Design and Manufacturing of a VIV Based Energy Harvesting Device with Multiple Cylinders

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ABSTRACT

This project aims to harness the potential of Vortex-Induced Vibrations (VIVs) for creating an environmentally friendly electricity generation device. As global attention shifts towards renewable energy due to the rapid depletion of fossil fuel reserves, our focus centers on leveraging water as an abundant and frequently utilized renewable resource for power generation. By strategically placing cylinders in a flowing water stream, vortices generated as water passes over them induce vibrations. The captured vibrational energy can subsequently be converted into a practical and sustainable form of electricity, contributing to the growing demand for clean energy solutions.

Our aim is to study this phenomenon, investigate the variables influencing the behavior of the flow across cylindrical structures and then to propose an efficient energy generation method based on this phenomenon. Three cylinders are placed horizontally and as water flows over them, it interacts with the cylinders, forming vortices which causes the cylinders to oscillate vertically. This oscillation provides mechanical energy that can be them converted to electrical energy by use of an electromagnetic induction mechanism.

ACKNOWLEDGMENTS

First and foremost, we'd like to thank Almighty Allah for all the help he blessed us with. Secondly, we'd like to thank our friends and family without the support of whom this journey would have been very difficult. We'd also like to thank our supervisor Dr. Emad ud Din and special thanks to Dr. Adnan Munir for rendering his guidance to us and being patient as we executed this project.

TABLE OF CONTENTS

LIST OF FIGURES

ABBREVIATIONS

VIV	Vortex Induced Vibrations

NOMENCLATURE

Re	Reynolds Number
Ur	Reduced Velocity
ν	Kinematic Viscosity
ζ	Damping Coefficient

1 INTRODUCTION

Energy serves as a fundamental pillar in human existence, underpinning crucial activities in the post-modern era. The historical realization of its importance dates back to early civilizations, exemplified by the Mesopotamian and Egyptian use of river flows to power irrigation systems and grain mills around 8000 BC. The human fascination with energy extended to endeavors like developing perpetual motion devices, exemplified by inventions such as Bhaskara’s Wheel, Villard’s Wheel, and the Overbalanced Clock. Despite the unattainability of perpetual motion due to thermodynamic constraints, humans have devised highly functional and efficient energy generation methods over the years, catalyzing technological progress and significantly enhancing our daily lives.

The predominant source of global energy production relies heavily on non-renewable fossil fuels, exacerbating pollution and contributing significantly to the escalating challenges of global warming. The World Health Organization (WHO) reports a staggering 4 million premature deaths annually attributable to air pollution, predominantly caused by fossil fuel emissions. Recognizing the imperative to address climate change, concerted efforts are essential to mitigate the adverse effects of burning fossil fuels. A strategic and gradual transition towards renewable energy resources emerges as a crucial solution. This not only promises a reduction in pollution but also offers the added advantage of diminishing energy generation costs, given the virtually limitless nature of these resources.

The primary contributor to the alarming levels of greenhouse gas emissions, a major driver of climate change, is the utilization of fossil fuels. As highlighted by the Intergovernmental Panel on Climate Change (IPCC), the warming of the planet, attributed to human activities, manifests in escalating temperatures, heightened occurrences of heatwaves, and an increase in extreme weather events, such as floods and droughts. Beyond the environmental impacts, the extraction, transportation, and combustion of fossil fuels lead to pervasive air and water pollution, posing significant threats to both human health and the overall ecosystem. According to estimates by the World Health Organization (WHO), the annual toll of premature deaths worldwide due to air pollution from fossil fuels exceeds 4 million, underscoring the urgent need for sustainable energy alternatives.

In the context of Pakistan, the extensive reliance on fossil fuels has emerged as a substantial contributor to both economic and environmental challenges. The substantial imports of oil and gas have imposed a considerable burden on the nation's economy. Simultaneously, air pollution stemming from coal-fired power plants has resulted in severe health issues, particularly in major urban centers like Lahore and Karachi.

A critical transition towards renewable energy sources, encompassing wind, solar, and hydroelectric power, is imperative for ensuring a sustainable future. By diminishing dependence on fossil fuels, Pakistan can alleviate the adverse effects of climate change, enhance public health, and stimulate economic growth through strategic investments in renewable energy technologies. Hydroelectric power, constituting 17% of global electricity production, assumes a pivotal role globally and contributes significantly in Pakistan, accounting for approximately one-third of the nation's total electricity generation. Despite its significance, the utilization of water for energy production presents challenges, with water scarcity induced by climate change posing a substantial threat to hydroelectric power production. Factors such as droughts, reduced snowfall, and changing rainfall patterns directly impact water availability, affecting the efficiency of hydroelectric power plants.

Moreover, the establishment of hydroelectric power plants carries potential adverse environmental consequences, including the displacement of communities and alterations to river ecosystems. However, the positive aspects of hydroelectric power cannot be overlooked. Serving as a clean and renewable energy source, it has the capacity to furnish reliable power to millions globally. In the Pakistani context, the Indus River system presents substantial potential for the expansion of hydroelectric power, emphasizing the dual challenge of harnessing its benefits while carefully managing its environmental impacts.

An alternative method to harness the kinetic energy of water involves strategically placing cylindrical structures in flowing water currents. As water courses over these cylindrical structures, an adverse pressure gradient forms on the downstream side, leading to the creation of vortices that alternate in shedding at the top and bottom of the cylinder. This process results in the development of an alternating pressure distribution around the cylinder, inducing oscillating lift and drag forces that ultimately cause the cylinders to vibrate. The magnitude and frequency of these forces are contingent on flow characteristics, surface roughness, and the diameter of the cylindrical body. The frequency of force aligns with the frequency of vortex shedding, expressed through the non-dimensional parameter known as the 'Strouhal Number.'

1.1 Motivation

Our reliance on traditional energy sources is unsustainable, posing significant environmental and economic challenges. Fossil fuels contribute heavily to climate change, air pollution, and resource depletion. This necessitates exploring alternative, renewable energy sources like Vortex-Induced Vibration (VIV) technology.

VIV harnesses the energy of fluid-induced vibrations in structures like cylinders. Despite its potential, current VIV-based energy harvesting devices face limitations in efficiency, durability, and configuration optimization. Addressing these challenges is crucial for unlocking the full potential of VIV technology.

This project tackles these limitations by designing and manufacturing a VIV-based energy harvesting device with multiple cylinders. Through meticulous design and engineering, we aim to:

Maximize energy output: We will explore strategies by varying the cylinders centre-to-centre distance to optimize cylinder geometry, arrangement, and material selection for reducing the weight of the oscillating mass in order to enhance energy conversion efficiency.

Enhance device durability: We will focus on material selection, structural design, and vibration control mechanisms to ensure the device withstands real-world conditions.

Optimize cylinder configurations: We will investigate the impact of cylinder number, spacing, and synchronization on energy harvesting performance.

