Energy Harvesting by Bio-Inspired Inverted C-Cylinders

Author
Abdullah Tanveer

Registration Number
00000319339

Supervisor
Dr. Emad Uddin

SCHOOL OF MECHANICAL & MANUFACTURING ENGINEERING

NATIONAL UNIVERSITY OF SCIENCES AND TECHNOLOGY

ISLAMABAD

MAY 2022

Energy Harvesting by Bio-Inspired Inverted C-Cylinders

Author
Abdullah Tanveer

Registration Number
00000319339

A thesis submitted in partial fulfillment of the requirements for the degree of MS Mechanical Engineering

Thesis Supervisor:
Dr. Emad Uddin

Thesis Supervisor's Signature: ____________________________

SCHOOL OF MECHANICAL & MANUFACTURING ENGINEERING

NATIONAL UNIVERSITY OF SCIENCES AND TECHNOLOGY
ISLAMABAD

MAY 2022

Declaration

I certify that this research work titled "Energy Harvesting by Bio-Inspired Inverted C-Cylinders" is my own work. The work has not been presented elsewhere for assessment. The material that has been used from other sources it has been properly acknowledged / referred.

Signature of Student

Abdullah Tanveer
MS-ME19-319339

Thesis Acceptance Certificate

Certified that final copy of MS thesis written by Mr. Abdullah Tanveer Registration No. 319339, of SMME has been vetted by undersigned, found complete in all respects as per NUST Statutes / Regulations, is free of plagiarism, errors, and mistakes and is accepted as partial fulfillment for award of MS degree. It is further certified that necessary amendments as pointed out by GEC members of the scholar have also been incorporated in the said thesis.

Signature:

Name of Supervisor: Dr. Emad Uddin

Date:

Signature (HOD):

Date:

Signature (Principal):

Date:

Plagiarism Certificate (Turnitin Report)

This thesis has been checked for Plagiarism. Turnitin report endorsed by Supervisor is attached.

Signature of Student
Abdullah Tanveer

Registration Number
00000319339

Signature of Supervisor

Copyright Statement

Acknowledgements

I am thankful to my ALLAH Subhanahu-Wata'la to have guided me throughout this work at every step and for every new thought which You setup in my mind to improve it. Indeed, I could have done nothing without Your priceless help and guidance. Whosoever helped me throughout the course of my thesis, whether my parents or any other individual was Your will, so indeed none be worthy of praise but You.

I am profusely thankful to my beloved parents who raised me when I was not capable of walking and continued to support me throughout in every department of my life.

I would also like to express special thanks to my supervisor Dr. Emad Uddin for his tremendous support and cooperation. Each time I got stuck in something, he came up with the solution, without his help I wouldn't have been able to complete my thesis. I appreciate his patience and guidance throughout the whole thesis.

I would also like to thank Dr. Adnan Munir, Dr. Zaib Ali and Dr. Niaz Bahadur Khan for being on my thesis guidance and evaluation committee and express my special thanks to them for their help.

I would also like to thank my fellow lab members Abdul Raheem, Shaban Nawaz and Safeer Ahmad for their support while passing through experimental phase of my research. Finally, I would like to express my gratitude to all the individuals who have rendered valuable assistance to my study.

Dedicated to my exceptional parents, my adored siblings, my better half and my dearest Fatima whose tremendous support and cooperation led me to this wonderful accomplishment.

Abstract

Key Words: *Piezoelectric eel, Bio-inspired, Stream wise gap, Bluff body, Inverted C, Vortex.*

In a uniform flow, the interaction of piezoelectric flag with bio inspired C shaped bluff bodies was examined. Based on vortex-induced vibration, the piezoelectric eel converts the kinetic energy of flowing water into electrical energy. The flapping behavior of a piezoelectric flag in the wake of a bluff body was studied in terms of stream wise gap between piezoelectric flag and bluff body. The experiments were carried out by placing a conventional piezoelectric flag in the wake of a bluff body in a low-speed water tunnel and varying the stream wise gap (Gx) behind a bio inspired inverted C shaped cylinder to see how the vortices produced by the bluff body affected the flapping amplitude, frequency, and voltage generated by the piezoelectric flags. The effect of different bluff bodies and varying streamwise gap on energy harvesting was observed and optimal results were obtained.

Table of Contents

List of Figures

List of Tables

List of Symbols and Abbreviations

Symbols

F	Frequency (Hz)
T	Tension Force (N)
D	Diameter of Cylinder (mm)
α	Cut Angle (°)
St	Strouhal number
Re	Reynolds number

Abbreviations

PIV	Particle Image Velocimetry
CFD	Computational Fluid Dynamics
ALE	Arbitrary Lagrangian-Eulerian
VFD	Variable Frequency Drive
GPEH	Galloping-based Piezoelectric Energy Harvester
EDM	Electric Discharge Machine
RO	Reverse Osmosis
DAQ	Data Acquisition

CHAPTER 1
INTRODUCTION

Due to the consequences of increasing global warming and the growing demand for fossil fuels, renewable energy resources have sparked the interest of many scholars. Energy harvesting is an advanced technology that enables low-power wireless electronic devices and remote power sources for running sensors. It improves community safety by enabling wireless health monitoring tools and providing green energy. It offers environmental benefits because it replaces traditional battery packs and minimizes chemical and toxic waste. That’s why, Energy harvesting has become more popular into low-powered wireless electronic applications. The weight and volume of a wireless sensor network's batteries have a major impact on its performance and design life.[1] The gases generated as a result of fossil fuel burning might cause respiratory and heart problems. These energy sources will generate electricity without harming the environment. As a result, environmental pollution is reduced, resulting in cleaner water and air.

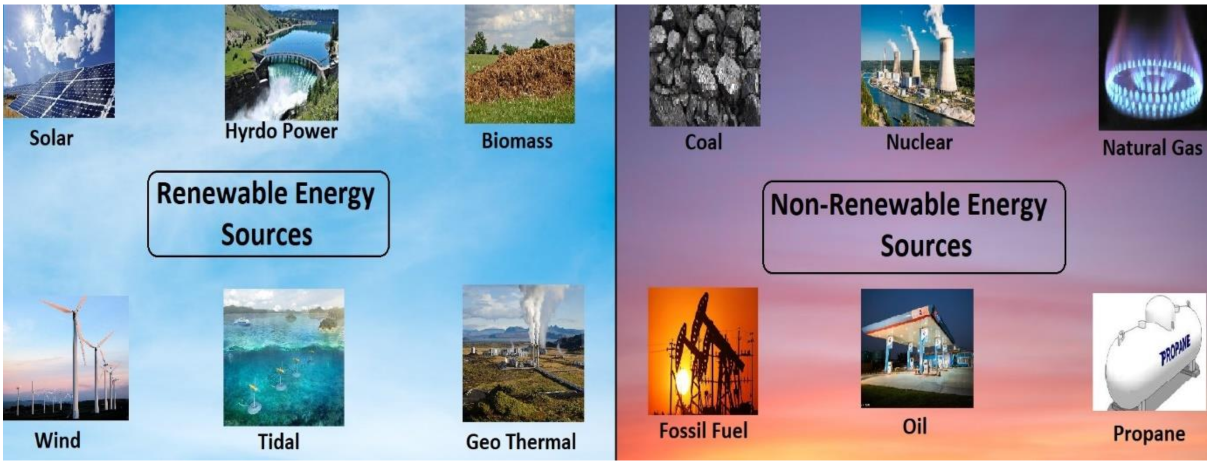


Figure 1: A comparison of Renewable and Non-Renewable energy resources

1.1 Motivation and Background

The threat of global climate change has been growing since last few decades which motivated the research and development to put their keen interest in renewable energy technologies. Ocean is a huge and abundant source of potential energy which can be utilized by sustainable energy extracting techniques. Most importantly, it’s renewable energy resource and its green energy can be utilized without harming the marine environment. The numerous researches have been conducted worldwide to develop self-sustaining sensing systems to overcome the engineering challenges caused by the oceans. Mostly scientific and military operations conducted in remote areas need small amount of energy for their sensors deployed at several locations. To collect data regarding upcoming disasters, pollution, exploring and research, we need small sensors packages in remote places which are self-sustaining and can get their energy from nearby oceans, rivers, lakes and streams.[2]

The advancement in science has introduced us to new materials which are more flexible and bear a lot of physical and chemical properties as compared to the traditional ones.[3] By combining the advance computing sensor packages with the new materials, this field of development has been boosted and opened the new areas of interest. However, we are still finding the more accurate, reliable and practical system in this regard.[4]

Sensors' ability to execute time taking operations is currently restricted by their capability to gather and manage energy throughout their operations. If energy consumption can be regulated, the next concern is whether the sensors will be able to create or receive extra energy in order to prolong their operation time.[5] When monitoring a fish holding station in an irregular fluid flow while migrating upstream to spawn, it is clear that the fish take use of their circumstances to conserve energy. The latter implies that energy may be extracted by using the fluid flow caused by tidal streams or forward velocity as a source of energy. To extract energy from the surroundings and charge the sensors, an approach could be used. Except in the case of unavoidable maintenance, the need to return the scheme to the exterior or send specialized underwater explorer into the water to substitute the batteries would therefore be underrated. This would save time and money, as well as broaden the spectrum of possible sensing applications.

This technology could also be used in a different fluid, such as air. There are devices that limit and keep a check on temperature, pressure, and moisture in complicated HVAC duct networks at enterprise buildings, for example. Energy harvesting devices that use the airflow to produce power around the clock, which is then reserved and assembled gradually at power banks, can greatly extend the life of such detecting schemes. At times, the gadgets themselves double as sensors and resonators, allowing them to partially or completely meet their power requirements. From an engineering standpoint, the way nature works has always piqued our interest. Engineers frequently attempt to mimic natural and behaviors.[6] Engineers and biologists are only now beginning to comprehend how marine organisms might instinctively harvest fluid-mechanical principles. Nature has generated speed, body mobility, and efficiency over time, all of which are suitable characteristics for energy harvesting and sensing devices.

The purpose of this research is to see if an inanimate object subjected to uneven flow may extract energy from its movement using the similar mechanisms as fish. This will need a mechanical structure that is coupled to the fluid flow that captures and converts kinetic energy into electrical energy. Airflows and the piezoelectric flag experiment planned for usage in the water have both shown examples of such devices.[7] The mechanical structure must be designed to maximize the linkage to the fluid flow, the energy harvesting processes must be compatible to the structure, and the power conditioning electronics must be cautiously reviewed to maximize efficiency of transformation in order to achieve a successful energy harvester.[8]

1.2 Energy Harvesting

The phrase "piezoelectricity" comes from the Greek terms "press" and "amber," which were both regarded as a source of electricity in ancient times. Piezoelectric polymers are designed to transfer mechanical energy into electrical energy in a variety of ways. In science and technology, piezoelectric sensors have a wide range of implementations. The majority of electrical devices get their power from piezoelectric technology. Audible alarms, patient monitors, air bag sensors, and keyless entry systems are just a few examples. Furthermore, they are employed in smart phone devices to convert the energy of a person's speech into electrical impulses, which are then received by another phone and converted into audible sound.[9] A piezoelectric flag, also known as an energy harvesting eel, is a device that can harvest energy from the ocean or a river. It is a renewable energy source that may be used to generate electricity in remote regions.

1.2.1 Piezoelectric Eel

The piezoelectric Eel is a device that transforms mechanical energy from a fluid medium into electric power using piezoelectric polymers. The system may gather energy from the ocean or a river, providing long-term power for sensors and robots that are positioned far away. Eel generators employ vortex shedding behind a bluff body to generate low frequency voltage. The eel's flow-driven oscillations cause strain on piezoelectric materials, resulting in low frequency voltage. Scientists are interested in the connections between the hydrodynamics of the flow and structural aspects of the eel, and have conducted both physical tests and numerical simulations, concentrating on the maximum strain energy and power output. As a result, positioning a bluff body in front of a piezoelectric eel causes vibrations in the flag due to wake.

