flapping flap with the cylinder, the flag's operational length is only 0.060 m. The thin metalized coatings encasing the 54 µm thick piezo film are utilized to transfer charges created on piezo material/film and linked to integrated terminals. It has a layer of protection (a thin, translucent plastic sheet). The strain created in the piezoelectric film and the applied pressure by the moving fluid determine how much energy is extracted. Piezoelectric film from the PVDF-DT series generates more than ten microvolts per micro-strain. These films may produce output voltages between 10 mV and 100 V depending on applied circuit impedance and pressure.

5.3 Post-proceed using MATLAB

Every experiment's video is recorded for 120 seconds at a rate of 50 frames per second with a 1920 x 1080 pixel resolution. To improve visibility, bright LED bulbs (Model: Mcopus TTV 204), placed on one side of the flag, are used to highlight the piezoelectric film. The test area of the tunnel is covered with a black cover to prevent video interference from the background. Matlab is used for post-processing of video data to determine the flag's dominant frequency and amplitude. Additionally, LabView is used to collect data on the energy produced by the PVDF flag at a frequency of 50 Hz for 120 seconds using a data collection card (DAQ, National Instruments, NI-USB 6009, multiple purposes I/O).

Video recorded through the high-resolution camera is then processed through a MATLAB code to record the flapping of the flag. That code initially gives the Microsoft Excel file which has the values of the flapping flap corresponding to the amplitude of the flag. This, later, gives the A/L value and the normalized frequency which helps in analyzing the data and validating the power generation in the flapping flag.

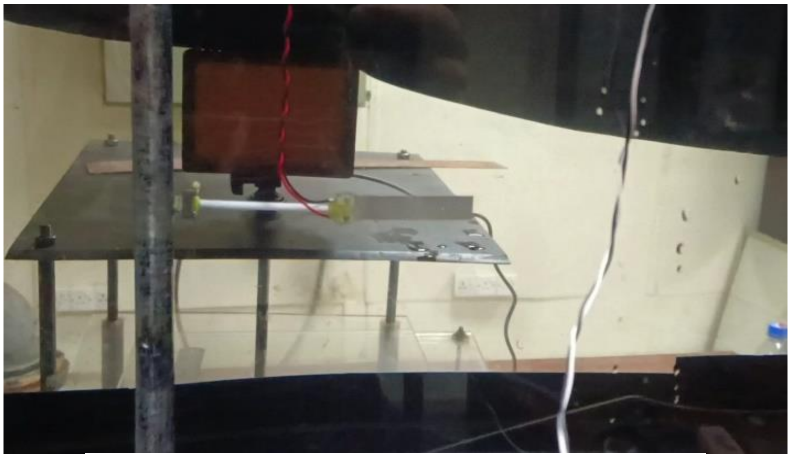


Figure 10: Active flapping flag setup underwater tunnel

5.4 Schematics

The integration of active flapping mechanisms into circular and 120-degree-cut cylindrical structures is a significant development in engineering, namely in the domains of aerodynamics and hydrodynamics. These mechanisms provide the cylindrical shapes with dynamic motion, which improves their functionality and performance in a variety of applications, from maritime engineering to aerospace.

The thesis's schematics provide a guide for putting active flapping devices on cylinders with a 120-degree cut as well as circular cuts. These schematics describe the complex mechanics needed to create precise oscillations around the surface of the cylinder. Through careful actuation system design and feedback control sensor integration, engineers can accurately control the flapping motion and get desired performance results.

Through the use of active flapping, the circular cylinder design manipulates the fluid or airflow around it by creating controlled oscillations over its surface. By altering the flow patterns, lift production, drag decrease, and overall aerodynamic efficiency may all be increased. These kinds of inventions might improve the efficiency of wind turbine blades, airplane wings, and other cylinder structures that are employed in fluid settings.

Meanwhile, these advantages are expanded to a wider range of applications with the incorporation of active flapping into 120-degree cut cylinders. Engineers may control the flapping motion to accomplish certain goals, including improving underwater vehicle mobility or optimizing lift-to-drag ratios, by carefully altering the cylinder's design.

These developments highlight how engineering research is multidisciplinary, connecting concepts from structural mechanics, fluid dynamics, and control systems. Active flapping mechanisms may be included in cylindrical designs, as shown by the schematics that are presented. This opens up new possibilities and pushes the envelope in domains where performance, efficiency, and flexibility are critical.

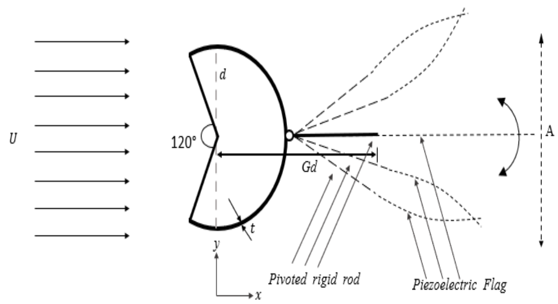


Figure 12: Schematic of active flapping on circuclar cylinder

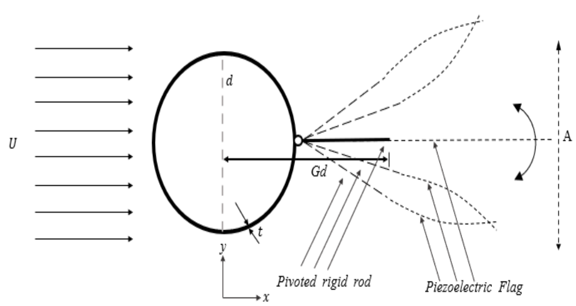


Figure 11: Schematic of active flapping on 120-Degree cut cylinder

5.5 Resistance

Resistance plays an important role in this energy generation process. As we are generating energy at the micro level it is essential to select the optimum resistance for the circuit. If we select less or more resistance this will directly affect the output of the circuit and we shall be unable to get the system for generating maximum energy. Here, used a resistance component to maximize power production in my energy-generating experiment where actively flapped the flag underwater. The effective production of energy via regulated flapping motion in the experimental setting was largely dependent on the use of resistance.

A methodical technique was used to find the optimal resistance for optimizing power production. The circuit was gradually filled with a succession of resistances, each time being observed for its effect on the power output. The ideal resistance value at which the circuit produced the most power production could be found thanks to this repeating procedure.