This research holds significant promise for the future of renewable energy. By addressing the critical challenges, our proposed device can pave the way for a novel and sustainable approach to harnessing VIV for power generation. Potential applications span across renewable energy systems, environmental monitoring, and other fields where clean and efficient energy harvesting is crucial.

1.2 Problem Statement

The objective of this project is to investigate and formulate viable renewable energy solutions tailored to meet Pakistan's energy requirements and support socio-economic development. The aim is to discover and apply cost-effective, reliable, and sustainable renewable energy sources, thereby diminishing dependence on imported fossil fuels and bridging the expanding disparity between energy consumption and demand. Such a setup can also be deployed to power low consumption offshore equipment.

2 LITERATURE REVIEW

Over the last five decades, much study has been conducted to better understand vortex-induced vibration (VIV) of cylindrical structures. Feng. [1] pioneered research on the response of elastically placed circular cylinders that are free to vibrate transversely to the flow. The wide range of challenges arising from VIV has prompted several numerical and experimental inquiry, as well as several thorough review studies.

Traditionally viewed as a destructive factor, efforts to reduce the negative impacts of VIV on engineering structures have been a major focus of study. However, Bernitsas [2] and his colleagues at the University of Michigan Marine Renewable Energy Lab proposed using VIV to harvest water current energy, resulting in a paradigm shift. Their new gadget, named VIVACE (Vortex generated Vibration for Aquatic Clean Energy), takes use of the oscillation of cylinders generated by VIV to create clean hydrokinetic energy from slow-moving water currents.

2.1 Vortex Shedding

Vortex shedding is a complicated fluid dynamics process that happens when a fluid flows past a bluff body, resulting in the periodic shedding of vortices from both sides of the body. This phenomenon has important consequences for a variety of engineering disciplines, including aerodynamics, civil engineering, mechanical engineering, and maritime engineering. Understanding vortex shedding and its impacts is critical for developing efficient and stable structures exposed to fluid flows.

The vortices separate regularly from the body's surface, resulting in rhythmic flow patterns downstream. The Strouhal number describes how the shedding frequency is normally related to the flow velocity and inversely proportional to the body's characteristic length.

Researchers classified the flow around a cylinder based on the Reynolds number. Various flow regimes have been identified for different Reynolds number ranges. This categorization assists in understanding the forces acting on cylinders within specified Reynolds number intervals, allowing for a method of estimating the vortex-induced vibration (VIV) properties of cylinders under the relevant flow circumstances. Re is given by

$$Re = \frac{UD}{\nu}$$

where U represents the free-stream velocity, D is the cylinder diameter, and ν denotes the kinematic viscosity.

2.2 Vortex Induced Vibrations (VIV)

VIV arises when fluid flow causes periodic oscillations in a structure, resulting in alternating lift and drag. The interaction of the shedding vortices with the structure's inherent vibration modes is critical in defining VIV's amplitude and frequency. Factors that impact the phenomena include flow velocity, Reynolds number, structural qualities, and fluid parameters.

Computational fluid dynamics (CFD) simulations have also helped anticipate VIV characteristics and optimize structural designs. The use of both experimental and numerical methods has allowed researchers to test theoretical models and generate empirical correlations for predicting VIV response.

In the maritime and offshore sectors, VIV is an important factor in the construction of risers, mooring lines, and underwater pipelines. Furthermore, VIV has emerged as a possible source of renewable energy, with researchers looking at ways to use the rhythmic motion of buildings to generate electricity.

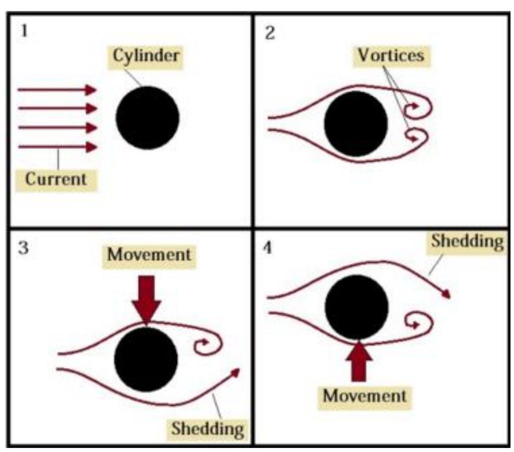

Figure 1: Vortex induced vibration phenomenon

2.2.1 Reduced Velocity

Reduced velocity is a key concept in fluid dynamics that is essential for understanding and analyzing fluid flow behavior around objects. It is defined as the ratio of the flow velocity to the system's characteristic velocity scale, which is commonly stated in terms of the Reynolds number. Reduced velocity reveals important details about the flow regime, such as boundary layer separation, turbulence, and vortex shedding. Reduced velocity gives a dimensionless measure of the flow's dynamic behavior, allowing for comparisons across different flow circumstances and systems. In hydrodynamics, lower velocity causes flow separation, vortex shedding, and the development of hydrodynamic stresses on submerged objects. It is given by:

$$V_r = \frac{UD}{\nu}$$

U is the velocity of the flow in the streamwise direction, fn is the natural frequency of the cylinder and D is the diameter of the cylinder. Within the range of $0 < Vr < 2.5$, the cylinder only vibrates along the inline direction. As the reduced velocity reaches $2.5 < Vr < 5$, vibrations start in the crossflow direction. During this phase, the cylinder oscillates bidirectionally until its motion is restricted in either direction. Further elevation of velocity beyond this range causes the cylinder to enter the lock-in phase, in which the shedding frequency of vortices coincides with the natural frequency, resulting in resonance and increased vibration amplitudes. This regime is very important for our application since magnified cylinder vibrations increase magnetic flux, which leads to greater energy generation.

2.2.2 The Lock-In Regime

The lock-in regime occurs when the shedding frequency of vortices in the fluid flow coincides with the structure's inherent frequency of vibration. This synchronisation causes constructive interference between the vortices and the structure's oscillations, which increases vibration amplitudes. Several elements impact the phenomena, including flow velocity, Reynolds number, structural qualities, and fluid parameters. The commencement of lock-in is often seen at specified lowered velocities when the shedding frequency corresponds to the structural frequency.

In the region of $5 < Vr < 7$, resonance occurs between the oscillating lift forces and the cylinder's inherent frequency. This is because the vortex shedding frequency equals the natural frequency as vortices are pushed to shed at a rate determined by the motion of the cylinder. As a result, the cylinder oscillates at significantly larger amplitudes. Researchers have appropriately named this Vr range the 'lock-in' regime because the vortex shedding frequency 'locks' into the cylinder's inherent frequency, producing in resonance and high-amplitude vibrations.

The lock-in regime was first explored by Bishop and Hasan in the year 1964 and was further studied by Govardhan and Williamson [3] in the year 2000. Other researchers like Feng (1968) [4] did some valuable additions in the literature concerning this phenomenon.