Figure 2: Piezoelectric Eel

1.3 Flow behind a circular cylinder

External flows past objects have been extensively studied due to their diverse applications. Airfoils, for example, are designed with laminar shapes to enhance lift while reducing wing aerodynamic drag.[10] The wake region behind a blunt body, such as a round cylinder, typically experiences boundary layer separation and very strong flow oscillations. A periodic flow motion emerges in the wake as a result of boundary layer vortices being shed alternately from both sides of the cylinder in a particular Reynolds number range.[11] In the wake, a Karman vortex street is a continuous pattern of vortices. It results in an oscillating flow with a discrete frequency proportionate to the Reynolds number of the flow. The periodic nature of the vortex shedding mechanism can sometimes generate unwanted structural vibrations, especially if the shedding frequency coincides with one of the structure's resonance frequencies.[12] One example is the well-known Tacoma Narrow Bridge event, which has been extensively addressed in the Tacoma bridge link. Using the Particle Image Velocimetry (PIV) technology, we can explore the flow through a circular cylinder and investigate the turbulent wake flow field.

1.3.1 Flow Separation

The existence of fluid viscosity causes the fluid particles to slow down exceedingly close to the solid surface, forming a thin, slow-moving fluid layer known as a boundary layer. The flow velocity at the surface must be zero to fulfil the no-slip border requirement. Because of the strong viscous flow resistance, the flow momentum inside the boundary layer is comparatively shallow. Therefore, the aerodynamic flow is affected by the external pressure gradient (as the form of a pressure force acting upon fluid particles). The pressure gradient is regarded to be beneficial if the pressure decreases in the flow route. There is no flow retardation in this situation since the pressure force is assisting the fluid progress. However, if the pressure rises in the course of the flow, this is known as an unfavorable pressure gradient situation. The fluid molecules now have to travel contrary to a rising pressure force in addition to a high viscous force. Therefore, the fluid molecules might be halted or overturned, forcing adjacent molecules to migrate apart from the surface. The boundary layer separation is the name for this occurrence.

1.3.2 Wake

Examine the movement of a fluid particle through a circular cylinder's boundary layer. As per the pressure dissemination obtained in the earlier project, the pressure is excessively high at the stagnation point and gradually decreases along the front half of the cylinder.[13] As predicted, the flow persists connected in this favorable pressure area. The pressure in the rear half of the cylinder, on the other hand, continues to increase, resulting in an unfavorable pressure gradient for the particle. As a result, the flow separates from the surface, generating the wake behind the cylinder, a very turbulent zone. The pressure inside the wake zone remains low when the flow separates, resulting in a net pressure force (pressure drag).

1.3.3 Vortex Shedding

The border layer breaks from the exterior, forming a very unbalanced free shear layer. This shear layer will ultimately separate from the surface and roll into a distinct vortex (a phenomenon called vortex shedding). When the vortices generated from the top and bottom surfaces of the shear layer interface, a new form of flow instability occurs.[14] They exit the cylinder alternately, leaving behind a consistent vortex outline (the Karman vortex street). The frequency of vortex shedding is a consequence of the Reynolds number and happens at a distinct frequency. When the Reynolds number is greater than 1000, the dimensionless frequency of vortex shedding, the shedding Strouhal number, St = f D/V, is nearly equivalent to 0.21.[12]

1.3.4 Vortex-Induced Vibrations

When vortices leave the bluff body, an unequal pressure dissemination arises among the cylinder's topmost and bottommost surfaces, resulting in oscillatory aerodynamic loading (lift). If the "resonance" requirement is fulfilled, this unstable force can cause considerable vibrations in a structure. The most well-known paradigm is the 1940 collapse of the Tacoma Narrow Bridge due to wind-induced vibrations. Natural vortex shedding frequency behind the bridge is thought to match one of the bridge's resonant modes, eventually causing a catastrophic vibration that destroys the bridge.

1.3.5 PIV Technology

The PIV is a quantitative flow visualization technology that records and processes the multiply-exposed molecule figure outline of microscopic traces floating in fluid to calculate instantaneous whole-field fluid velocities. The seeded flow field is first illuminated with a slim laser film to get the PIV particle picture. The seed molecules scatter light, creating a particle image pattern.

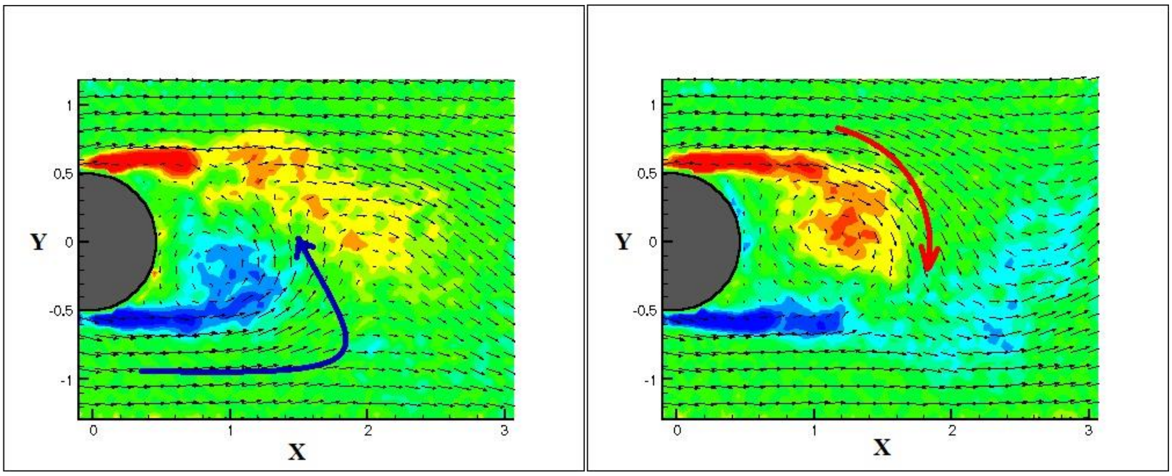


Figure 3: Development of lower & upper vortex

1.4 Thesis Aims and Objectives

There are two main concerns in this work. First of all, we'll see if a non-living thing can be configured to counter to an instable flow field. Second, is the motion of the lifeless thing adequate for it to function as an energy collecting device.

The following goals were defined to meet the above-mentioned problems and reveal that a properly adjusted lifeless figure may yield energy from an unstable subsurface fluid flow:

1) To arrange a recirculating water channel which could be used in experimental study to investigate the response of piezoelectric eel attached behind a bluff body.
2) To design and develop bio-inspired finned cylinders which act as bluff body.
3) To develop a method for placing piezoelectric material into a bluff body.
4) To determine the intimate object's amplitude and frequency tuning to a specific unsteady flow pattern. It was feasible to experimentally determine these two parameters using a customized MATLAB® algorithm at varied flow regimes.
5) To post process the experimental data and obtain the appropriate results.
6) To conduct comparative study of results and obtain appropriate figures in the form of tables, bars, graphs.

1.5 Research Plan

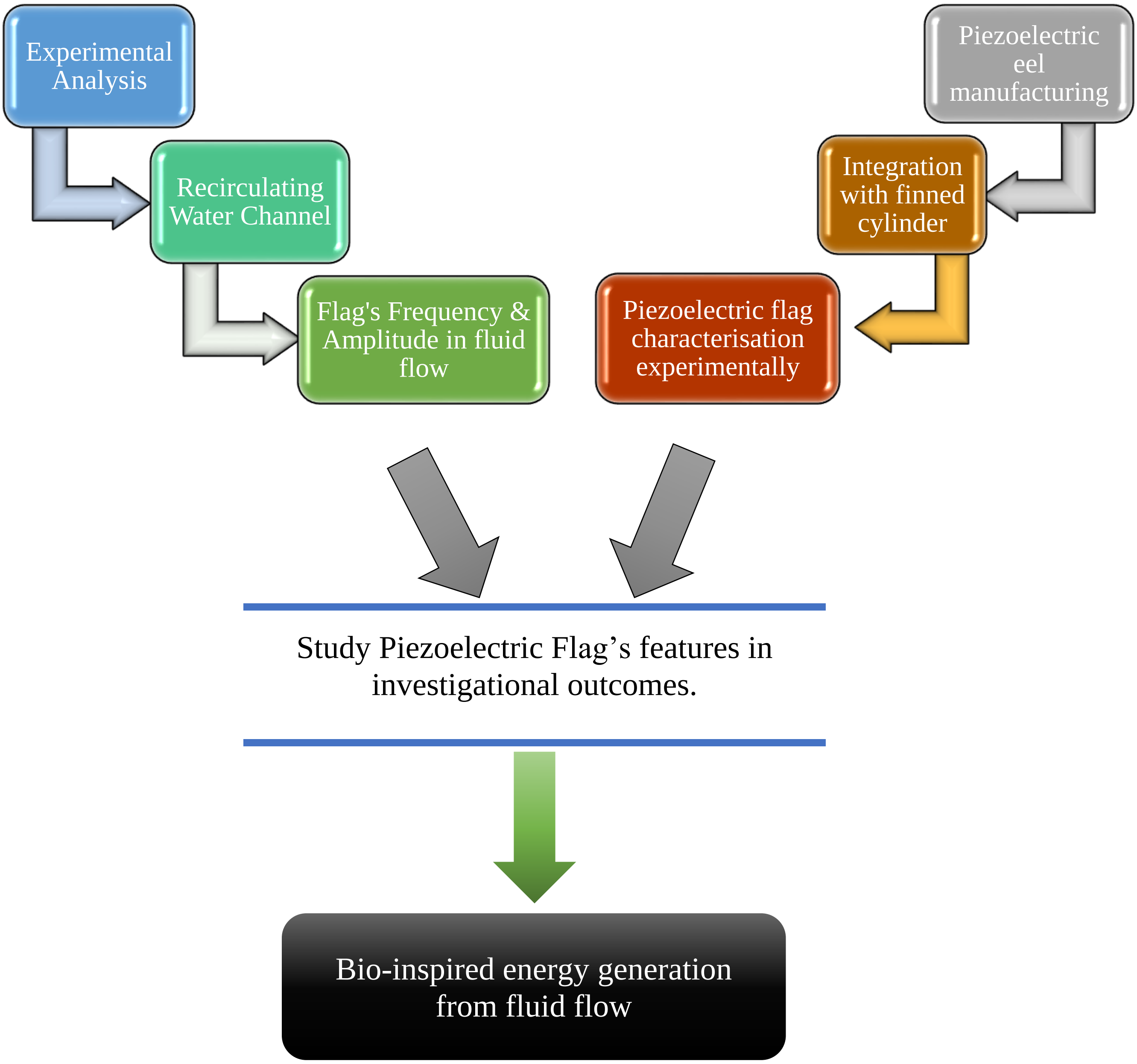


Figure 4: Research plan

1.6 Thesis Outline

Chapter 1: Introduction

This section contains brief foreword and overview of problem statement along with the basic scientific concepts of the thesis. The objectives and research outline are also included in this portion.

Chapter 2: Literature Review

This chapter includes the past researches in the area of Renewable anergy and energy harvesting in the light of piezoelectricity.

Chapter 3: Methodology

This chapter contains the development of experimental setup and conduction of experiments in an appropriate scientific environment to obtain fortunate results.

Chapter 4: Results & Discussion

This chapter includes the individual outcomes as well as the comparison among different cases of our study in the form of line graphs, surface plots, tables and charts.

Chapter 5: Conclusions

This chapter contains a summary of the thesis and highlights the overall outcomes in a brief manner.

Chapter 6: Future Recommendations

This chapter includes the future scope of the study and research gap for upcoming authors and researchers.

Chapter 7: References

This chapter contains the articles, conference papers and research paper's trajectory which are referenced in this study.