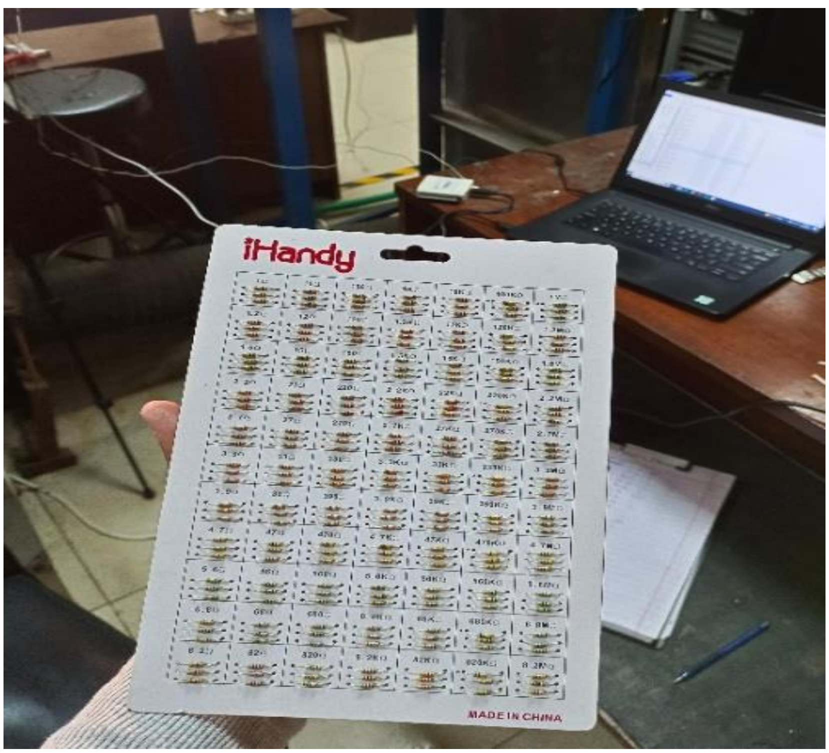


Figure 13: Set of various resistances

The link between resistance, current, and voltage in an electrical circuit serves as the foundation for this method's reasoning. The voltage drop between the components is affected by the resistance, which also modifies the current flow through the circuit. Using meticulous testing, the resistance value that enabled the maximum power transmission in the circuit was identified.

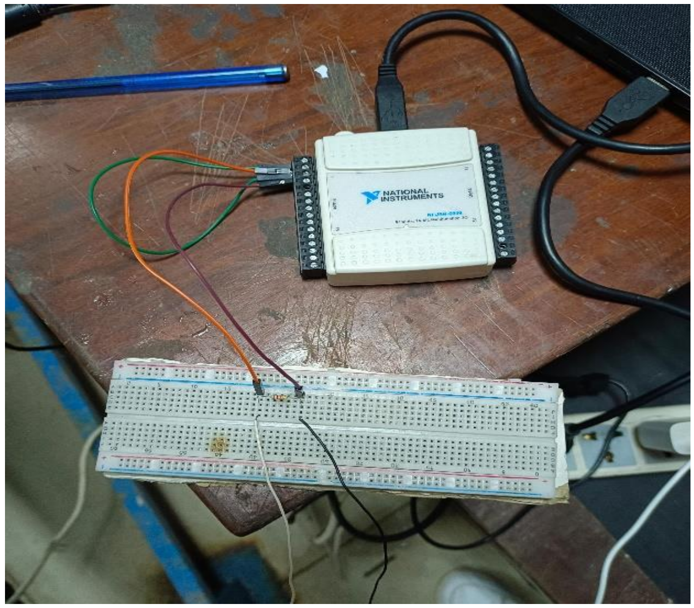


Figure 14: Breadboard and National Instruments connection

This repeated resistance value study was essential to optimizing the energy production process. It made it possible to pinpoint the exact circumstances in which the active flapping mechanism could function at its best, effectively converting mechanical motion into electrical energy.

This method also highlights the value of systematic optimization and experimentation in engineering research. Future energy-generating systems using similar concepts will be designed and operated using the insights obtained from the systematic variation of one parameter while maintaining the other parameters constant.

A set of resistances is being utilized as shown in Fig, 3a. A variety of resistances are used and the voltage output for each resistance. Fig. 3b shows the experimental setup for calculating the resistance. A breadboard is being used to complete the circuit which has connections with the flapping flag, national instrument, and the resistance. The graph shows that the resistances range from 82 kΩ to 1500 kΩ. The following formula ($P=V^2/R$) is used to calculate the power of the circuit.

The trend of the graph shows that the optimum resistance for our circuit is 120 kΩ because at that resistance the circuit gives the maximum power output of an estimated 18.13

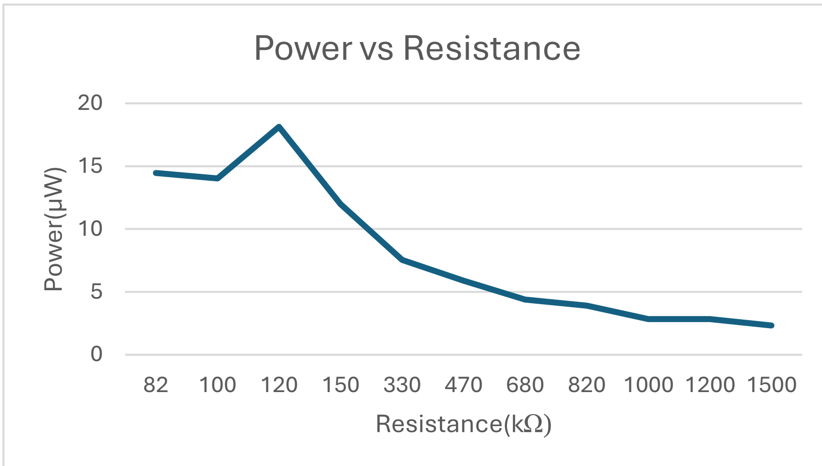


Figure 15: Graphical representation of optimum resistance

5.6 Particle Image Velocimetry

Particle picture Velocimetry (PIV) is a remarkable optical technique developed by scientists to analyze the fluid-structure and flow behavior, particularly in the wake zone. The technique uses tracer particles to create a picture that helps explain the features of the flow. PIV is a stream visualization method utilized to acquire scalar data, including fluid-related parameters, and instantaneous fields of vectors (velocity). The most important feature of this arrangement is seeding particles, which are introduced into the flowing fluid to acquire information on flow behavior. Depending on the application and medium, many types of particles are available on the market. For example, smoke is used in flow fields for air fluids, while beads, dye, or hollow glass particles are used in flow fields for water fluids. Particle densities are almost identical to those of the fluid under study. To make these particles visible on the digital camera mounted underneath the test section, an optical laser or pair of lasers, depending on the application, are used to light them. Using a cross-correlation approach, the sequential photos captured by the camera while the tracer particles were moving are then processed to get data on the flow field under investigation about flow velocity (the direction and speed of the particles). The distribution of view field parameters, flow vortices, and flow lines, also known as speed lines, are revealed by the analysis and processing of this data. A digital CMOS/CCD camera, a laser with an optical arrangement to produce a physical light sheet to illuminate the required/specified flow field, a synchronizer to regulate the timing of the camera and laser's triggering, tracer particles, and the fluid under investigation make up a typical setup for a particle image velocimetry system.