Lock-in is a highly nonlinear phenomena that may occur at a variety of shedding frequencies. Lock-in has also been referred to as a self-limiting and self-regulating phenomenon. Cylinder vibrations impact the vortex shedding process, and vice versa. It is characterised as self-limiting because when the cylinder displacement increases, the vortex shedding weakens and therefore lowers more motion.

2.3 Electricity Generation:

Traditionally, vortex-induced vibration (VIV) has been predominantly studied within the realm of deep-sea oil pipelines, focusing on strategies to mitigate its adverse effects. However, there has been a recent shift towards exploring the potential of VIV as a source of electricity generation. Researchers are now actively investigating the feasibility of harnessing VIVs for power production. Numerous models and methodologies have been proposed, utilizing both numerical simulations and analytical techniques. Another critical factor influencing the extractable energy from the flow is the Betz law, which sets a theoretical limit on the maximum energy that can be captured from the flow.

Lefebure, Dellinger, François, & Mosé (2020) [5] introduced an innovative mechanical system that utilizes Vortex Induced Vibrations (VIVs) via a belt-generator mechanism to generate electrical power. The researchers determined the system's efficiency to be 40%, with an estimated annual energy production of nearly 2 MWh/m2 achievable at flow velocities as low as 1 m/s. This groundbreaking technology holds significant promise for enhancing clean energy production.

Mehmood et al. (2013) [6] explored the feasibility of electricity generation from VIVs using piezoelectric means. Employing a computational fluid dynamics (CFD) approach that considered electromechanical damping, they found that optimal power generation from VIVs occurred when the load varied between high and low values.

3 METHODOLOGY

In the following section, the work that we have carried out so far has been summarized, including prototype designing, CFD modelling and analysis, and numerical modelling of the system.

3.1 Process Summary

3.1.1 Idea Generation:

In the project's initial phase, we explored diverse energy harvesting mechanisms, initially focusing on the piezoelectric eel concept. However, due to insufficient power generation, alternative ideas were systematically analyzed. Extensive literature review led us to identify electromagnetic induction using water waves as the most promising option for efficient energy harvesting.

3.1.2 Prototype Designing:

Subsequently, attention turned to prototype designing. Through an iterative approach, we considered materials, dimensions, and structural integrity to achieve the most optimum design. Using computer-aided design (CAD) software SolidWorks, we revised the prototype design multiple times to balance feasibility, manufacturability, and optimal performance.

3.1.3 Numerical Modeling

The next step involved implementing numerical simulation tools to create a numerical model of the energy harvesting device. Through iterative refinement, parameters and configurations were adjusted to achieve optimal results consistent with theoretical expectations. This process facilitated the refining of our numerical model based on feedback from simulations.

3.1.3.1 CFD Analysis

The simulations were conducted using Ansys Fluent. Five cases were simulated, with the following variations:

- L/D: This refers to the length-to-diameter ratio of the cylinders. The five values used were 2, 2.5, 3, 3.5, and 4.
- Re: This is the Reynolds number, a dimensionless quantity that measures the ratio of inertial forces to viscous forces in a fluid. The value used in all the simulations was 1000, which is in the subcritical regime.

Geometry and Setup:

We investigated flow around 3 cylinders arranged in a 2D domain. This simplified the geometry while still capturing key aspects of flow interactions.

Using finer mesh near the cylinder walls was crucial for capturing complex flow phenomena near the solid boundaries, resulting in more accurate lift and drag predictions.

For this, body sizing was incorporated keeping the element size to 0.0044m, face sizing was set up keeping the element size 0.0009m and inflation was set on boundaries of the cylinder walls keeping maximum layers to 50 and a growth rate of 1.2.

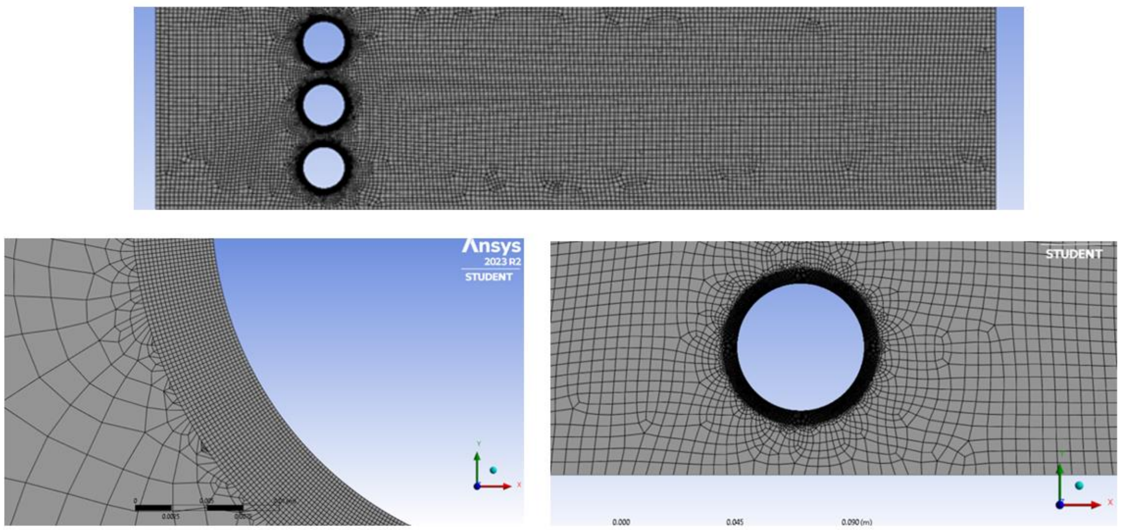

Figure 2: Mesh

Boundary Conditions:

- Inlet: Specified a water flow inlet defining the incoming fluid characteristics like velocity.
- Outlet: Defined the outlet keeping outlet velocity to zero.
- Walls: Setting a no-slip condition ensures the fluid adheres to the wall, mimicking real-world behaviour.

- Cylinders: Using their circumferences as reference surfaces for force analysis ensures accurate integration of pressure and shear stress acting on the cylinders.

Results and Analysis:

- Lift and drag coefficients for each cylinder provided quantitative data on the forces experienced by each object.
- Lift results were combined to compute a mean lift coefficient.
- We analyzed velocity contours over time to help us visualize vortex formation, shedding, and their impact on the forces acting on the cylinders.

Possible Enhancements:

- While 2D simulations offered valuable insights, considering 3D simulations for complex interactions or if cylinder orientation matters.
- Along with the static meshing, dynamic meshing was also done to get better and accurate results for flow around the cylinders, with the gap between the cylinders which gave the maximum mean lift coefficients.

3.1.4 CFD Analysis:

Our focus then shifted to Computational Fluid Dynamics (CFD) analysis, utilizing Ansys software to model fluid flow around multiple cylinders. Employing static and dynamic meshing techniques, we dedicated considerable time to refining CFD simulations.

Ultimately, we obtained desired results, particularly through the implementation of dynamic meshing, ensuring an accurate representation of flow characteristics.