CHAPTER 2
LITERATURE REVIEW

Future scenarios with major climate change show massive increases in global fossil fuel output which is the primary source of CO2. Meanwhile, depletion of fossil fuels has been recognized as a potential problem.[15] According to mounting data, the global climate (i.e., circumstances spanning 30 years or more) is now altering as a result of anthropogenic, notably those which result in the generation of global warming from fossil fuels.[16] Apart from technological modifications like growing non-fossil-fuel energy generation, reducing the usage of fossil fuels will necessitate other changes.[17]

Renewable sources are pure energy sources, and their optimal use minimizes atmospheric impacts, creates low secondary pollution, and is stable in the perspective of current and future financial and sociocultural demands.[18] The purpose of using renewable energy is to reduce the negative environmental effects of non-renewable energy sources such as coal, oil, and natural gas. Adopting renewable source not only benefits money long term, but it also helps to protect the earth from the hazards of fossil fuel waste.[19]

The creation of tiny, low-cost, low-power multifunctional sensor nodes that can communicate wirelessly over short distances has been facilitated by recent breakthroughs in wireless communications and electronics.[20] Oceanographic facts assortment, contamination management, catastrophe precaution, aided navigation, tactical surveillance operations, and study of natural undersea marine means are just a few of the uses for successful underwater communication.[21]

The Energy Harvesting Eel (Eel) is a revolutionary technology that converts mechanical flow energy found in seas and waterways into electrical power using piezoelectric polymers. To strain the piezoelectric materials, eel generators employ a consistent track of moving vortices beyond a bluff body; the subsequent surging movement mimics that of a genuine eel swimming.[22] Small, unattended sensor packages must produce and gather electricity from their environment in order to undertake long-duration military operations. The experiments detailed here build on past research into the use of piezoelectric polymers as power generators.

With the rectangular bluff body, thin flexible piezoelectric membranes, or "eels," are activated by vortex shedding in the wake of the body. This flapping motion causes strain energy to be generated in the material, which may then be converted to electric power and stored in a battery to power tiny sensors and an acoustic modem.[23]

Vai Kuong Sin managed a numerical study to find out the interaction between a piezoelectric eel and vortex shedding behind a bluff body. The effects of different factors such as length of eel, width of bluff body and flow speed on vibrations of eel were also aimed to be studied. The results successfully modeled the undulating motion of eel along with Arbitrary Lagrangian-Eulerian (ALE) method.[24] Mohd Nor Fakhzan Mohd Kazim conducted a 2-dimensional computational fluid dynamics (CFD) simulation analysis of wake region generated by placing several bluff bodies such as U-shape, D-shape, triangle, square and cylinder in order to determine the best bluff body for piezoelectric eel. The results concluded that the triangle shape bluff body is most suitable shape to induce the vortex shedding to piezoelectric eel in a certain range.[25]

Based on the piezoelectric effect, Krit Koyvanich's work shows a micro-generator that converts energy from fluid flow into an electrical output. In the energy harvesting system, a flexible PVDF was employed as a transducer. Additionally, several arrays of the piezoelectric unit appear to have the potential to generate larger output power.[26] H. D. Akaydn measured the impact of short-length piezoelectric beams as energy generators in the wake of a circular cylinder at high Reynolds numbers. When the beam tip is around two diameters downstream of the cylinder, the maximum power output is measured. This power decreases off the wake's central line and decays as (x/D)-3/2 with downstream distance.[27]

Usman Latif had been using a flexible piezoelectric eel in a contained way to examine energy harvesting from underwater waves. At various wave situations, the energy generating sources was investigated as an outcome of streamwise distance from the immovable cylinder and spanwise opening end to end with the cylinder. When the eel was positioned near the surface, it was able to extract the most energy due to the high thrashing amplitude and frequency. Keeping the wavelength constant while adjusting the spanwise gap of the eel resulted in a 31.5 percent increase.[28]

The work of Junlei Wang depicts a Galloping-based piezoelectric energy harvester (GPEH) with triangular cross-section piezoelectric bodies with variable vertex angles. Computational Fluid Dynamics (CFD) was utilized to compute the aerodynamic properties, which were then confirmed using experimental data. With feeble connection, the obtuse angle of 130° is shown to be the most favored vertex angle. The findings may be used to create effective GPEHs with triangular bluff bodies.[29]

D-A Wang designed a new piezoelectric energy generator that utilized flow-induced vibration to generate energy. To evaluate the produced power of a piezoelectric coat exposed to a dispersed load, a finite element model was created. When the innervation pressure vibrates with an amplitude of 1.196 kPa and a frequency of around 26 Hz, an exposed circuit output voltage of 2.2 V and an instant output power of 0.2 W were created, according to the results. The derived voltage solution founded on the fixed element model matched the tests nicely.[30]

A polyethylene terephthalate thin plate fastened to a square cylinder and put in a water tunnel was developed by Emmanuel Binyet. The Reynolds number for a square cylinder was varied between 1500 and 20,000. Two distinct high-speed cameras were used to capture the plate deflection and accompanying flow pattern at 5000 and 500 frames per second. Higher order mode geometries enhanced strain energy, which was only the case for longer plates due to lower natural frequencies resulting in more plate wake contact. Longer plates produce more power when the bending pattern is kept two-dimensional, according to the findings.[31]

A. Mujtaba conducted an experiment to see how the collaboration of piezoelectric flags in a sequential arrangement affected energy generating in a wake flow. To assess the impact of wake flow on the oscillation amplitude, fluttering frequency, and collected power by the bluff body flags, the experiments were carried out in a low-speed water channel by altering the flow velocity and stream wise slit beyond an inverted C-shape cylinder. The results reveal that inverted drafting occurs in flags when the rear flag's flapping amplitude is boosted by stimulation from the front flag's vortices and wake. When related to a solo flag energy harvester, the sequential arrangement harvests 116 percent more power and considerably advances energy gathering effectiveness.[32]

CHAPTER 3
METHODOLOGY

3.1 Water Tunnel Setup

Experiments were carried out at the National University of Sciences and Technology (NUST), Islamabad, at the Department of Mechanical Engineering's low-speed closed-circuit water channel facility. A trial unit of 2000×400×400 mm (L×W×H) was located in that water channel. The freestream velocity (U) was varied in the range of 0.1 to 0.5m/s using a variable frequency drive (VFD) motor. The frequency of centrifugal pump was kept 30 Hz. To make the flow consistent, aluminum honeycombs with dimensions of 1830×500×25.4 mm (L×W×H) and hexagon structure were employed. High-capacity RO plant for the purpose of purification of water was used to fill water in closed-circuit water network to avoid the consequence of impurities in water for better experimentation experience.

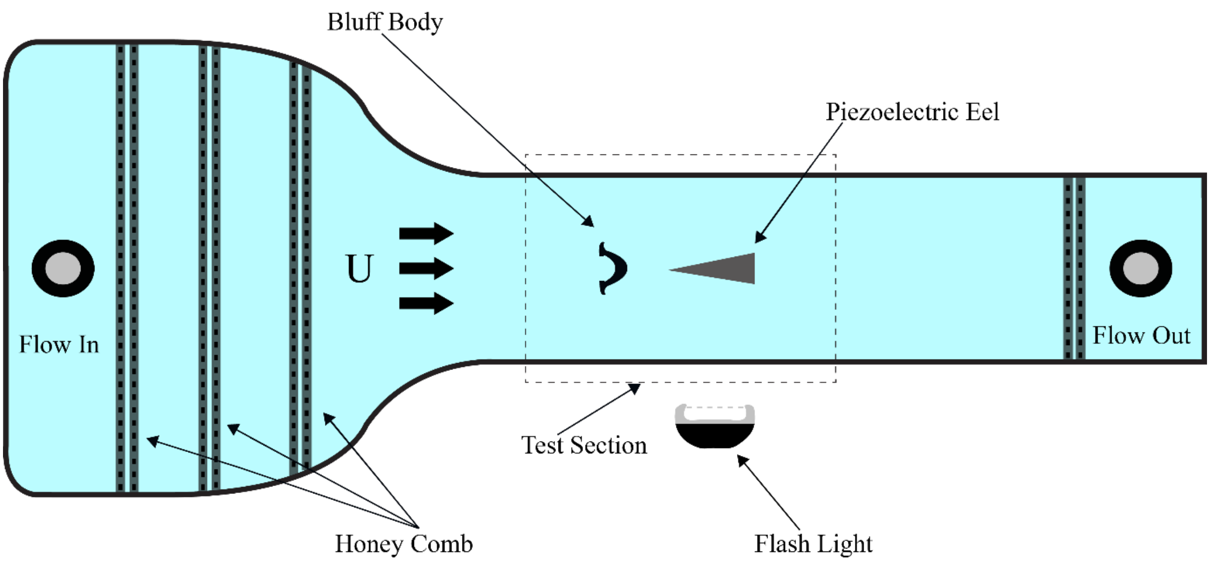


Figure 5: Schematic diagram of water tunnel apparatus

3.2 Design of Cylinders

Hollow inverted C shaped cylinders along with bio-inspired fins were manufactured from stainless steel blocks by using automatic Electric Discharge Machine (EDM) which utilizes wire cut technique. The cylinder's diameter was 25mm each. Reason behind the reasonable cylinder's thickness was to avoid the blockage effect.[33] The length of the cylinders was kept 400mm and cylinder wall thickness was 1.5mm. These cylinders were coated with nickel-chrome to reduce the effect of corrosion and to increase their life span and durability of stainless-steel. There were three different cylinder cut angles (α) of 120°, 150° and 180°. Three types of bio-inspired fins were attached with each type of cut angle. These bio-inspired fins were regarded as,

- Dorsal Fin
- Pectoral Fin
- Pelvic Fin

The mounting mechanism was designed at the top of each cylinder by making a groove and passing nut and bolt through it. This nut and bolt mechanism was captured by two aluminum plates at the top of test section. The cylinders are mounted tightly above the test section to avoid any sort of vibrations. These cylinders act as bluff body and produce wake region. In our case of study, the arrangement of cylinders is kept along x-axis with various cut angles and bio-inspired fins.

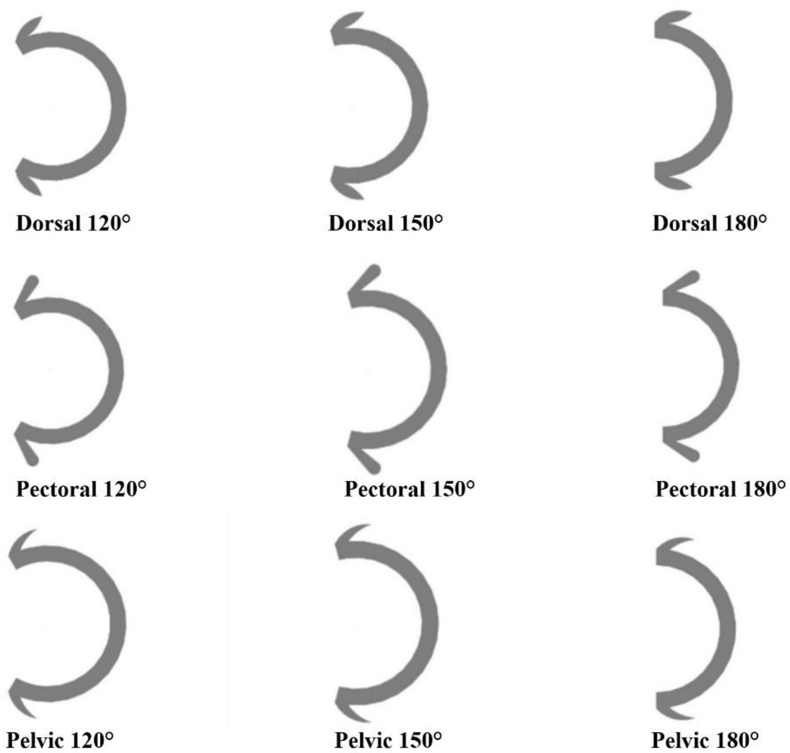


Figure 6: A collage of bio-inspired inverted C cylinders

3.3 Energy Harvesting Eel

The Energy Harvesting Eel is a revolutionary technology that converts mechanical flow energy found in seas and waterways into electrical power by means of piezoelectric polymers. Future autonomous oceanic sampling networks are intended to rely heavily on such devices. Long strips of piezoelectric polymers that move up and down in a water flow, similar to the motion of a swimming eel, are used in this energy-harvesting device. PVDF are future Eels may use more efficient electro strictive polymer.[13]

In our case of study, piezoelectric flag (DT2-028 K/L) was used. The following tables contain mechanical, electrical and material characteristics of described piezoelectric flag.