5.7 Research methodology

To thoroughly explore the nuances of both circular and 120-degree cut cylinders in the context of active flapping mechanisms, a carefully planned set of 50 experiments was carefully carried out. Twenty-five trials of each kind of cylinder were carefully arranged to provide fair representation across the experimental spectrum. This methodical approach made it easier to analyze in detail how the geometry of the cylinder affects the operation of active flapping mechanisms. It is impossible to exaggerate the importance of such a rigorous process. Every cylinder arrangement would get the same number of tests, thus any differences in performance could be ascribed to geometric differences rather than experimental bias. This careful planning protects the accuracy of the data and raises the validity of the study's results.

To guarantee the consistency and dependability of the dataset, meticulous preparation and implementation were essential. Every experiment was carefully designed to reduce unimportant factors and maintain uniformity across all trials. Every detail, from method execution to equipment calibration, was painstakingly examined to ensure the accuracy of the outcomes. The result of these combined studies provided an extensive amount of information on the complex interactions between fluid dynamics, cylinder shape, and active flapping energy production. Patterns emerged after thorough study, illuminating how little changes in cylinder design may have significant effects on performance.

Every experiment carried out for the research produced data via two different channels, giving rise to a comprehensive knowledge of the operation of the flapping mechanism. The first method of gathering data was taking a thorough picture of the fluttering flag in operation. Every attempt was painstakingly recorded by a high-resolution camera, which also produced a two-minute movie of the dynamic action. With the use of this film, researchers were able to see the minute details of the flapping action in real-time.

Concurrently, the energy production of the flying flag was measured using an advanced measurement system. The mechanical energy produced by flapping the flag was recognized by sensors implanted in it, and this energy was converted into electrical impulses. After that, these signals were sent to a data-gathering platform like the National Instruments platform, which painstakingly recorded the power output for every trial. A thorough grasp of the qualitative and quantitative facets of the flapping mechanism's functioning was made possible by this dual approach to data collecting.

To get significant insights from the unprocessed data, a customized MATLAB algorithm was created. This code functioned as a link between the signals that were captured and useful measurements like flapping frequency and amplitude. The MATLAB code used sophisticated signal processing methods to convert the obtained data into values that could be understood, allowing for a more thorough examination of the dynamics of the flapping mechanism. Researchers were able to measure the effectiveness of the flapping mechanism under various experimental situations by using MATLAB to derive important performance metrics. Researchers might determine the best operating settings and learn a great deal about the underlying processes controlling the behavior of the system by examining patterns in amplitude and frequency.

Furthermore, the process of extracting useful insights from the massive quantity of data that was gathered was made easier by the incorporation of MATLAB into the data analysis pipeline. Researchers were able to find patterns, anomalies, and correlations in the information using sophisticated data visualization tools and automated algorithms, which resulted in a more complex knowledge of the flapping mechanism's operation.

To summarise, the integration of eye observation, equipment, and computer analysis provided a thorough framework for assessing the flapping mechanism's performance. Researchers were able to glean important insights that shaped subsequent studies and directed future research paths by using sophisticated tools and procedures. This integrated approach emphasizes how crucial interdisciplinary cooperation is to improving our comprehension of intricate fluid-structure interactions and promoting the creation of novel renewable energy solutions.

The study's conclusions highlight how crucial it is to take cylinder form into account while designing and refining active flapping systems for energy generation. They provide useful advice for raising the efficacy and efficiency of renewable energy systems in addition to clarifying the fundamental principles driving fluid-structure interaction. The fact that even apparently little changes in cylinder shape may have a big impact on performance is one of the study's main conclusions. Through methodical investigation of the effects of various geometries, scientists may pinpoint the best designs that optimize energy production while using the fewest resources.

Furthermore, the systematic methodology used in this work provides a model for further investigations into fluid-structure interaction and the generation of renewable energy. Researchers may expand on the groundwork this study created by using rigorous experimental methods and analytical approaches to better our knowledge of these intricate events. Apart from its scientific ramifications, the research has pragmatic importance for sectors and decision-makers that want to use sustainable energy resources. By clarifying the variables impacting active flapping mechanisms' functionality, it offers insightful information that may guide the creation of more effective and environmentally friendly energy solutions.

Finally, the rigorous approach used in this work has provided priceless new information on the function of cylinder shape in active flapping processes for energy generation. Through methodically examining the effects of various geometries, scientists have improved our comprehension of fluid dynamics and established the foundation for future advancements in renewable energy technologies. Studies such as this point the way towards a more sustainable and affluent future, even as we continue to struggle with issues related to energy sustainability and climate change.

Table 1: Experimental cases for circular and 120-degree-cut cylinder

Circular Cylinder			120 Degree Cut-Cylinder		
Parameters	Value	Cases	Parameters	Value	Cases
Gx = gx/D	2, 2.5, 3, 3.5, 4	5	Gx = gx/D	2, 2.5, 3, 3.5, 4	5
U (m/s)	0.136, 0.155, 0.2, 0.25, 0.3	5	U (m/s)	0.136, 0.155, 0.2, 0.25, 0.3	5
Total (A)		25	Total (B)		25

CHAPTER 6: RESULTS AND DISCUSSION

6.1 Experimental and Calculated Data

This research will give the ideal conditions for the flapping flag to give maximum power output. There are two varied variables involved in this experiment. These two variables are the fluid velocity and the distance of the cylinders with the flapping flag. The fluid velocity range that is being used in this experiment is $0.136ms^{-1} \leq v \leq 0.3m^{-1}$, while the distance between the cylinders (Circular and 120^0-cut cylinders) changes in the range of $2D \leq Dx \leq 4D$. By making the sets of these ranges of data, it made up 25 cases for each cylinder. The total number of cases performed in this research is 50(25 for circular cylinder and 25 for 120^0-cut cylinder).