3.1.5 Manufacturing and Prototyping

Moving forward, current efforts are directed towards the physical realization of the design through the manufacturing and prototyping phase. This phase emphasizes the alignment of the manufacturing process with the specifications outlined in the design phase.

3.1.6 Experimentation

After prototyping our system, we will commence experimental testing on the manufactured prototype to validate theoretical assumptions. Our focus will be on monitoring and collecting data during testing to evaluate the system's performance and power output. Any discrepancies between theoretical predictions and actual experimental results will be addressed through iterative adjustments to refine the system further.

3.1.7 Validation

The final steps of the project will involve completing the validation process by comparing experimental data with numerical simulations. A comprehensive analysis will confirm consistency between theoretical predictions and observed outcomes. Our goal is to ensure the device meets or exceeds the target specifications set at the beginning of the project.

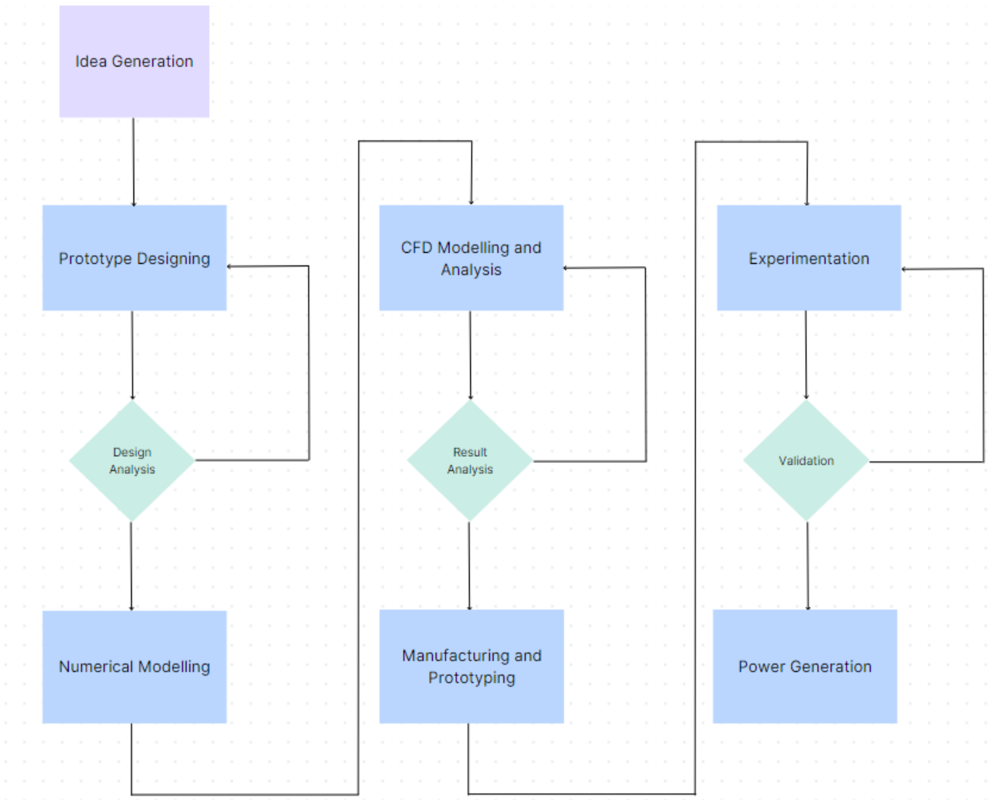

Figure 3: Flow Diagram

3.2 Prototype Designing

The prototype designing phase played a pivotal role in refining our VIV-based energy harvesting device to ensure optimal performance, manufacturability, and affordability. The process involved meticulous consideration of design parameters based on different fluid flow factors. The chosen parameters, such as aspect ratio (L/D) and mass ratio (m*), were carefully tailored to achieve maximum output within specified Reynolds numbers and reduced flow velocity.

3.2.1 Design Parameters

Our device's design parameters were linked to its functionality and efficiency. The aspect ratio (L/D) and mass ratio (m*) were of particular significance. The aspect ratio, defined as the ratio of the cylinder's length (L) to its diameter (D), shaped the overall geometry of the device. Through careful adjustment, we aimed to strike a balance between the aspect ratio and the associated fluid dynamic effects such as synchronization in lock-in regime, resonance, lift coefficients and vortex shedding frequency, ultimately optimizing performance.

The mass ratio (m*) was equally critical, representing the ratio of the added mass of the cylinder to the fluid displaced by the cylinder. This parameter directly impacted the device's ability to harvest energy efficiently from the fluid flow. By fine-tuning the mass ratio, we aimed to achieve a design that maximized energy extraction while considering practical constraints.

These design parameters were adjusted iteratively to align with specific Reynolds numbers and reduced flow velocities, ensuring the device's adaptability to varying environmental conditions and fluid dynamics.

flow velocity, $U := 0.32 \ \frac{m}{s}$

diameter of cylinders, $dia := 0.05 \ m$

Kinematic viscosity of water, $\upsilon := 1.002 \cdot 10^{-6} \ \frac{m^2}{s}$

$$Re := \frac{U \cdot dia}{\upsilon} = 1.597 \cdot 10^4$$

The above Reynolds number shows that we are dealing with sub-critical regime.

$m_{osc} := 1.5 \ kg$

density of water, $\rho := 998 \ \frac{kg}{m^3}$

length of cylinders, $len := 0.36 \ m$

$$m_d := \frac{\pi}{4} \cdot \rho \cdot dia^2 \cdot len = 0.705 \ kg$$

mass ratio, $m_{star} := \frac{m_{osc}}{m_d} = 2.126$

Theoretical power generated by a single cylinder, $P_{single} := \frac{1}{2} \cdot \rho \cdot U^3 \cdot dia \cdot len = 0.294 \ W$

Figure 4: Target Specifications

3.2.2 Final Design

The final design was built upon iterative improvements of the initial designs to achieve an optimum configuration to harvest energy. The final design comprises key components – a top frame, cylinder with struts, helical springs, MGN block and rail, rack and pinion assembly, and generator. The cylinder is mounted between struts, which are then attached to two springs, one on each side. The springs ensure oscillatory motion of the cylinder under fluid flow. The oscillating linear motion of the cylinder is converted to rotary motion by means of a rack and pinion arrangement which is further connected to a generator to produce electricity. The primary goal is efficient energy capture from the oscillating cylinder, with linear motion transformed into rotary motion through a rack and pinion assembly to drive a conventional generator.

The cylinder, mounted between struts, has a diameter of 5 cm and a length of 7 cm, resulting in an aspect ratio of 1.4. The material choice for the cylinder is PVC for durability and weight considerations, while aluminum is used for the frame and struts to ensure structural integrity without compromising weight.

Dimensions were calibrated to match the flow properties of the water tunnel in the flow lab, ensuring optimal performance within the specific experimental setup.