Symbol	**Parameter**	**PVDF**	**Units**
T	Thickness	9, 28, 52, 110	µm (micron, 10-6)
Y	Young's Modulus	2-4	109 N/m^2
Å	Permittivity	106-113	10-12 F/m
ρ_m	Mass Density	1.78	103 kg/m
P	Pyroelectric Coefficient	30	10-6 C/m^2 °K

Table 1: Mechanical and Electrical Properties of Piezoelectric Flag

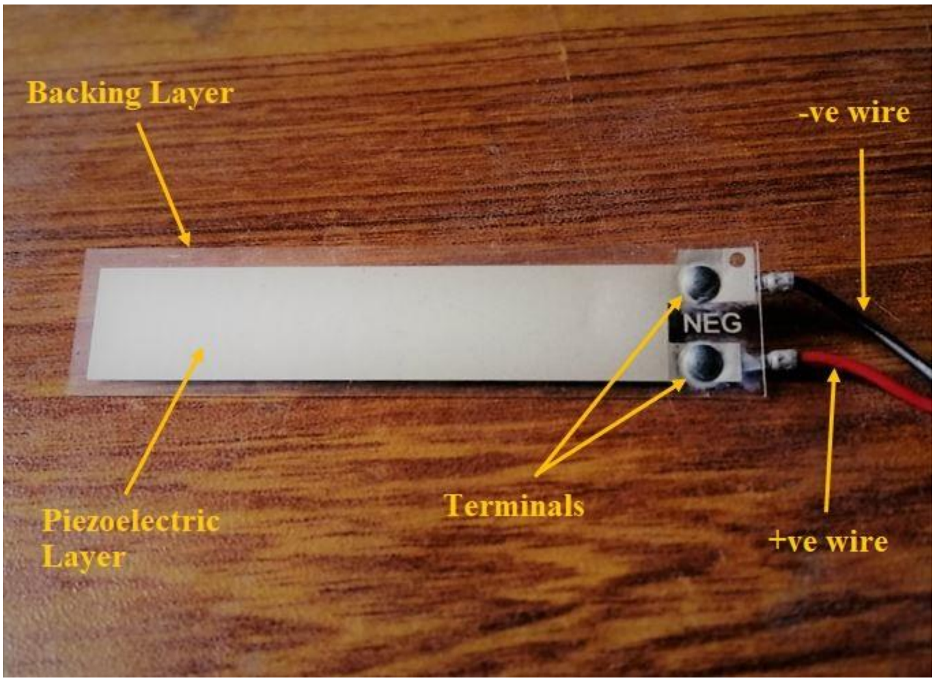


Figure 7: Labelled diagram of Piezoelectric Eel

Parameter	Value	Units
Capacitance @ 1KHz	600	pF/m
Relative Permittivity	9	@1KHz
Energy Output	10	MJ/Strain (%)
Voltage Output	5	kV/Strain (%)
Electromechanical Coupling	20	%
Acoustic Impedance	4.0	MRayl

Table 2: Material Properties of Piezoelectric Flag

3.4 Data Acquisition System

DAQ is a module of National Instruments Lab View. The voltage generated by the piezoelectric flags was computed using DAQ as a data acquisition system. Voltages were recorded at a sampling rate of 50 and a number of samples to read 50, implying that 50 voltage samples were measured in one second. The assistant passes the data to the indicator after obtaining it from the DAQ. The indicator analyzes the information into Lab View and presents it as numbers, charts, or bars for post processing.

Figure 8: NI DAQ

3.5 Sequence of Procedure

The experiments were conducted in flow lab of Department of Mechanical Engineering, National University of Sciences and Technology, Islamabad. The basic and essential module of our experimentation was water tunnel. A centrifugal pump circulated the water at velocity of 0.3 m/s and 30 Hz frequency. The water in the tunnel was purified. A high capacity 3-stage Reverse Osmosis was installed in the lab to fill the purified water in the tunnel. That RO plant maintained the water purity up to 20 PPM. The high quality of water was assured to prevent our experimental values from the effect of impurities and crystal-clear visualization.

After the setup of water tunnel, there came our bluff bodies. Hollow inverted C shaped cylinders along with bio-inspired fins and different cut angles were used as bluff bodies. Dorsal, Pectoral and Pelvic fins were attached with cylinders of 120°,150° and 180° cut angles. The cylinders were anchored in the water channel by a fastening at the top. The cylinder and aluminum rod (which holds the piezoelectric flag) were tightly consolidated with the border positioned on topmost of the trial unit, to eliminate any displacement or horizontal movement. When the water passed through the bluff body, a wake region was produced behind the bluff body. The vortices generated through the interference of water with bluff body interacted with the flag next to cylinder and induce vibrations in the flag. The voltages were generated through the movement of flag due to piezoelectric properties of the flag.

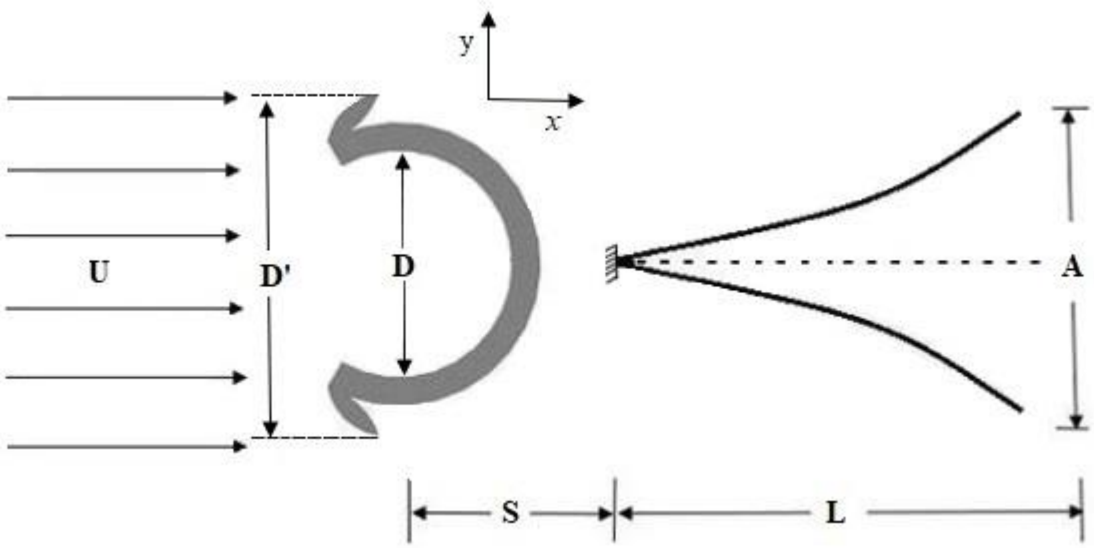


Figure 9: Mechanism of bio-inspired cylinder and piezoelectric flag

A Data Acquisition (DAQ) system was attached with the piezoelectric flag. Using DAQ as a data collecting system, the voltages produced by the piezoelectric flags were calculated. Voltages were measured at a sampling rate of 50 samples per second, indicating that 50 voltage samples were collected in one second. After getting the data from the DAQ, the assistant delivers it to the indicator. For post-processing, the indicator examines the data in Lab View and presents it as numbers, charts, or bars.

The processed data, obtained from DAQ, was further processed in MATLAB and values of Power, Frequency and Amplitude were determined using three different codes.

CHAPTER 4
RESULTS AND DISCUSSIONS

The flapping dynamics and energy harvesting ability of a conventional piezoelectric flag in horizontal arrangement behind a bio-inspired inverted C-shaped cylinder in a uniform fluid flow were examined. The streamwise gap Gx (S/D) between the bluff body and the flag was changed from 1 to 4 to explore the hydrodynamic interaction and behavior of a conventional piezoelectric flag. In this research, all other variables (i.e., flow velocity and Re.) were held constant. The flapping amplitude was indicated on the flag, as well as the output power.

4.1 Effect of Streamwise gap on Power, Frequency and A/L of Piezoelectric flag by using Dorsal finned inverted C cylinders

On the surface plot in figure 11, the output power, frequency and A/L of piezoelectric flag as a function of streamwise gap Gx were presented. In case of Dorsal fin, maximum power was obtained at Gx=2, which was marked as Pmax in surface plot, by using 120° opening angle cylinder as a bluff body. At this point, the interspace from the middle of the cylinder to eel in x- axis was 50 mm. The analysis of tail position of flag (Figure 19) was conducted at this point, which clearly indicates highest flapping frequency. It justified the high energy harvesting at this point as compared to other cut angle cylinders having Dorsal fin. However, for 150° opening angle cylinder, as the streamwise interspace Gx between the inverted C cylinder and piezoelectric flag on amplified by 4, a drop in power, frequency and A/L was observed. Lowest energy generation point was indicated by Pmin. At this point, the gap from the center of the cylinder to eel in x-axis was 100 mm. This clearly indicated that critical point is beyond stated point.