When a flapping flag is positioned behind a cylinder, vortex shedding is a natural occurrence that influences the flag. The higher-pressure cylinder's vortices cause the flag to bend, which in turn causes strain in the piezoelectric flag to amplify and produce the charge of electricity within the flag. The flag structure theory forms may be used to determine the strain caused by a flag. The thickness of the flag, its normalized flapping frequency, peak amplitude, capacitance, and other parameters all affect the magnitude of energy the piezoelectric flag extracts. According to research by He and colleagues, there is a clear correlation between the creation of electrical energy and distortion in the piezoelectric flag. Experimental research is done to determine the ideal tail location and generation of electricity by utilizing the same concept of deformation and power generation. Various flapping modes of a flexible flag, including biased, periodic, and continuous, are detected during the studies. The formula for calculating the average power produced is P = V2 /R, where V is the voltages measured over 2 minutes using a DAQ, R is the circuit load resistance determined by applying the theorem of maximum power transfer, and P is the power generated because of deformation of the flag.

6.2 Calculations for circular cylinder

The following table no.2 presents a thorough examination of many characteristics related to the evaluation of active flapping on circular cylinders. The most important of these characteristics is power production, which indicates how well energy is converted via the flapping process. Furthermore, knowledge of the force distribution throughout the cylinder's surface—which is essential for comprehending the hydrodynamic or aerodynamic interactions at work—is provided by the A/L ratios of the head and tail segments. Moreover, the oscillating frequencies depict the system's dynamic properties, which impact energy production and transmission. Our goal in providing these computations is to shed light on the complex connection between energy production and flapping dynamics on circular cylinders. The information provided here serves as a foundation for further study and interpretation, providing insights into how to optimize active flapping mechanisms for improved performance in a range of technical applications.

Table 2: Experimental values of power generated, A/L ratio for head and tail, and flapping frequency for circular cylinder

Circular Cylinder					
Fluid velocity(m/s)	Distance	Power(μW)	A/L ratio (Head)	A/L ratio (Tail)	Flapping frequency
0.136	2	11.26025574	0.104166667	0.311458333	0.0036533
	2.5	18.49276394	0.102171137	0.398467433	0.0418466
	3	18.89898984	0.113907285	0.458278146	0.0492133
	3.5	17.80585662	0.155704698	0.502013423	0.0611093
	4	19.23446975	0.170868347	0.610644258	0.0688058
0.155	2	19.68075537	0.163372859	0.482213439	0.0344587
	2.5	20.3470621	0.174372523	0.504623514	0.0415157

	3	20.29618182	0.20212766	0.579787234	0.0509971
	3.5	20.83754721	0.226018397	0.541392904	0.0598743
	4	20.47030563	0.242587601	0.654986523	0.0691366
0.2	2	20.56950855	0.160982265	0.452933151	0.0358685
	2.5	21.49094115	0.220338983	0.542372881	0.0443268
	3	19.67328056	0.23628692	0.545710267	0.0519352
	3.5	22.93383661	0.473906911	0.712411848	0.071783
	4	18.57985669	0.347480106	0.594164456	0.0618591
0.25	2	21.89552955	0.279596977	0.602015113	0.0039696
	2.5	21.69063003	0.311231394	0.682002706	0.0408567
	3	22.24842985	0.375979112	0.671018277	0.0496196
	3.5	21.91113583	0.351531292	0.639147803	0.0573311
	4	22.2576712	0.43715847	0.704918033	0.0691366
0.3	2	20.8054042	0.278350515	0.50257732	0.0368648

	2.5	18.5333616	0.380566802	0.636977058	0.042342
	3	21.51936813	0.393442623	0.683060109	0.050612
	3.5	15.55543839	0.403872752	0.680497925	0.0611975
	4	21.09604081	0.409012876	0.658082976	0.0710727

6.3 Analysis of power generation for a circular cylinder

Table 2 shows the experimental results obtained at various sets of fluid velocity and the distance between the circular cylinder and the flapping flag. The analysis of the data shows that the power generation is maximum when the fluid velocity is $0.2ms^{-1}$ and the distance Dx is 3.5D. At that moment, this setup gave the maximum amount of harvesting energy which is approximately 22.93µW. This output result will assist in the future to develop this setup at a higher level and get the maximum amount of energy by getting useful pieces of information from this experiment. Another thing to notice in this experiment is the minimum amount of energy which is obtained at a fluid velocity of $0.136ms^{-1}$ and the distance of 2D. This is also an impressive output of this experiment. However, our focus is to develop a setup that can generate the maximum amount of energy by utilizing the minimum number of resources. This result of the minimum amount of energy produced at $v=0.136ms^{-1}$ and Dx=2D will be beneficial in the future to guide the conditions that we need to avoid. In this way, it will save time and the investigator can directly focus on the conditions that give the optimum results.

6.4 Calculations for 120-degree cut cylinder

The following table no.3 summarizes a thorough examination of critical factors required to evaluate the effectiveness of active flapping on 120-degree cylinders. The most important of these characteristics is power production, which acts as a gauge for the effectiveness of energy conversion via the flapping mechanism. Furthermore, by illuminating the aerodynamic or hydrodynamic interactions at work, the A/L ratios of the head and tail segments provide important insights into the distribution of forces throughout the cylindrical surface. Furthermore, the oscillating frequencies shown in the table represent the dynamic properties of the system that impact energy production and transmission. We attempt to clarify the complex connection between flapping dynamics and energy production on 120-degree cylinders by presenting these computed numbers. To provide a better understanding of active flapping processes and their optimization for improved performance across a range of engineering applications, the data given below establishes the foundation for further study and interpretation.

Table 3: Experimental values of power generated, A/L ratio for head and tail, and flapping frequency for 120-degree cut cylinder

120 Degree cut cylinder					
Fluid velocity(m/s)	Distance	Power(μW)	A/L ratio (Head)	A/L ratio (Tail)	Flapping frequency
0.136	2	21.2187835	0.178378378	0.843243243	0.026133
	2.5	21.3131634	0.311428571	1.017142857	0.0334105
	3	21.7855031	0.338935574	1.078431373	0.0383984
	3.5	18.944461	0.470072993	1.179562044	0.0525107
	4	21.6588994	0.441489362	1.223404255	0.0510708
0.155	2	23.6753343	0.224806202	0.772609819	0.0262731
	2.5	24.486282	0.318954248	0.917647059	0.0345964