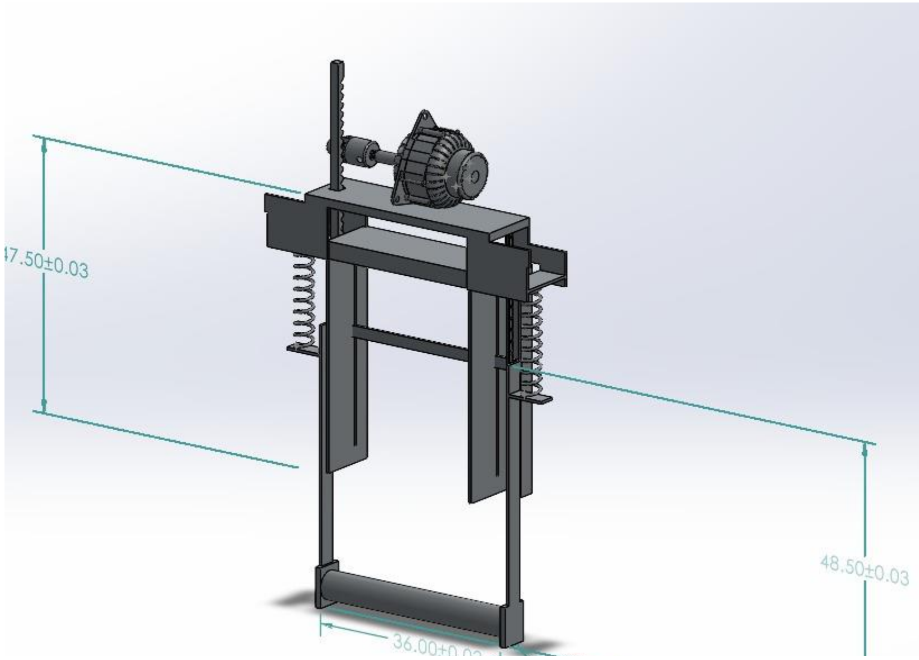

Figure 6: Final Design Isometric View

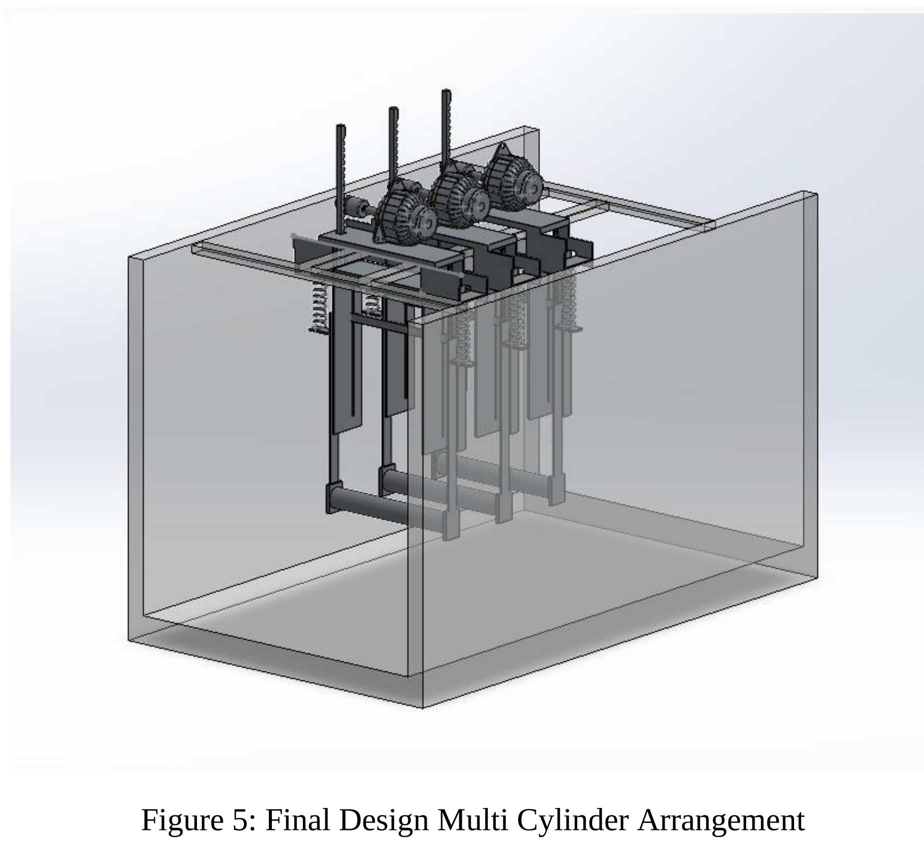

Figure 5: Final Design Multi Cylinder Arrangement

4 RESULTS AND DISCUSSIONS

Ran simulations of 5 cases with following variations:

L/D = 2, 2.5, 3, 3.5 & 4 (where L is the center-center distance of the cylinders)

Re = 1000 (sub critical regime)