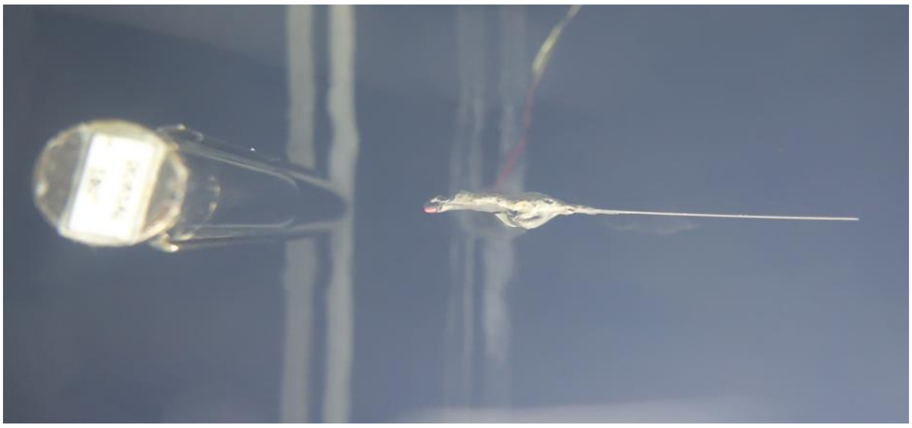
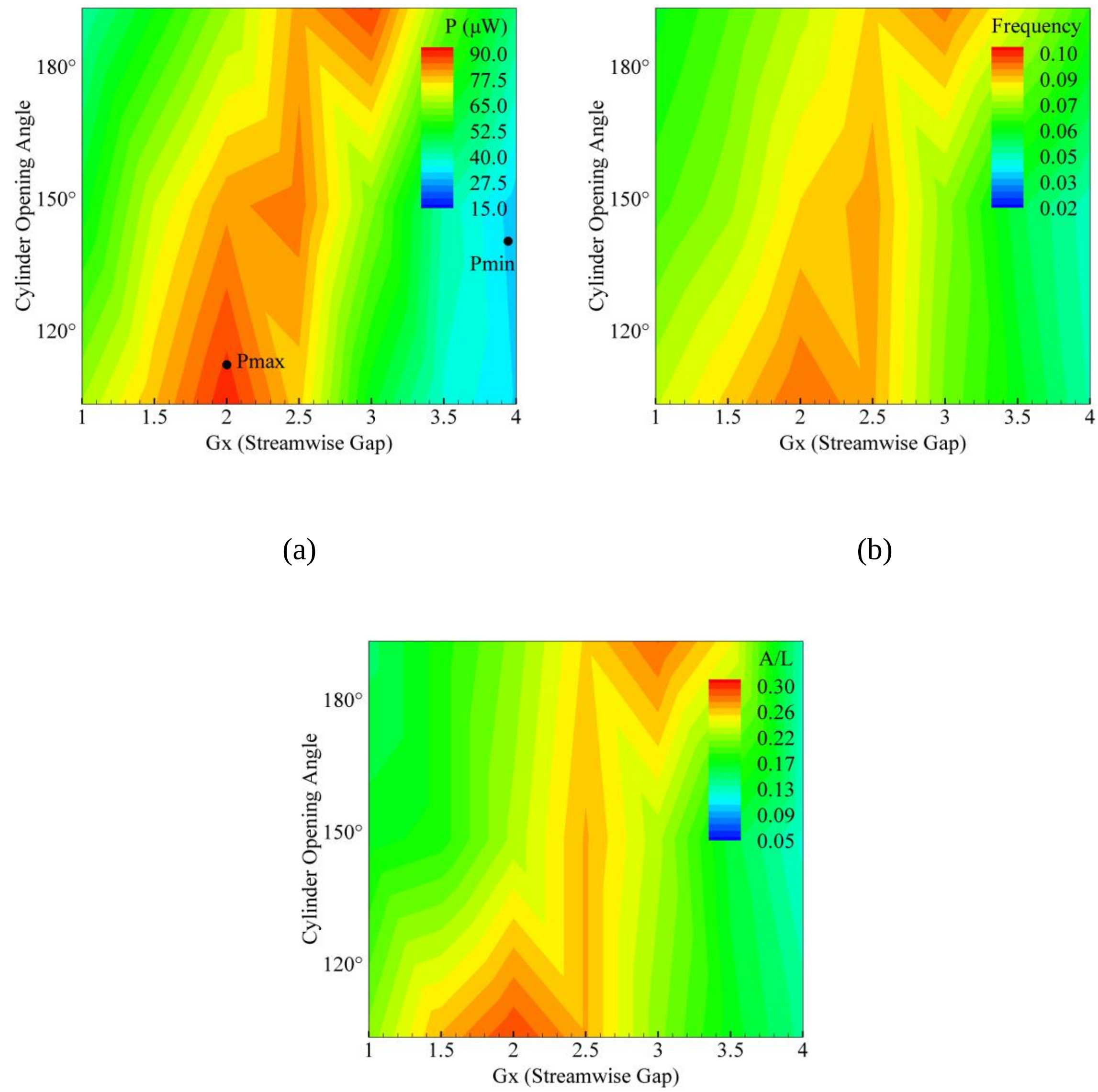


Figure 10: Bottom view of inverted C Dorsal finned cylinder in couple with piezoelectric flag at Gx=2



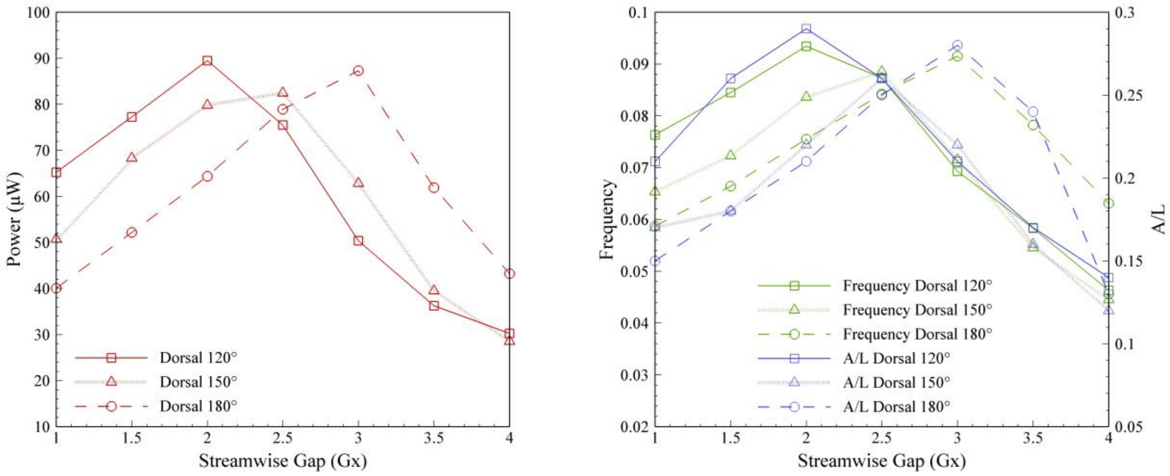
(a) (b)

(c)

Figure 11: (a) Power, (b) Frequency, (c) A/L for piezoelectric flag Infront of Dorsal finned cylinders

The highest energy production was highlighted with Pmax in Figure 11(a) and reflects a maximum energy generation at Gx=2, while the frequency and A/L are represented by the consistent points on Figure 11(b) and 11(c). This demonstrates a significant degree of distortion in the flag, similar to twisting energy, resulting in an increase of produced voltage at point Pmax.

At Gx=4, for 150° opening angle cylinder, the lesser power harvesting location was also found and highlighted with Pmin, indicating that the flag interacts negatively with the wakes of the water stream, results in a considerable reduction in energy generating. The shift from a low-energy area to a high-energy region occurs when streamwise gap increases as the 2nd vortex is on its way to vibrate the flag.



(a) (b)

Figure 12: Line plots to elaborate the trend in results of (a) Power, (b) Frequency & A/L by using Dorsal finned cylinders as bluff bodies

4.2 Effect of Streamwise gap on Power, Frequency and A/L of Piezoelectric flag by using Pectoral finned inverted C cylinders

The output power, frequency and A/L of piezoelectric flag as a function of streamwise gap Gx were presented in surface plot figure 14. In case of Pectoral fin, maximum power was obtained at Gx=2, which was marked as Pmax in surface plot, by using 120° opening angle cylinder as a bluff body. At this point, the gap from the midpoint of the cylinder to eel in x-axis was 50 mm. The analysis of tail position of flag (Figure 19) was conducted at this point, which clearly indicates highest flapping frequency. It justified the high energy harvesting at this point as compared to other cut angle cylinders having Pectoral fins.

However, for 150° opening angle cylinder, as the streamwise distance Gx among the inverted C cylinder and piezoelectric flag on amplified by 4, a drop in power, frequency and A/L was observed. Lowest energy generation point was indicated by Pmin. At this point, the gap from the middle of the cylinder to eel in x-axis was 100 mm. This clearly indicated that critical point is beyond stated point. The power obtained by Pectoral finned cylinders was reduced as compared to Dorsal finned cylinders. Similarly, a low energy generation point (Pmin) was identified in case of Pectoral fin. Due to the unstable fluid forces, a flapping membrane may create elastic strain energy far greater than a flag of distorted mode by enhancing the transition of fluid kinetic energy to elastic strain.

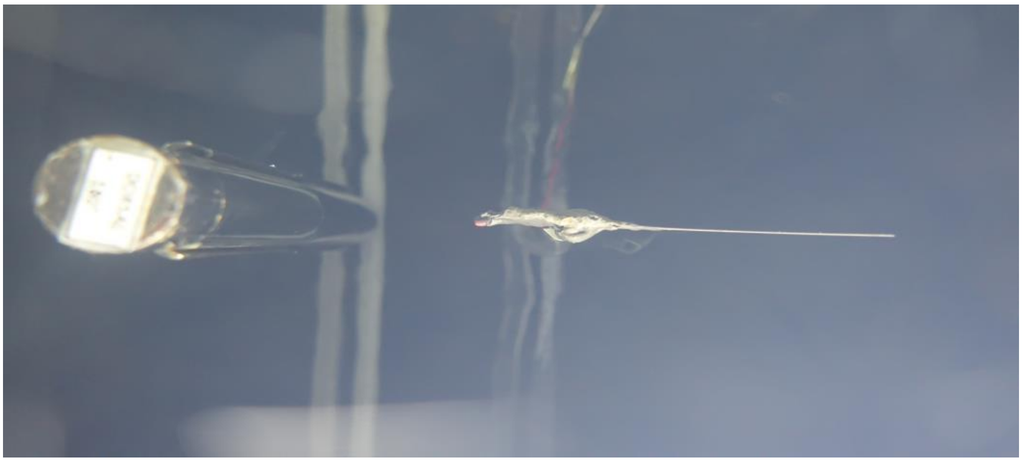


Figure 13: Bottom view of inverted C Pectoral finned cylinder in couple with piezoelectric flag at Gx=2

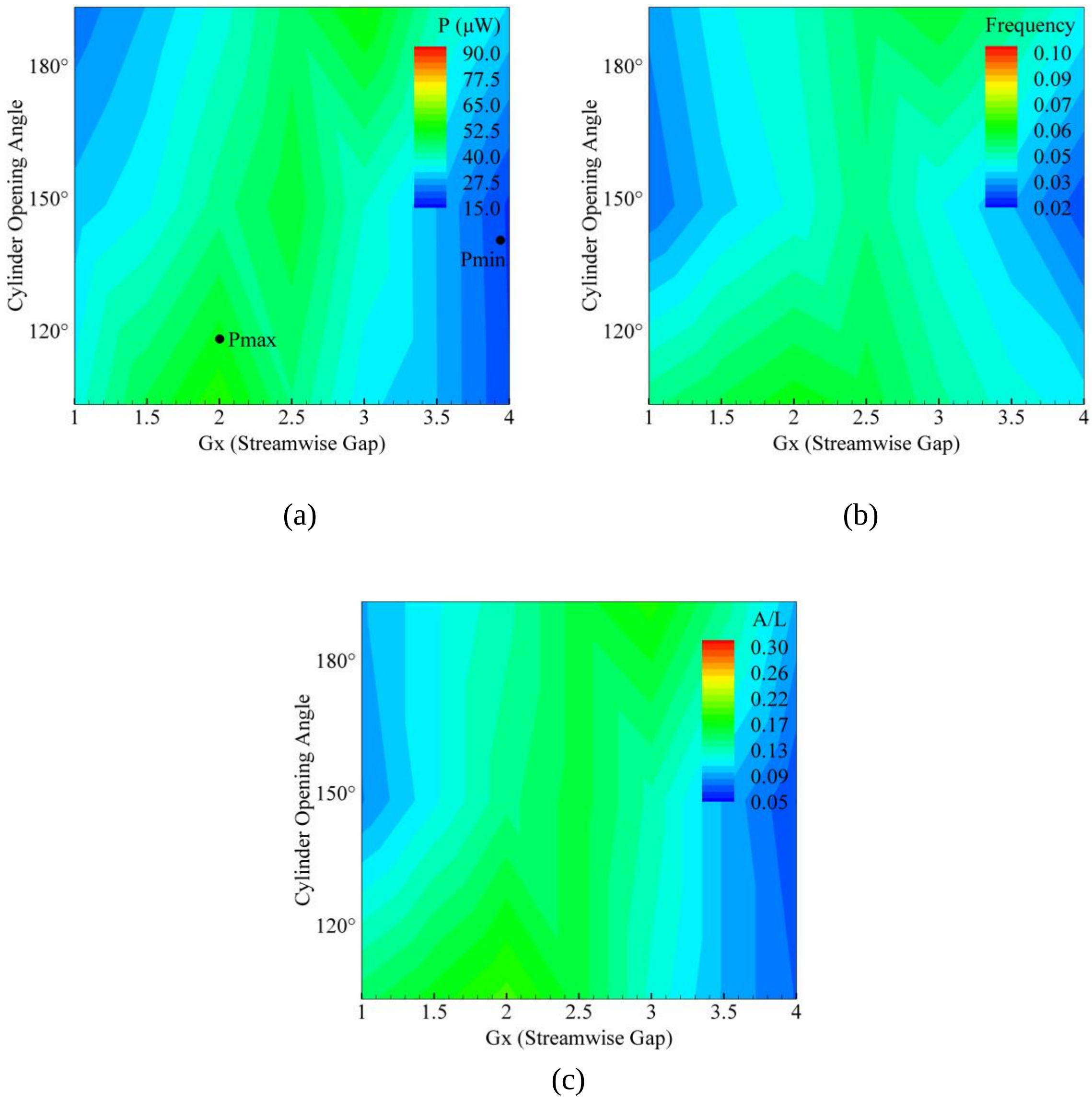
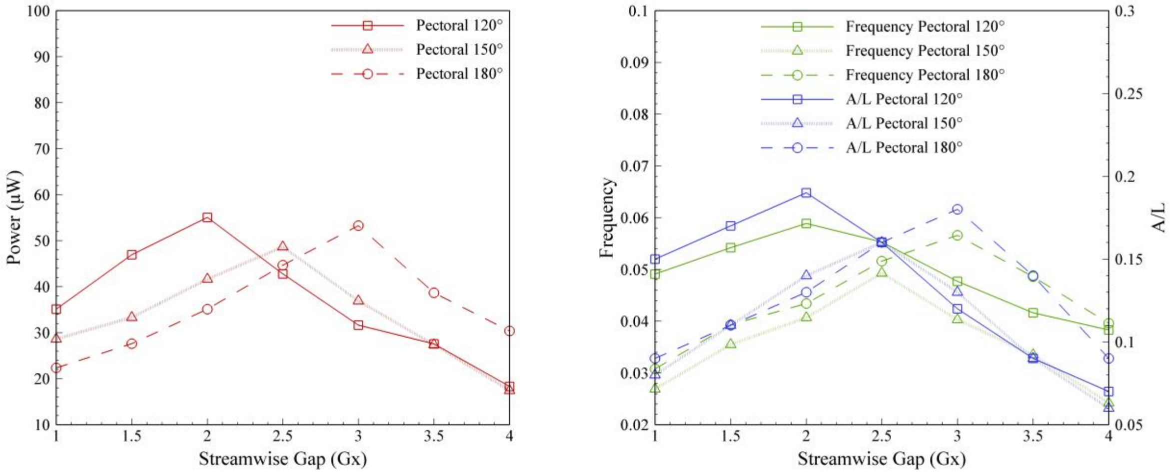