	3	24.8876619	0.428571429	0.946091644	0.0396957
	3.5	28.5768578	0.584848485	1.410192837	0.0453192
	4	24.5370174	0.615156018	1.435364042	0.0539199
0.2	2	25.2760703	0.413793103	0.954907162	0.0264638
	2.5	24.232026	0.537313433	1.137042062	0.0350645
	3	23.066098	0.522756827	1.061118336	0.0370493
	3.5	21.8386299	0.516010855	1.011058345	0.0363116
	4	25.9713427	0.57219973	1.055330634	0.0523888
0.25	2	24.6210306	0.571022727	1.261363636	0.0267946
	2.5	24.9482945	0.696132597	1.273480663	0.0340721
	3	25.7012867	0.729050279	1.262569832	0.0396957
	3.5	29.3431292	0.913217623	1.423347398	0.0578895
	4	28.4188763	0.823287671	1.361815754	0.0523039
0.3	2	25.9464724	0.479784367	0.884097035	0.0276771

	2.5	29.1860157	0.872521246	1.419263456	0.0463116
	3	24.2531452	0.566579634	1.046997389	0.0396957
	3.5	26.7849223	0.669577875	1.213973799	0.0337413
	4	27.2075914	0.832630098	1.326027395	0.0459808

6.5 Analysis of power generation for 120^0 cut cylinder

120-degree cut cylinder generates more energy as compared to the circular cylinder because of its geometry. The edges of the cylinder create more turbulence in the water which results in more disturbance in the flapping flag. However, the optimum fluid velocity and the distance from the cylinder are always an important factor. Table no.3 shows 25 cases performed in this research to analyze the factors and point to the optimum conditions to generate maximum energy. The data shows that throughout the experiment the 120-degree cut cylinder gives maximum energy as compared to the circular cylinder. The optimum condition comes out to be at the fluid velocity of $0.25ms^{-1}$ and distance of 3.5D. At this point, maximum energy is obtained which comes out to be approximately 29.34µW. Also, the minimum energy is obtained at the condition of fluid velocity of $0.136ms^{-1}$ and distance of 3.5D. This shows that we need to avoid this point while arranging the setup to extract maximum energy from the kind of system.

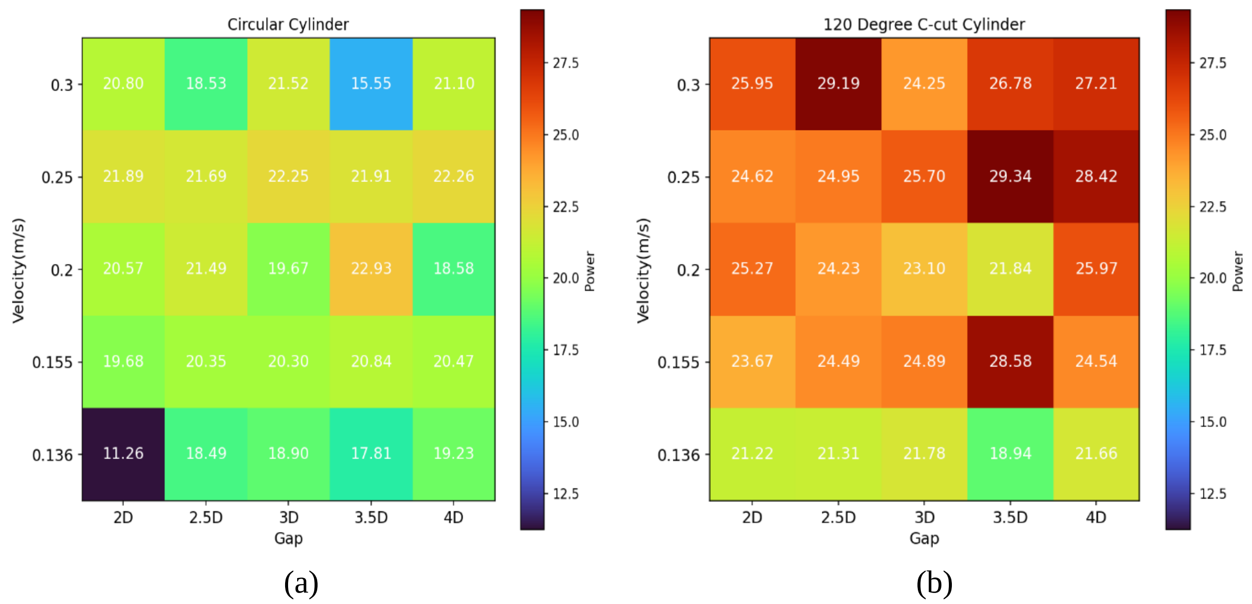


Figure 16: (a) Power generation in the circular cylinder, (b)Power generation in the 120-degree cut cylinder

6.6 A/L ratios analysis

6.6.1 A/L ratio for circular cylinder

The flapping frequency and the A/L ratio corroborate the experimental findings. These are the main arguments in favor of the experiment's successful completion. For example, the head and tail A/L ratios for the circular cylinder are around 0.47 and 0.71, respectively, at the point of maximal energy production. When compared to other values determined throughout the experiment, these values are about the highest. Furthermore, the experiment's maximum flapping frequency, with a value of around 0.072, is also the highest. Additionally, the A/L ratios for the head and tail, which are 0.1 and 0.31, respectively, at the point where the least amount of energy is taken represent the approximate lowest values in this experiment. The flapping frequency, which is 0.0036, is also rather low when considering the A/L ratios. If we take into account the overall circumstances, its value is a little higher than the other values in the column, but it still leads to a complete explanation that this data completely supports the point where the least amount of energy is given by the fluid velocity of 0.136 ms^{-1} and the distance of 2D.