4.1 Simulations for Case 1

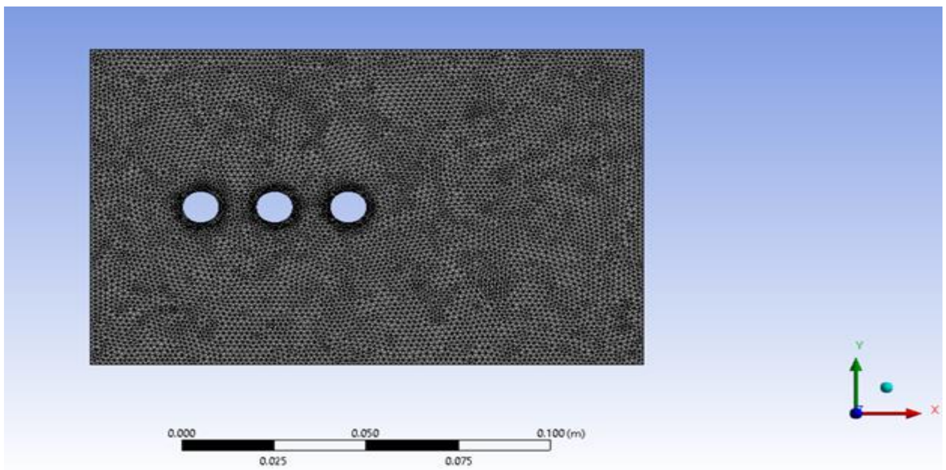

Figure 7: Dynamic Mesh

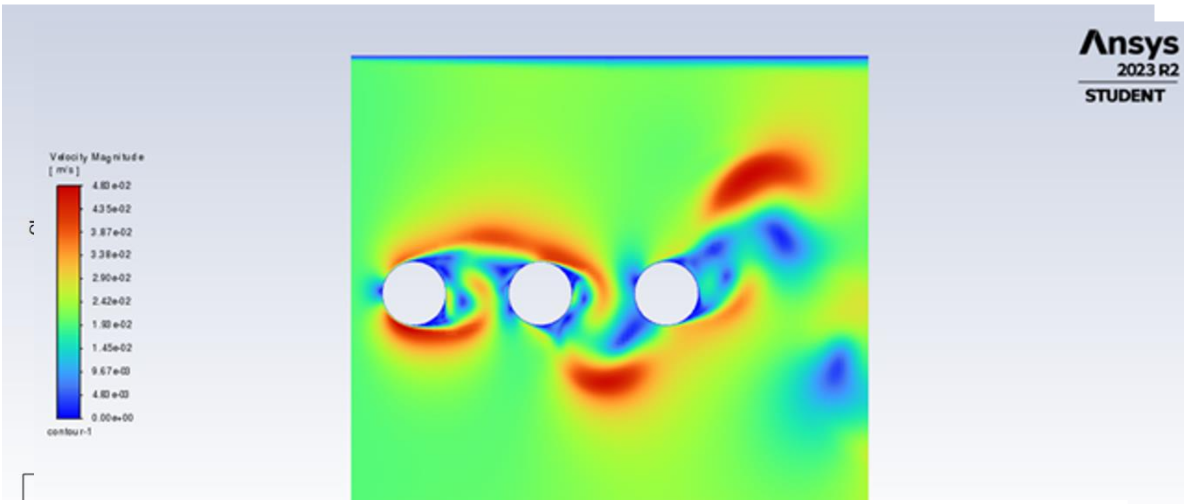

Figure 8: Velocity Contours

Figure 8: Lift Coefficient

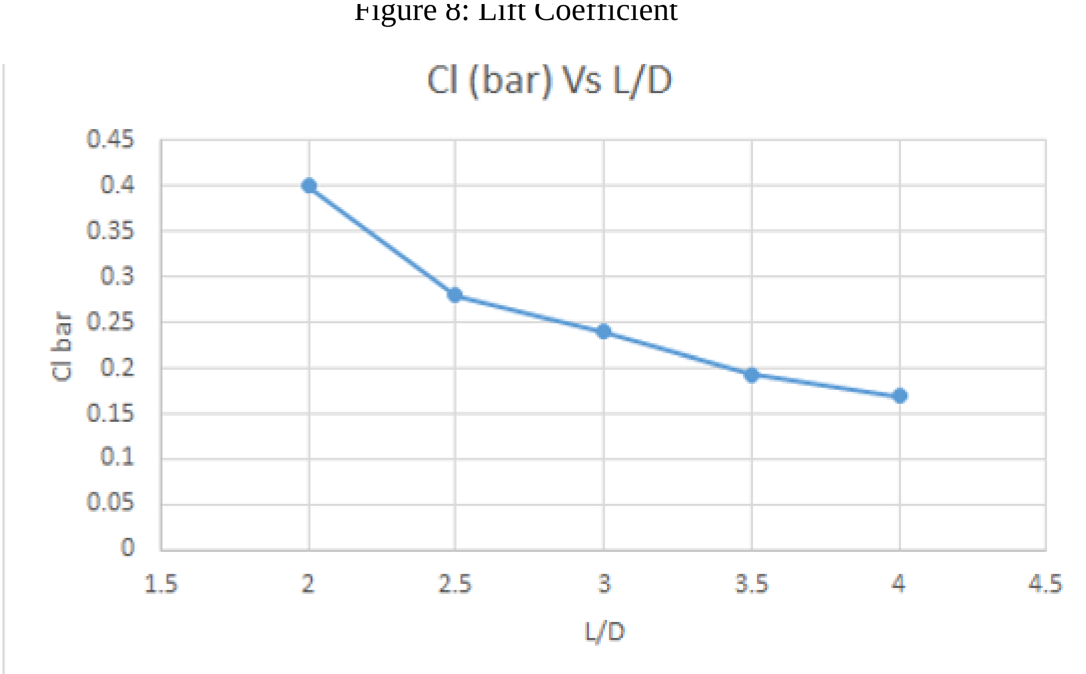

Figure 9: Graph of mean lift coefficient Vs L/D

As distance between the cylinders decrease the lift coefficient increases.

5 DESIGNING AND MANUFACTURING OF ENERGY HARVESTING DEVICE:

5.1 Supports for cylinders:

5.1.1 Iron Supports:

Iron supports initially planned to be used for the main frame of the assembly were quite heavy which increased the oscillating mass. Iron supports also were prone to rust which made them unsuitable for this project.

5.1.2 Thin Aluminium Sheets

For the second iteration thin aluminum sheets were utilized. This resolved the weight issue but the rigidity of the system was compromised.

Figure 10: Aluminum sheet supports

5.1.3 U-Shaped Aluminum Supports (Alloy AD-31)

The third and final iteration utilized U-shaped Aluminum supports like the ones used in windows. These were light and rust-proof and the U-shape provided much needed rigidity to the system. These supports also provided easy opportunities for machining allowing us to directly fix bearings to the support itself.

5.2 Bearings (MGN12H)

To restrict the motion of the cylinders to the vertical axis only, linear bearings were selected specifically MGN-12H. Two bearing each are used on both of the supports to allow the cylinder to oscillate freely and with minimum frictional losses. The MGN-12H block provided the proper size and cost compromise for this project.

In another iteration we tried 2 bearings in tandem on each of the supports. This divided the axial force on each bearing but the alignment issues and the extra friction deemed this configuration unsuitable for our use.

Figure 11: MGN-12H Block

5.3 Rail (MGN-12)

MGN-12 stainless steel rails were used for the bearings to glide over smoothly, two for each cylinder assembly. These provided rust protection and a smooth path for the bearings but were expensive and difficult to machine.

Figure 12: 12mm Linear Rail

5.4 Cylinder

5.4.1 Stainless Steel

In the first iteration, stainless steel cylinders were used. They had 2 main advantages, in that the surface finish was excellent and because of being welded to the supports, they sealed very effectively. However, steel cylinders increased the oscillating mass and were expensive because of which we were motivated to use PVC cylinders.

5.4.2 PVC Cylinder

The second iteration utilized PVC cylinders which were cheap and didn't add much to the oscillating mass. They were also easy to work with. However, they did cause sealing problems which were later fixed by using epoxy sealant. The surface roughness of the cylinders as improved by painting over them.

Figure 13: Stainless steel cylinder (top two) and PVC cylinder (bottom)

5.5 Helical Compression Springs

Stainless steel compression springs were selected to be used to provide the required damping and the return force for proper oscillations. Various different spring designs with varying spring stiffnesses were tested to shortlist the ones which provided the best combination of rigidity and damping for the system. The spring stiffness was calculated by the spring design formula;

$$k = \frac{Gd^4}{8D^3 n_a},$$

Where k is the spring stiffness, G is the shear modulus, D is the mean diameter of the spring, d is the spring wire diameter and n_a is the number of active coils of the spring.

5.5.1 High stiffness springs

High stiffness springs were robust but offered too much damping which reduced the oscillation amplitude. This was definitely not suitable as power output of the system is directly related to the oscillation amplitude.