Figure 14: (a) Power, (b) Frequency, (c) A/L for piezoelectric flag Infront of Pectoral finned cylinders



(a) (b)

Figure 15: Line plots to elaborate the trend in results of (a) Power, (b) Frequency & A/L by using Pectoral finned cylinders as bluff bodies

4.3 Effect of Streamwise gap on Power, Frequency and A/L of Piezoelectric flag by using Pelvic finned inverted C cylinders

The surface plots of output power, frequency and A/L of piezoelectric flag as a function of streamwise gap Gx are presented in figure 17. In case of Pelvic fin, maximum power was obtained at Gx=2, which was marked as Pmax in surface plot, by using 120° opening angle cylinder as a bluff body. At this point, the gap from the middle of the cylinder to eel in x- axis was 50 mm. The analysis of tail position of flag (Figure 19) was conducted at this point, which clearly indicates highest flapping frequency. It justified the high energy harvesting at this point as compared to other cut angle cylinders having Pelvic fins.

At Gx=4, by using 120° opening angle cylinder as bluff body, a low energy generation point was also found and highlighted with Pmin, indicating that the flag interacts negatively with the wakes of the water stream, results in a considerable reduction in energy generating. The shift from a low-energy area to a high-energy region occurs when streamwise gap increases as the 2nd vortex is on its way to vibrate the flag. At this point, there was a dip in the power output, indicating that the rapid drop in power output was due to the splitter plate effect, since the flag's terminals were sealed with epoxy, making it rigid enough to operate as a splitter plate.

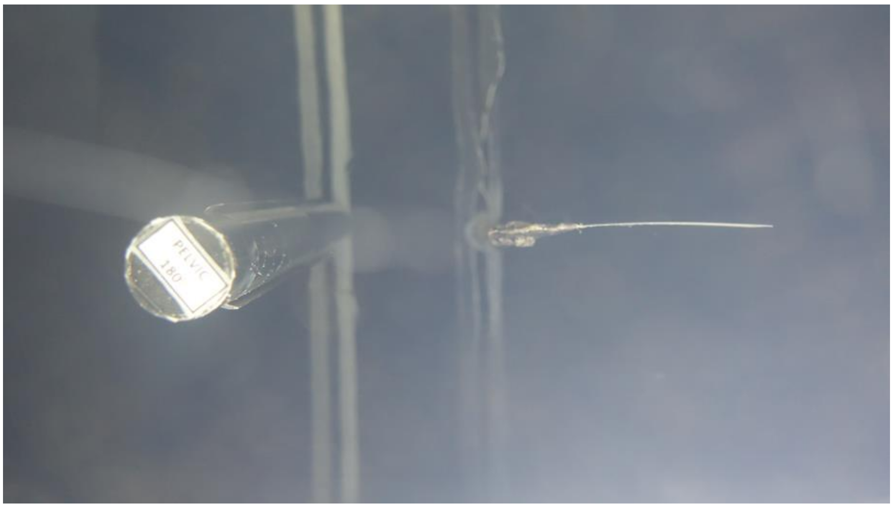
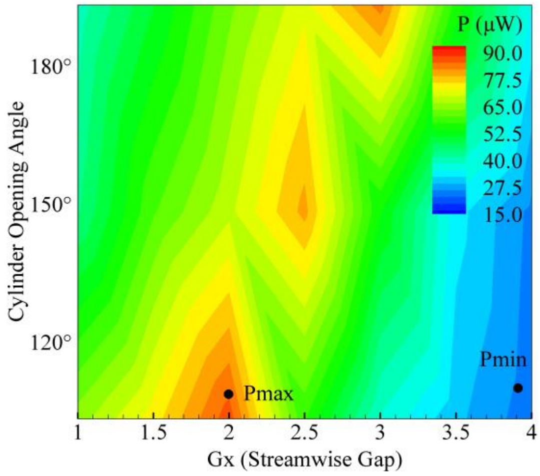
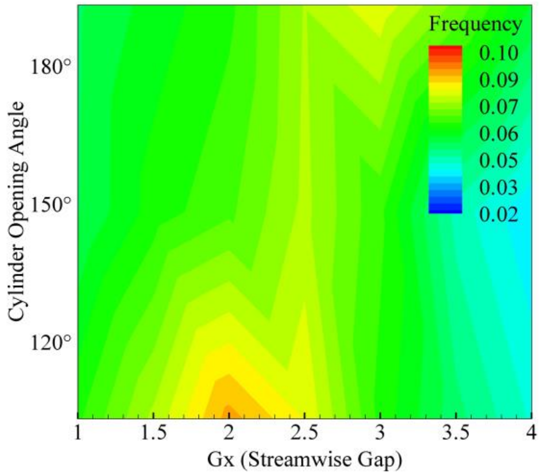


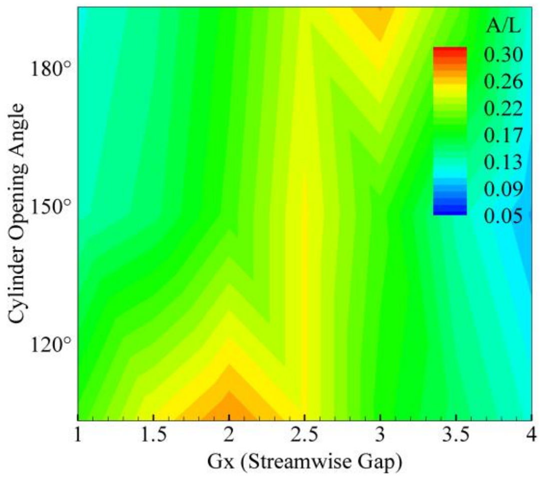
Figure 16: Bottom view of inverted C Pelvic finned cylinder in couple with piezoelectric flag at Gx=2



(a)

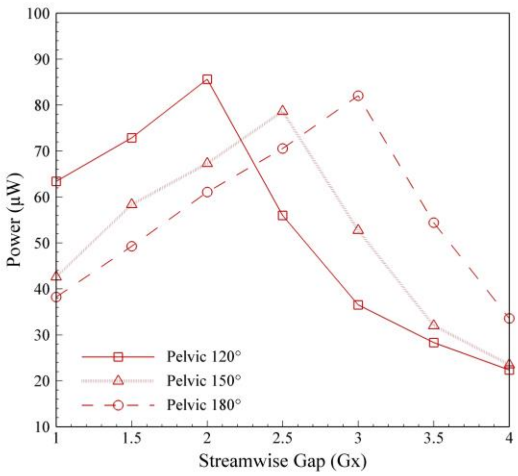


(b)

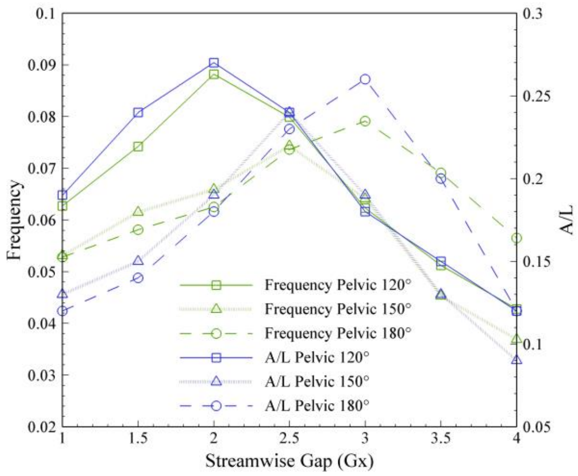


(c)

Figure 17: (a) Power, (b) Frequency, (c) A/L for piezoelectric flag Infront of Pelvic finned



(a)



(b)

Figure 18 : Line plots to elaborate the trend in results of (a) Power, (b) Frequency & A/L by using Pelvic finned cylinders as bluff bodies

4.4 Comparative Study of different bluff bodies' performance

The detailed results were discussed in above topics. Output obtained from individual cases was compiled in the form of surface plots and line plots. Overall comparison of our study depicts that the Dorsal finned 120° opening angle bluff body harvested maximum output power at Gx=2. While lower most output power was obtained by Pelvic finned 150° cut angle cylinder at Gx=4. The following table contains the detailed statistics of output power, flapping frequency and Amplitude (A/L) at various peak points.