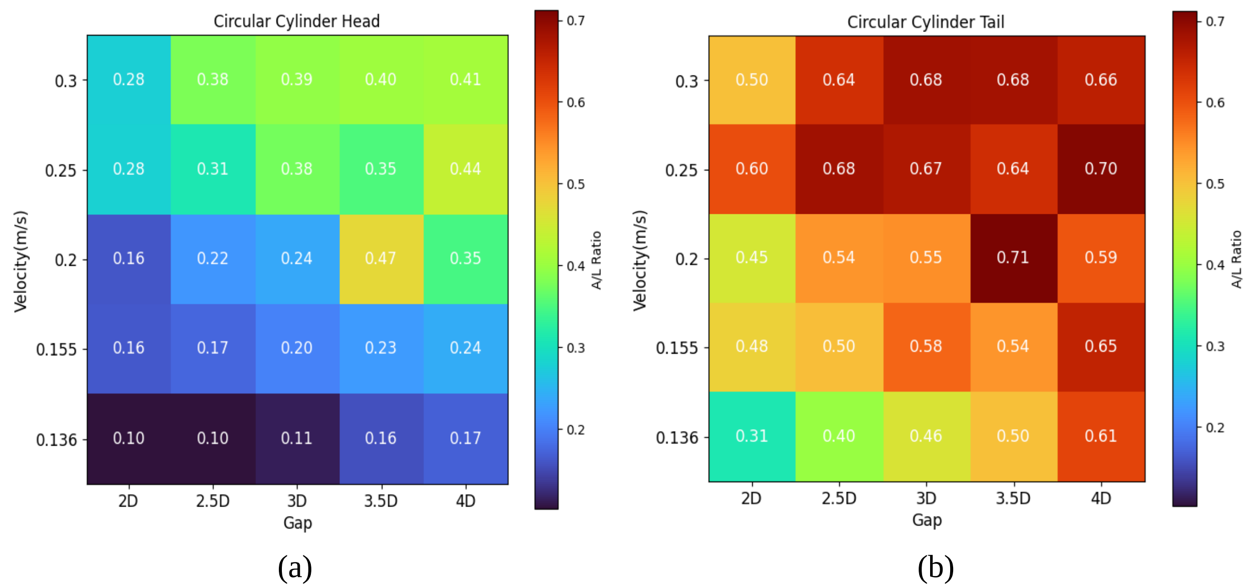
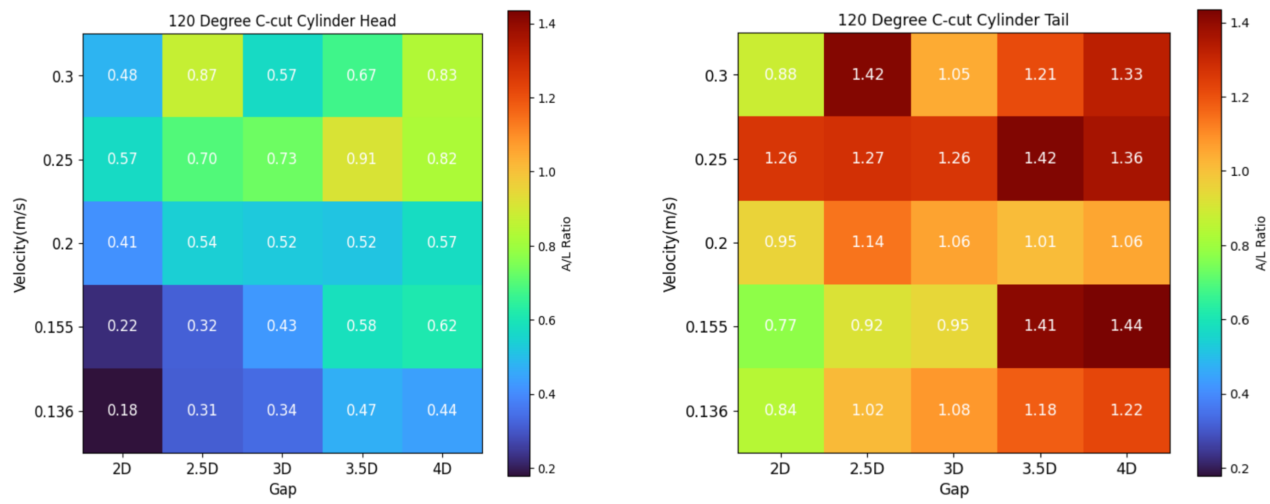


Figure 17: (a) A/L ratio of the head of circular cylinder, (b) A/L ratio of the tail of circular cylinder

6.6.2 A/L ratio for 120-degree cut cylinder:

The A/L ratio and the flapping frequency also support the results of the experiment. These are the major factors that justify the experiment being done effectively. For instance, at the point of maximum energy generation, the A/L ratios of head and tail are approximately 0.91 and 1.42 respectively. These values are approximately the highest ones as compared to other values calculated in the experiment. Additionally, the flapping frequency whose value is approximately 0.058 is also the highest one in the experiment. Also, at the point where minimum energy is extracted the values of the A/L ratios for head and tail which are 0.47 and 1.18 respectively are roughly the minimum values in this experiment. With the A/L ratios, the flapping frequency which is 0.052 is also comparatively low. Although its value is a bit higher than other values in the column if we consider the overall conditions, it results in complete justification that this evidence fully supports this point where the fluid velocity is 0.136ms^{-1} and the distance is 3.5D gives the least amount of energy. The main reason behind this is less movement of the flapping flag due to less disturbance in the moving fluid.



(a) (b)

Figure 18: (a) A/L ratio of the head of 120-degree cut cylinder, (b) A/L ratio of the tail of 120-degree cut cylinder

6.7 PIV outcomes and the hydrodynamic properties of the system

To get a deeper understanding of energy harvesting and the reasons behind the varying energy harvesting capabilities of cylinders, particle image velocimetry (PIV) is used to study the time-averaged wake of cylinders. Fig. 19 has the PIV results for the circular cylinder for two cases. One is the condition at which the power generation is minimum and the second one is for the maximum power generation configuration. This PIV analysis is done without attaching the flapping flag to the cylinder and it gives the vortices generated by the cylinder at that specific velocity of the fluid. These results elaborate that the vortices generated are causing the flapping flag to flap underwater. In Fig. 19(a) the vorticity range is less thus resulting is making the flapping flag flap at low speed but if we compare it to the Fig. 19(b), it is clear that the vorticity range is expanded and the disturbance due to the cylinder is effecting the water to a long range.

Fig. 20 analysis describes the vortices generated due to the 120-degree cut cylinder. It is visualized that vortices in the 120-degree cut cylinder are much higher as compared to the circular cylinder. The main reason is the geometry of the 120-degree cut cylinder which is making the water at high range. Fig. 20(a) is the PIV of the configuration of the 120-degree cut cylinder at which the cylinder gives the minimum energy. But here is clear that even at the minimum point, the 120-degree cut cylinder is giving more energy as compared to the circular cylinder just because more vortices form in it. These results indicate that the overall disturbance in the 120-degree cut cylinder is more than the circular cylinder. These results are very useful while analyzing the energy generation process in the flapping flag because these results identify the spots that can result in generating more energy.

As a consequence, the piezoelectric flag receives maximal flow/mechanical energy transfer, which increases the creation of electrical energy. More force corresponds to greater displacement in terms of piezoelectric flag deformation. This directly affects energy production, leading to a larger captured energy since stronger vortices have higher vortices.