5.5.2 Low stiffness springs

Although a little less robust than the high stiffness springs, these provided the proper amount of damping which maximized the oscillation amplitude, thus maximizing the power output of the system.

diameter of wire, $d := 1.2\ mm$

shear modulus, $G := 79\ GPa$

diameter of spring, $D := 28\ mm$

no. of turns, $n_a := 70$

spring stiffness, $k := \dfrac{G \cdot d^4}{8 \cdot D^3 \cdot n_a} = 13.326\ \dfrac{kg}{s^2}$

Figure 14: Spring parameters

Figure 15: Different spring variations

5.6 Rack and Pinion

A rack and pinion setup was used to convert the linear motion of the cylinders to rotary motion of the alternators (motors). Two different options were explored for this setup but we settled for the acrylic laser cut rack and pinion.

5.6.1 3-D printed ABS plastic

This was costly and provided a poor finish which caused jerks and inability to operate at higher RPMs. The 3D printing process was also quite slow which caused unwanted delays.

5.6.2 Acrylic laser cut

Laser cut acrylic provided the best finish with minimal jerk and higher tensile strength meant that RPMs could be achieved. The laser cutting procedure was quite quick allowing for rapid prototyping and testing. All these benefits motivated us to use laser cut acrylic rack and pinions.

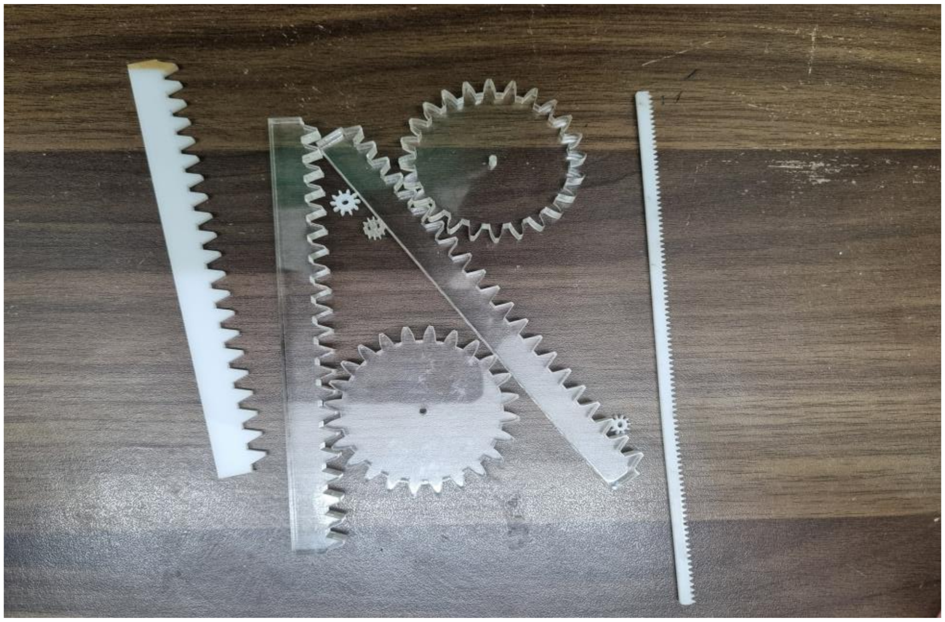

Figure 16: Acrylic laser cut rack & pinion sets

6 DESIGNING AND TESTING MECHANISMS FOR ENERGY HARVESTING FOR DIFFERENT CYLINDER CONFIGURATIONS USING EM.

6.1 Testing Different Cylinder Configurations:

Single Cylinder: Begin with a single rigid cylinder mounted on springs, as described in the VIVACE papers. This serves as a baseline for understanding VIV behavior and energy harvesting efficiency.

Multiple Cylinders: Investigate configurations with multiple cylinders arranged in series, parallel, or other arrangements. Analyse how cylinder spacing, synchronization, and interactions affect VIV and energy output.

6.2 Testing Different spring types and stiffnesses

Different spring configurations were tested to see which provided the best compromise of rigidity and oscillation amplitude. We started off with the highest possible spring stiffness and gradually reduced it until we achieved the best balance of rigidity and the amplitude.

6.3 Testing Different Bearing Configurations

Tandem bearings and single bearing configurations were tested to see which provided the best results. Tandem bearings were effective in distributing the axial load but they increased the overall friction of the system and introduced alignment issues due to which we had to go with single bearing configuration.

6.4 Testing Different Spacing ratios (L/D)

The following L/D spacing ratios were tested to determine the most effective ratio:

- 2
- 2.5
- 3
- 3.5
- 4

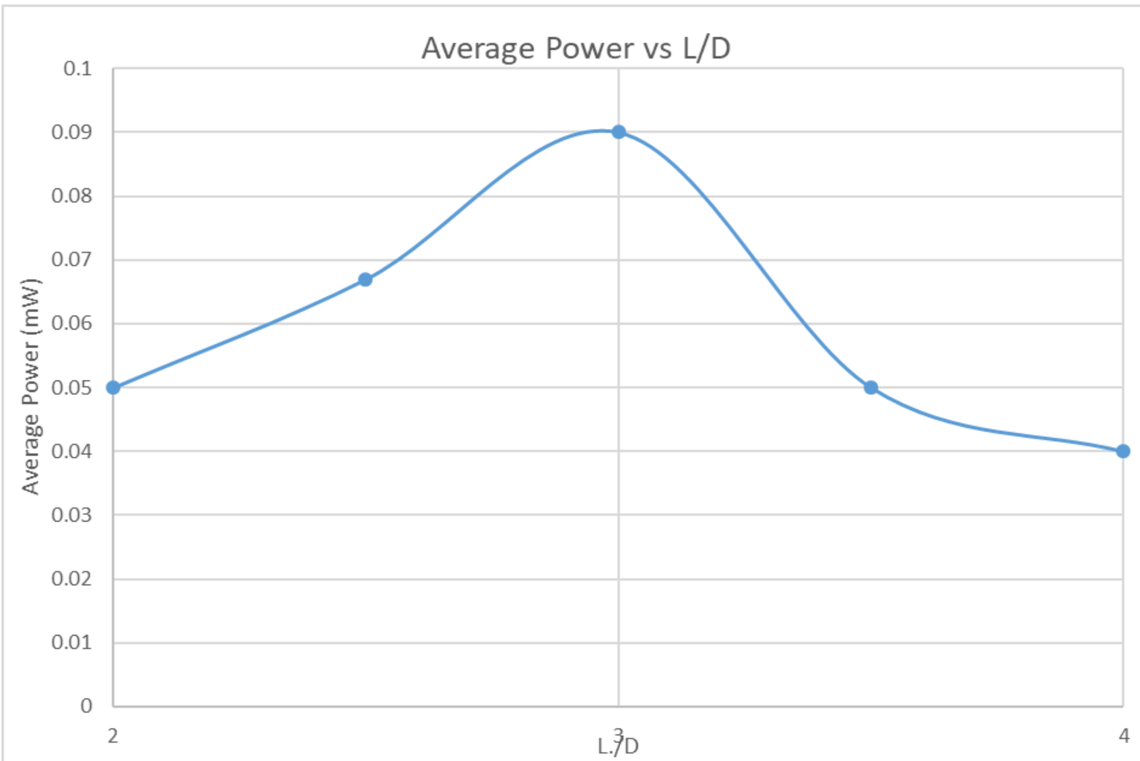

Figure 17: Graph of average power vs. L/D

6.5 Parameters calculations

density of water, $\rho_w := 988 \ \frac{kg}{m^3}$

Diameter of cylinder, $D := 6 \ cm$

Length of cylinder, $L := 27 \ cm$

displaced mass, $m_d := \rho_w \cdot \pi \cdot \frac{D^2}{4} \cdot L = 0.754 \ kg$