Fin Type	Cut Angle	Gx	Power (µW)	Frequency	A/L
Dorsal	120°	2	89.49	0.0934	0.29
	150°	2.5	82.46	0.0885	0.26
	180°	3	87.29	0.0915	0.28
Pectoral	120°	2	55.06	0.0589	0.19
	150°	2.5	48.67	0.0493	0.16
	180°	3	53.25	0.0566	0.18
Pelvic	120°	2	85.61	0.0882	0.27
	150°	2.5	78.63	0.0743	0.24
	180°	3	82.03	0.0791	0.26

Table 3: Summary of power, frequency, A/L output of different Bio-Inspired fins

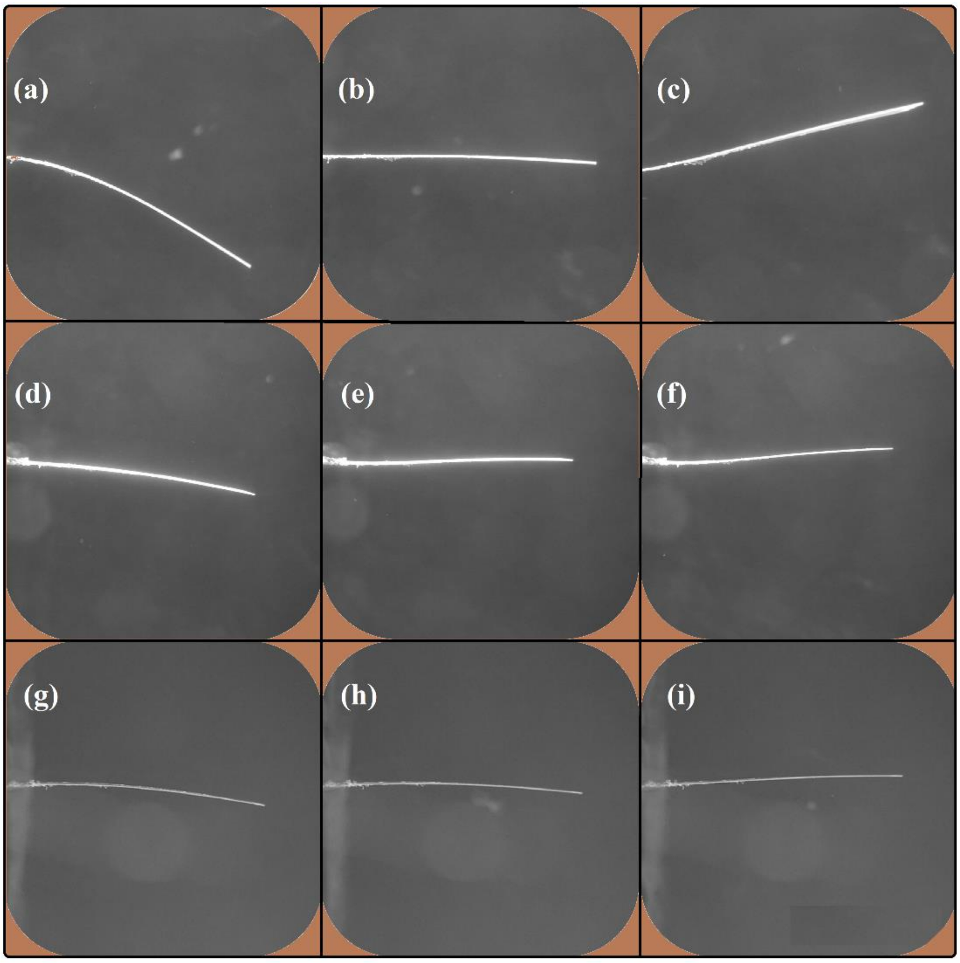


Figure 19: Tail Position Analysis of Piezoelectric Flag at Maximum flapping (a)(b)(c), Moderate flapping (d)(e)(f) and Minimum flapping (g)(h)(i)

By taking the baseline case from the experimental study of U. Latif et al ,2021[33], we considered the inverted C 180° cut angle cylinder as baseline case. In case of 120° Opening angle cylinder, it was found that a rise in harvested power, flapping frequency and flapping amplitude was 11.46%, 13.34% and 13.18% respectively. In case of 150° Opening angle cylinder, it was observed that a decrease in harvested power, flapping frequency and flapping amplitude was 7.05%, 8.41% and 8.64% respectively. In case of 180° Opening angle cylinder, it was found that a rise in harvested power, flapping frequency and flapping amplitude was 10.96%, 12.60% and 12.27% respectively.

Fin Type	Cut Angle	Gx	% Difference in Power	% Difference in Frequency	% Difference in A/L
Dorsal	120°	2	+11.46	+13.34	+13.18
	150°	2.5	+10.56	+12.64	+11.82
	180°	3	+11.17	+13.07	+12.73
Pectoral	120°	2	-7.05	-8.41	-8.64
	150°	2.5	-6.23	-7.04	-7.27
	180°	3	-6.82	-8.09	-8.18
Pelvic	120°	2	+10.96	+12.60	+12.27
	150°	2.5	+10.07	+10.61	+10.91
	180°	3	+10.50	+11.30	+11.82

Table 4: Percentage difference in output of Bio-Inspired inverted C-shaped cylinders in comparison with a baseline bluff body

The baseline case indicated the power range in between Dorsal and Pelvic finned cylinders which highlighted a remarkable increase in Power, Frequency and Amplitude. The flow patterns were improved by the use of these fins along the inverted C cylinders. While, the Pectoral finned bluff body indicated a drop in Power, Frequency and Amplitude as compared to the baseline case. This indicated that the flow structure behavior was changed by the use of Pectoral fin along the bluff body which can be observed clearly by flow dynamics in the given bar chart.

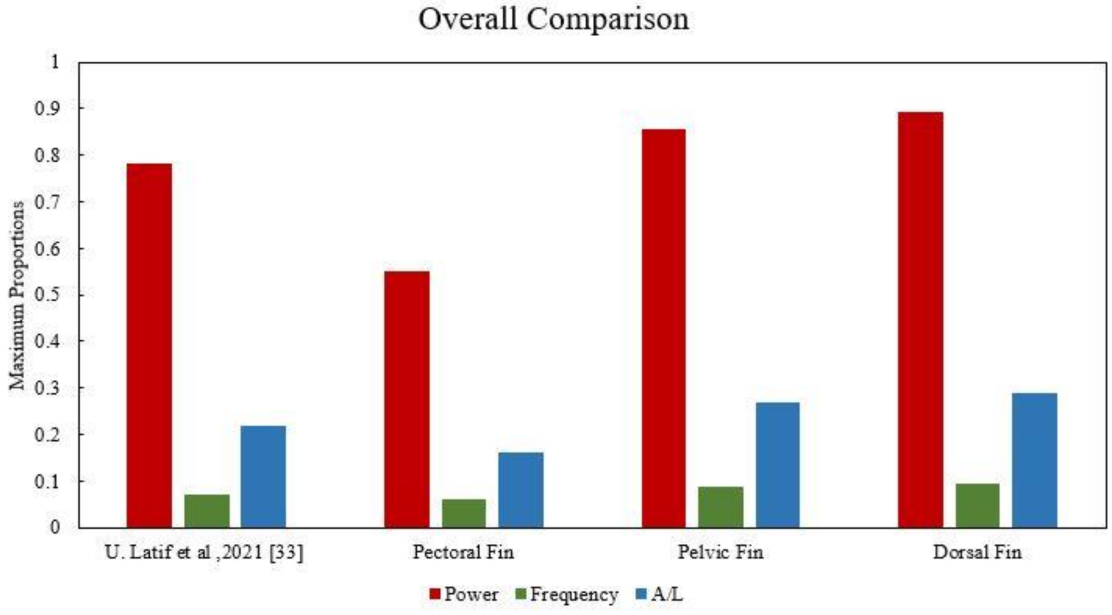


Figure 20: Overall comparison with published work

The overall comparison of Power, Frequency and A/L are given below for better visibility and understanding of our outcomes.

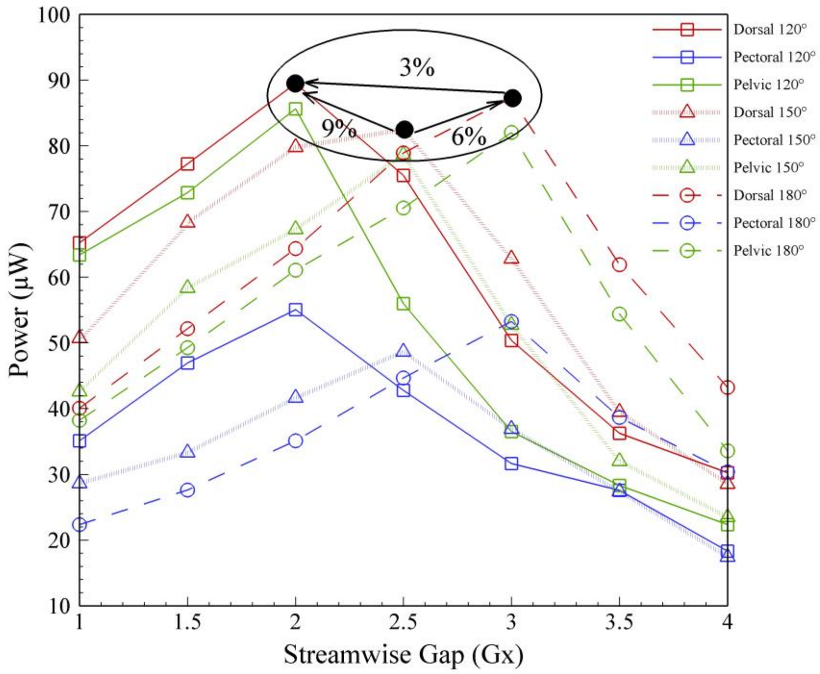


Figure 21: Overall comparison of harvested power (μW) against streamwise Gap (Gx)

When we concise all the outcomes of power on a single plot, we can see the highest powers obtained by each bluff body. The Dorsal 120° cylinder gives highest power when placed in the water tunnel. Although, there involve many other parameters to evaluate the performance of each bluff body. In above graph, we can see that the Pectoral finned cylinders provide less power as compared to Dorsal and Pelvic finned cylinders. The increase in Power obtained by Pelvic fin and Dorsal fin was 6% and 9% respectively, as compared to the Pectoral fin. The Dorsal fin with 120° cut angle was found most effective fin as compared to all other bluff bodies.

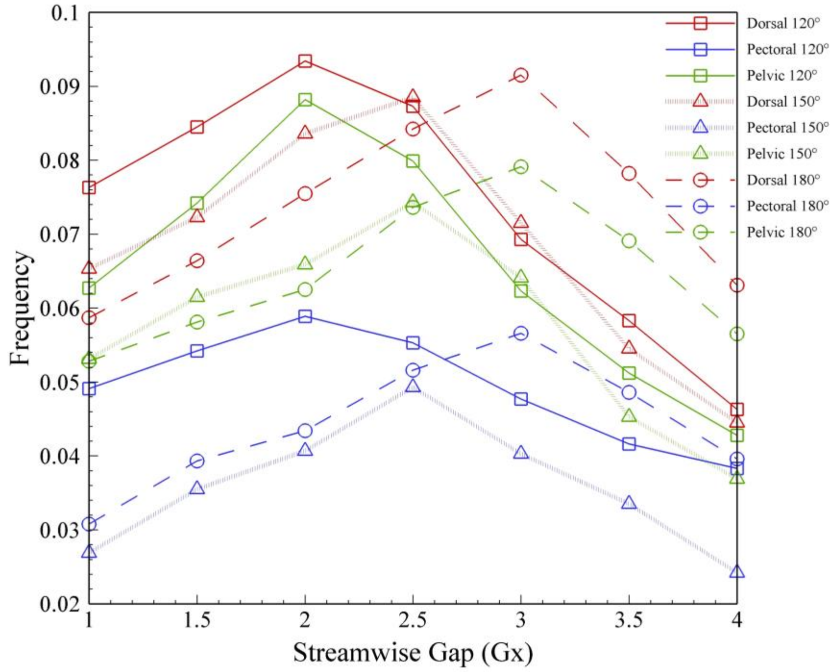


Figure 22: Overall comparison of flapping frequency against streamwise Gap (Gx)

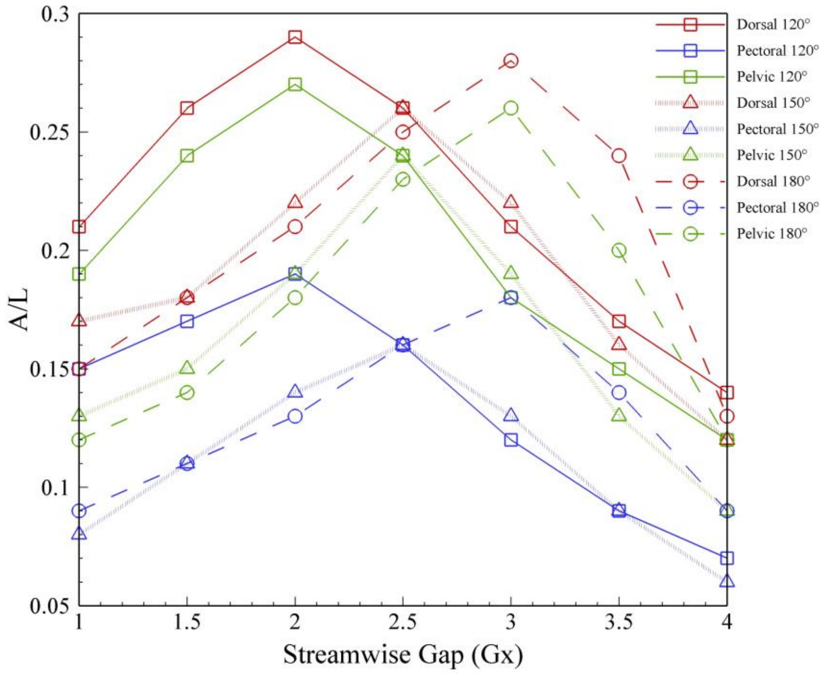


Figure 23: Overall comparison of normalized amplitude (A/L) against streamwise Gap (Gx)

CHAPTER 5
CONCLUSION

An investigation and discussion of energy generating from a piezoelectric flag triggered by inducing vortices generated by different cut angles inverted C-shaped bio-inspired bluff body has been conducted. Complete experimental research was carried out on three different bio-inspired finned cylinders by varying the streamwise gap (Gx) for each cylinder with the flag. By completing multiple experiments and performing a complete assessment, this work covers the energy harvesting by these bluff bodies.