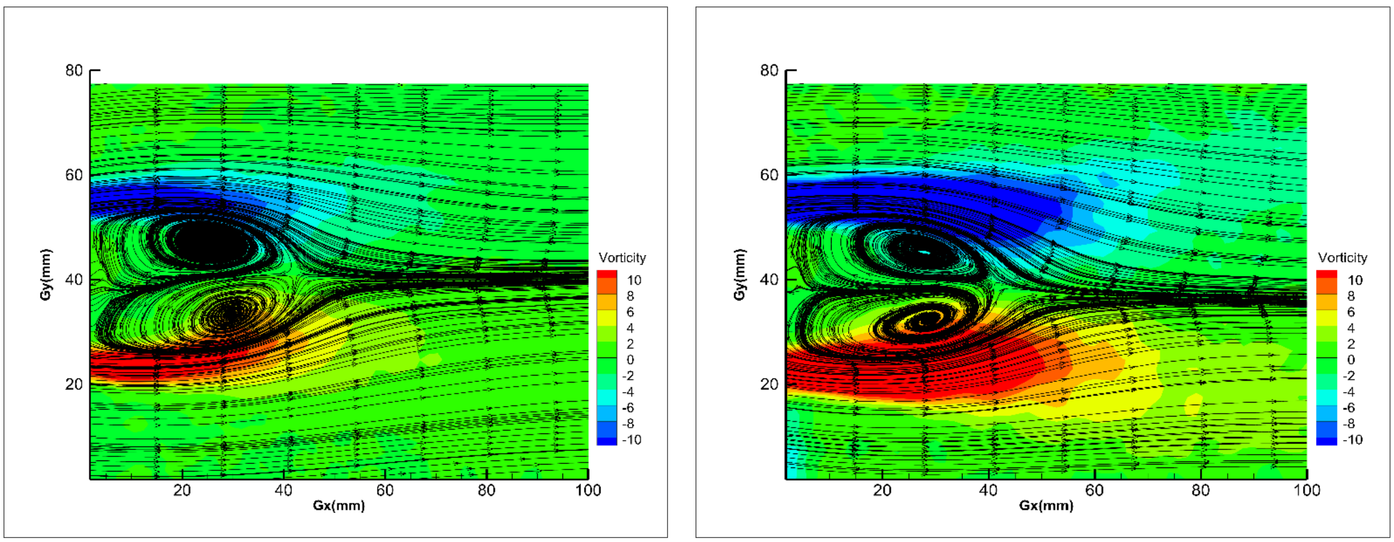


Figure 19: Formation of a continuous wake in the flow field behind CIRCULAR CYLINDER without a flag (a) At minimum power generation conditions (b) At maximum power generation conditions

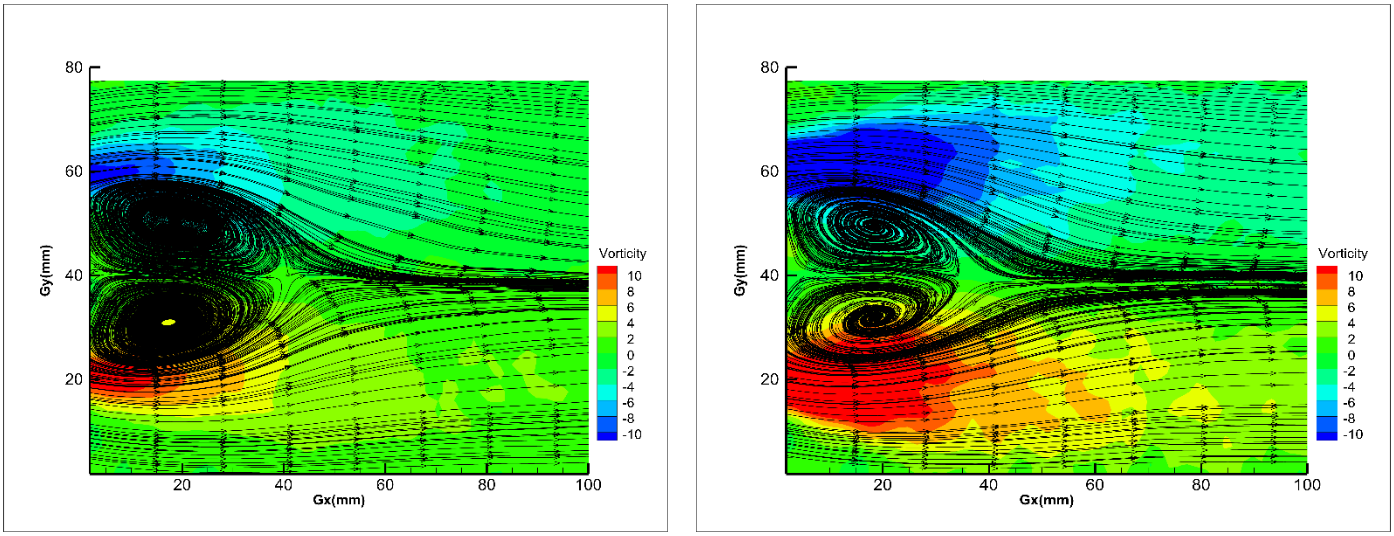


Figure 20: Formation of a continuous wake in the flow field behind 120-DEGREE CUT CYLINDER without a flag (a) At minimum power generation conditions (b) At maximum power generation conditions

6.8 Flapping frequency:

This is an additional investigation to check out and compare the flapping frequencies of the head and tail of the circular and 120-degree cut cylinders. Table no.4 shows the values of flapping frequencies for all the possible cases of varying fluid velocity and the distance of the flapping flag from the cylinders. This data shows that the flapping frequencies remain approximately the same for the head and the tail. This behavior is because of many valid reasons just like the hydrodynamic symmetry and uniform force distribution. Symmetric forces operating on both ends of the flag result from the geometry and shape of the flag as well as the fluid dynamics in the surrounding environment. The head and tail have identical flapping frequencies because of this symmetry. Another reason for the same frequencies of tail and head is that they both are under the influence of the frequency of the vortices created. As the length of the flapping flag is not much so the same frequency is acted on both the tail and head. This is justified in Fig. 20 below that the phase difference between the head and the tail is zero throughout the experiment. This figure also displays the amplitude of the head and the tail in the second part which overlap in all the cases.

Just the difference of their amplitude can be noticed but they are following the same pattern throughout the experiment.