The experiments were conducted by using a low speed closed circuit water tunnel. Test section of the experimental setup contained two most important components. First one was Bio-inspired cylinders having different cut angles and fins. Dorsal, Pectoral and Pelvic finned cylinders of 120°,150° and 180° cut angles were manufactured and used in this study. Second most important constitute of experimentation was Piezoelectric eel, which acted as energy harvesting device. The objective of the thesis was to find out the impact of various parameters/factors on the piezoelectric flags-based energy harvesting technique. The main factors to critically observe were the effect of change of shape of bluff bodies and change in streamwise gap (Gx).

The inverted C bluff bodies with different cut angles were already been considered by different researchers.[33] The effect of attaching Bio-Inspired fins by the sides of these cylinders was the aim of this study. The effect of varying cut angles of C-shape bluff body on piezo-flag performance was shown after a thorough investigation. The Dorsal fin was found to be the most effective when utilized with 120° cut angle cylinder. The overall conclusion of this experimental analysis is that the geometry of the bluff body combined with the streamwise gap is a highly important factor. Maximum amount of energy can be harvested by considering the most suitable bluff body and the other parameters.

CHAPTER 6
FUTURE RECOMMENDATIONS

Many efforts were made in the study to provide some additional elements for a better understanding of the concepts studied in the thesis; however, some questions unanswered, and some additional ideas originated during the research period, for which the following recommendations are discovered for future work.

- The detailed CFD analysis of the experiments can be conducted by using a variety of bluff bodies in different experimental conditions.
- More Bio-Inspired fins (e.g., Anal fin) can be attached at the sides of different cut angle cylinders to investigate their behavior in same circumstances.
- Variety of operations can be performed in water tunnel test section by using load cells of different range.
- Real world applications of Piezo-electric energy harvesting still need to be designed to work in local environmental conditions.
- Analysis of multi grade eels by using same experimental conditions can lead us to the optimal selection of the flag.
- Further research and study in vortex induced vibrations can highlight the new phases for more optimum design of the system.
- Energy harvesting efficiency of the flag can be analyzed by keeping the temperature a variable factor in real time applications.

CHAPTER 7
REFERENCES

[1] D. Carroll, "Miniaturised Electromagnetic Generators for Portable," *Interface*, vol. 2, pp. 2–6.

[2] I. Akyildiz, D. Pompili, and T. Melodia, "Underwater Acoustic Sensor Networks: Research Challenges," *Ad Hoc Networks*, vol. 3, pp. 257–279, May 2005, doi: 10.1016/j.adhoc.2005.01.004.

[3] T. L. N. Nguyen and Y. Shin, "An Efficient RSS Localization for Underwater Wireless Sensor Networks," *Sensors*, vol. 19, no. 14, 2019, doi: 10.3390/s19143105.

[4] A. S. Haghighi, I. Zare, M. A. Balootaki, M. Orak, and O. Zare, "Modeling of Bio-inspired Thunnus Albacares and Inchworm-gammarus with Micro Actuators in One Structure," *Int. J. Sci. Qual. Anal.*, vol. 1, no. 3, pp. 54–63, 2015, doi: 10.11648/j.ijsqa.20150103.13.

[5] G. K. Ottman, H. F. Hofmann, A. C. Bhatt, and G. A. Lesieutre, "Adaptive piezoelectric energy harvesting circuit for wireless remote power supply," *IEEE Trans. power Electron.*, vol. 17, no. 5, pp. 669–676, 2002.

[6] 1European Commission, "see https://ec. europa. eu/digital-single-market/en/internet-of-things for 'The Internet of Things'(2020). 2L. M. Miller, E. Halvorsen, T. Dong, and PK Wright,"Modeling and experimental verification of low-frequency MEMS energy harvesting from ambient vib," *J. Micromech. Microeng*, vol. 21, p. 45029, 2011.

[7] D. Zhu, S. P. Beeby, M. J. Tudor, N. M. White, and N. R. Harris, "Novel miniature airflow energy harvester for wireless sensing applications in buildings," *IEEE Sens. J.*, vol. 13, no. 2, pp. 691–700, 2013, doi: 10.1109/JSEN.2012.2226518.

[8] J. J. ALLEN and A. J. SMITS, "ENERGY HARVESTING EEL," *J. Fluids Struct.*, vol. 15, no. 3, pp. 629–640, 2001, doi: https://doi.org/10.1006/jfls.2000.0355.

[9] S. Michelin and O. Doaré, "Energy harvesting efficiency of piezoelectric flags in axial flows," *J. Fluid Mech.*, vol. 714, pp. 489–504, 2013, doi: 10.1017/jfm.2012.494.

[10] A. Mehmood, A. Abdelkefi, M. R. Hajj, A. H. Nayfeh, I. Akhtar, and A. O. Nuhait, "Piezoelectric energy harvesting from vortex-induced vibrations of circular cylinder,"

J. Sound Vib., vol. 332, no. 19, pp. 4656–4667, 2013.

[11] K. Shoele and R. Mittal, "Energy harvesting by flow-induced flutter in a simple model of an inverted piezoelectric flag," *J. Fluid Mech.*, vol. 790, pp. 582–606, 2016, doi: 10.1017/jfm.2016.40.

[12] A. E. Perry, M. S. Chong, and T. T. Lim, "The vortex-shedding process behind two-dimensional bluff bodies," *J. Fluid Mech.*, vol. 116, pp. 77–90, 1982.

[13] C. H. K. Williamson, "Vortex dynamics in the cylinder wake," *Annu. Rev. Fluid Mech.*, vol. 28, no. 1, pp. 477–539, 1996.

[14] M. Matsumoto, "Vortex shedding of bluff bodies: a review," *J. Fluids Struct.*, vol. 13, no. 7–8, pp. 791–811, 1999.

[15] M. Höök and X. Tang, "Depletion of fossil fuels and anthropogenic climate change-A review," *Energy Policy*, vol. 52, pp. 797–809, 2013, doi: 10.1016/j.enpol.2012.10.046.

[16] A. J. Mcmichael *et al.*, "Comparative Quantification of Health Risks: Global climate change," *Comp. Quantif. Heal. Risks*.

[17] R. York, "Do alternative energy sources displace fossil fuels?," *Nat. Clim. Chang.*, vol. 2, no. 6, pp. 441–443, 2012, doi: 10.1038/nclimate1451.

[18] N. L. Panwar, S. C. Kaushik, and S. Kothari, "Role of renewable energy sources in environmental protection: A review," *Renew. Sustain. Energy Rev.*, vol. 15, no. 3, pp. 1513–1524, 2011, doi: 10.1016/j.rser.2010.11.037.

[19] W. Rowley and A. Westwood, "The need for renewable energy," *Pet. Rev.*, vol. 57, no. 676, pp. 26–28, 2003.

[20] E. Cayirci, H. Tezcan, Y. Dogan, and V. Coskun, "Wireless sensor networks for underwater survelliance systems," *Ad Hoc Networks*, vol. 4, no. 4, pp. 431–446, 2006, doi: 10.1016/j.adhoc.2004.10.008.

[21] A. Khan and L. Jenkins, "Undersea wireless sensor network for ocean pollution prevention," in *2008 3rd International Conference on Communication Systems Software and Middleware and Workshops (COMSWARE '08)*, 2008, pp. 2–8, doi: 10.1109/COMSWA.2008.4554369.

[22] G. W. Taylor, J. R. Burns, S. A. Kammann, W. B. Powers, and T. R. Welsh, "The

Energy Harvesting Eel: a small subsurface ocean/river power generator,” *IEEE J. Ocean. Eng.*, vol. 26, no. 4, pp. 539–547, 2001, doi: 10.1109/48.972090.

[23] A. H. Techet, J. J. Allen, and A. J. Smits, “Piezoelectric Eels For Energy Harvesting In the Ocean,” 2002, vol. All Days.

[24] V. K. Sin, W. Y. Deng, and W. H. Xiao, “Study of motion of flexible eel from the wake of bluff body in a cross flow,” *AIP Conf. Proc.*, vol. 1479, no. 1, pp. 161–164, 2012, doi: 10.1063/1.4756087.

[25] M. N. F. M. Kazim, R. Rasani, M. Z. Nuawi, Z. Harun, Y. K. Hau, and M. S. A. Majid, “Analysis of wake region behind bluff body for piezoelectric energy harvester,” *J. Adv. Res. Fluid Mech. Therm. Sci.*, vol. 55, no. 2, pp. 249–263, 2019.

[26] K. Koyvanich, P. Smithmaitrie, and N. Muensit, “Perspective microscale piezoelectric harvester for converting flow energy in water way,” *Adv. Mater. Lett.*, vol. 6, no. 6, pp. 538–543, 2015, doi: 10.5185/amlett.2015.SMS4.

[27] H. D. AkaydIn, N. Elvin, and Y. Andreopoulos, “Wake of a cylinder: A paradigm for energy harvesting with piezoelectric materials,” *Experiments in Fluids*, vol. 49, no. 1. pp. 291–304, 2010, doi: 10.1007/s00348-010-0871-7.

[28] U. Latif *et al.*, “Experimental investigation of energy harvesting eel in the wake of bluff body under ocean waves,” *Proc. Inst. Mech. Eng. Part M J. Eng. Marit. Environ.*, vol. 235, no. 1, pp. 81–92, 2021, doi: 10.1177/1475090220949334.

[29] J. Wang, L. Tang, L. Zhao, and Z. Zhang, “Efficiency investigation on energy harvesting from airflows in HVAC system based on galloping of isosceles triangle sectioned bluff bodies,” *Energy*, vol. 172, pp. 1066–1078, 2019, doi: 10.1016/j.energy.2019.02.002.

[30] D. A. Wang and H. H. Ko, “Piezoelectric energy harvesting from flow-induced vibration,” *J. Micromechanics Microengineering*, vol. 20, no. 2, 2010, doi: 10.1088/0960-1317/20/2/025019.

[31] E. Binyet, C. Y. Huang, and J. Y. Chang, “Water tunnel study of a cantilever flexible plate in the wake of a square cylinder,” *Microsyst. Technol.*, vol. 26, no. 11, pp. 3435–3449, 2020, doi: 10.1007/s00542-020-04901-x.

[32] A. Mujtaba *et al.*, “Hydrodynamic energy harvesting analysis of two piezoelectric

tandem flags under influence of upstream body's wakes," *Appl. Energy*, vol. 282, no. PA, p. 116173, 2021, doi: 10.1016/j.apenergy.2020.116173.

[33] U. Latif *et al.*, "Experimental electro-hydrodynamic investigation of flag-based energy harvesting in the wake of inverted C-shape cylinder," *Energy*, vol. 215, 2021, doi: 10.1016/j.energy.2020.119195.