Table 4: Flapping frequencies of head and tail for circular and 120-degree cut cylinders

Fluid velocity(m/s)	Distance	Head circular cylinder	Tail circular cylinder	Head C-cut cylinder	Tail C-cut cylinder
0.136	2	0.0036533	0.0036533	0.026133	0.026133
	2.5	0.0402534	0.0418466	0.0334105	0.0334105
	3	0.0492133	0.0492133	0.0383984	0.0383984
	3.5	0.0611093	0.0611093	0.0525107	0.0525107
	4	0.0688058	0.0688058	0.0510708	0.0510708
0.155	2	0.0344587	0.0344587	0.0262731	0.0262731
	2.5	0.0415157	0.0415157	0.0345964	0.0345964
	3	0.0509971	0.0509971	0.0396957	0.0396957
	3.5	0.0598743	0.0598743	0.0453192	0.0453192
	4	0.0691366	0.0691366	0.0539199	0.0539199
0.2	2	0.0358685	0.0358685	0.0264638	0.0264638
	2.5	0.0443268	0.0443268	0.0350645	0.0350645
	3	0.0519352	0.0519352	0.0370493	0.0370493

	3.5	0.071783	0.071783	0.0363116	0.0363116
	4	0.0618591	0.0618591	0.0523888	0.0523888
0.25	2	0.0039696	0.0039696	0.0434895	0.0267946
	2.5	0.0408567	0.0408567	0.0340721	0.0340721
	3	0.0496196	0.0518754	0.0396957	0.0396957
	3.5	0.0573311	0.0573311	0.0578895	0.0578895
	4	0.0691366	0.0691366	0.0523039	0.0523039
0.3	2	0.0368648	0.0368648	0.0276771	0.0276771
	2.5	0.042342	0.042342	0.0463116	0.0463116
	3	0.050612	0.050612	0.0396957	0.0396957
	3.5	0.0611975	0.0611975	0.0337413	0.0337413
	4	0.0710727	0.0710727	0.0459808	0.0459808

6.9 Phase difference:

Computational tools like MATLAB are invaluable in the quest to comprehend the complex dynamics of active flapping processes. Using MATLAB, examined the behavior of the system to try to understand the phase difference between the head and tail segments of a 120-degree cylinder. The MATLAB algorithm produced fascinating insights into the relative phase relationship between these important components through rigorous computation and data processing.

When the code ran, something unexpected happened: for a certain random example, the phase difference between the head and tail segments seemed to be always zero degrees. This result, which is represented graphically in the output as a straight line, highlights the synchronization between the two segments and points to a harmonized motion pattern that merits additional research. This result encourages further investigation into the fundamental mechanisms governing such coherence, while also highlighting the complexities of the flapping dynamics.

Additionally, a graphic depiction of the amplitude comparison between the head and tail segments was supplied by the MATLAB analysis. The final image showed a remarkable overlap between the two, with just very tiny amplitude fluctuations visible. Interestingly, the tail segment showed a somewhat larger amplitude than the head, indicating subtle variations in the forces applied over the surface of the cylinder. This subtle difference in amplitude distribution highlights the significance of precisely calibrated flapping mechanisms in maximizing energy generation and fluid interaction, providing insightful information about the aerodynamic or hydrodynamic forces at work.

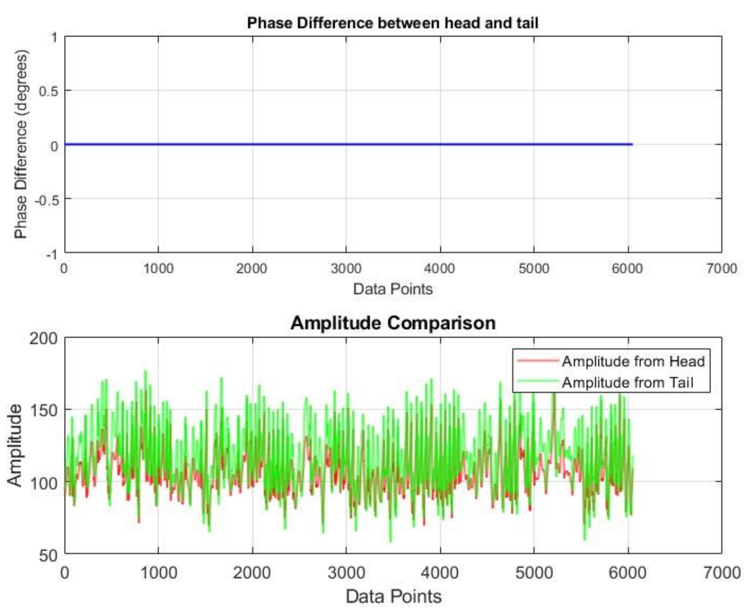


Figure 21: Phase difference and amplitude for head and tail of flapping flag

CHAPTER 7: CONCLUSION

Drawing Based on results from large-scale energy harvesting experiments using active flapping mechanisms and circular and 120-degree cut cylinder flags submerged in fluid media, this work provides important new understandings into fluidic energy production optimisation. Through a thorough analysis of the complex interaction between several parameters and the resulting power generation, the research reveals important variables that affect the efficiency of energy extraction.

This study's main contribution is its methodical examination of the effects of varying the fluid's velocity and distance from the cylinder on the efficiency of energy harvesting. The research clarified the complex interactions between these factors by meticulous testing, providing insight into the ideal operating parameters for maximizing power production.

Notably, the analysis produced strong evidence that the 120-degree cut cylinder structure generates more energy than its circular equivalent under certain fluid velocity and distance parameters. Peak power generation for the circular cylinder was found at a distance of 3.5 times the cylinder diameter (3.5D) and a fluid velocity of 0.2 m/s, resulting in a maximum power output of 22.93 μW. The 120-degree cut cylinder, on the other hand, performed better, extracting the highest amount of energy at a fluid velocity of 0.25 m/s and 3.5D away from the cylinder. This disparity in performance emphasizes how important geometric design is to fluid flow energy harvesting system optimisation.

Additionally, Particle Image Velocimetry (PIV) methods were used in the investigation to validate the power-generating processes that were discovered. The PIV findings validated the effectiveness of the energy-collecting mechanism by providing strong visual evidence of vortices created by both cylinder designs. The 120-degree cut cylinder's increased power output emphasizes, even more, its potential as the best option for energy harvesting applications, especially in settings with plenty of fluid motion.

These results not only guide the development and refinement of energy harvesting apparatuses but also highlight how crucial it is to use geometric design principles to efficiently utilize the intrinsic dynamics of fluid-structure interactions. The foundation for the creation of more effective and long-lasting energy harvesting devices is laid by this study, which offers useful insights into the variables affecting energy extraction efficiency.

To sum up, this study's findings greatly advance our knowledge of the mechanics behind energy harvesting in fluid settings. This study opens the door for the creation of more potent energy harvesting systems by emphasizing the significance of geometric design optimization and clarifying the fundamental principles determining energy extraction efficiency. Research like this is essential to moving us closer to a more sustainable future as we look for new ways to solve the world's energy problems.

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