coefficient, $cn := 0.75$

$m_a := cn \cdot m_d = 0.566 \ kg$

oscillating mass, $m_{osc} := 0.62 \ kg$

$$m_{star} := \frac{m_{osc}}{m_d} = 0.822$$

natural frequency of oscillating system, $f_n := \frac{1}{2\pi} \cdot \sqrt{\frac{k}{m_{osc} + m_a}} = 0.534 \ \frac{1}{s}$

Figure 18: Final design parameters.

6.6 Design and Optimize Energy Harvesting Mechanisms:

The energy harvesting mechanism is the heart of the system as it is solely responsible for converting the mechanical energy to electrical energy. It consists of various different parts;

Electromagnetic Generators: Implement electromagnetic generators coupled to the cylinder oscillations. This approach involves converting mechanical motion into electrical energy through magnetic field interactions. A simple DC motor was utilised for in our setup.

Arduino UNO: The output of the DC motors was connected to an Arduino Uno which allowed us to visualize the power generation in a graphical form. This was essential during the testing phase to see which configurations were performing the best.

Resistors: Resistors were connected to the output to act as the arbitrary loads. A range of resistances was experimented with to find out the ideal resistor resistance for the best power output.

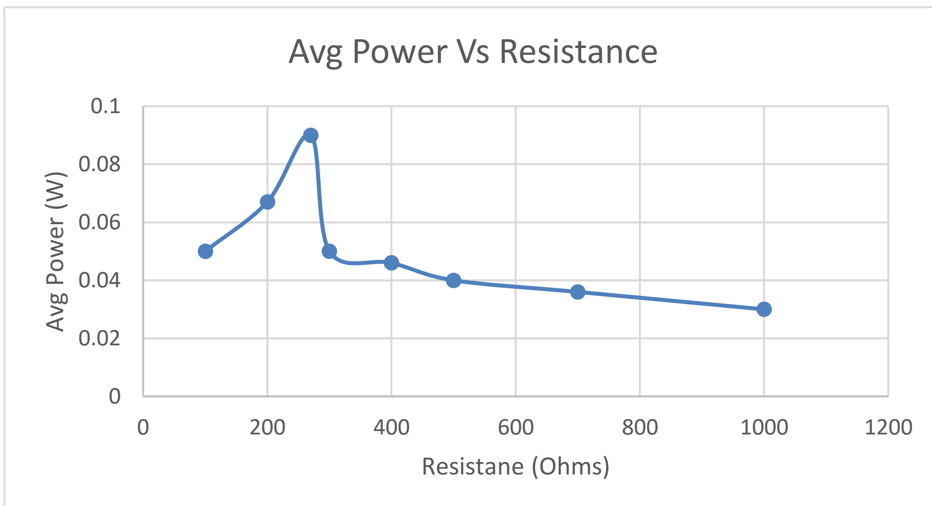

Figure 19: Graph of avg power vs. resistance

7 VALIDATION OF RESULTS

7.1 Average Power Output vs Centre to Centre cylinder Distance comparison with simulations results

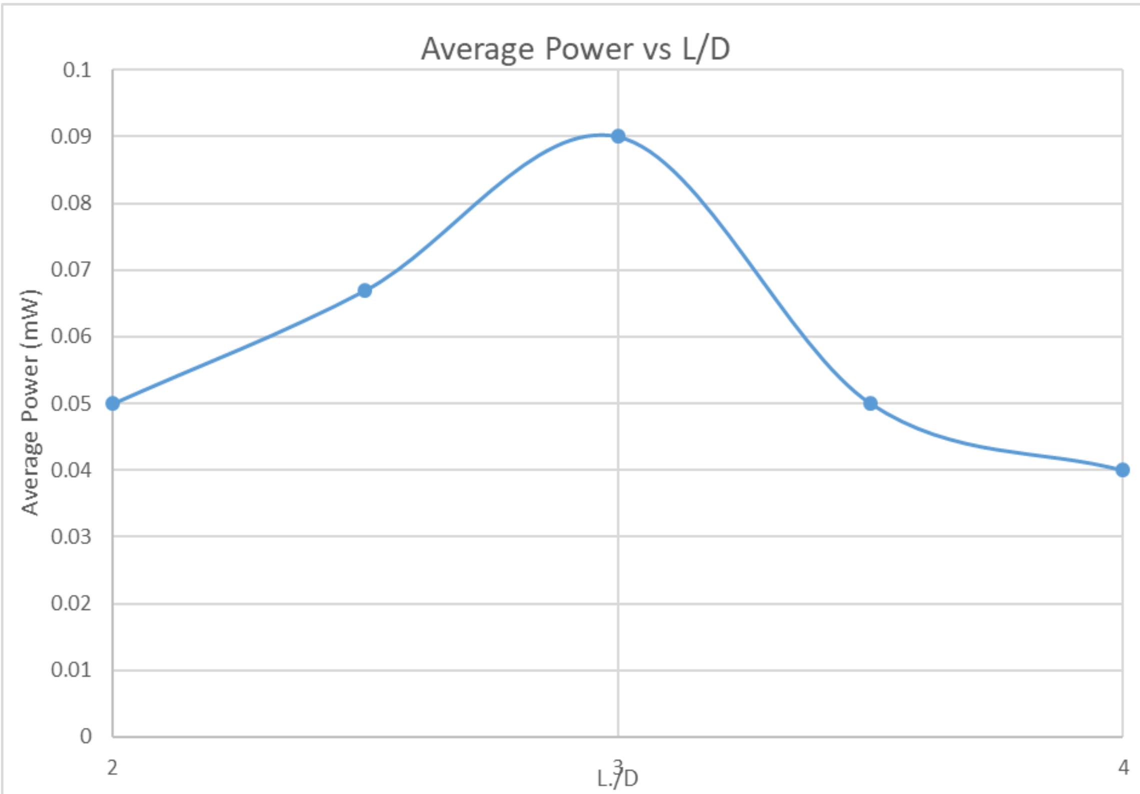

Figure 20: Average power vs L/D **(Actual)**

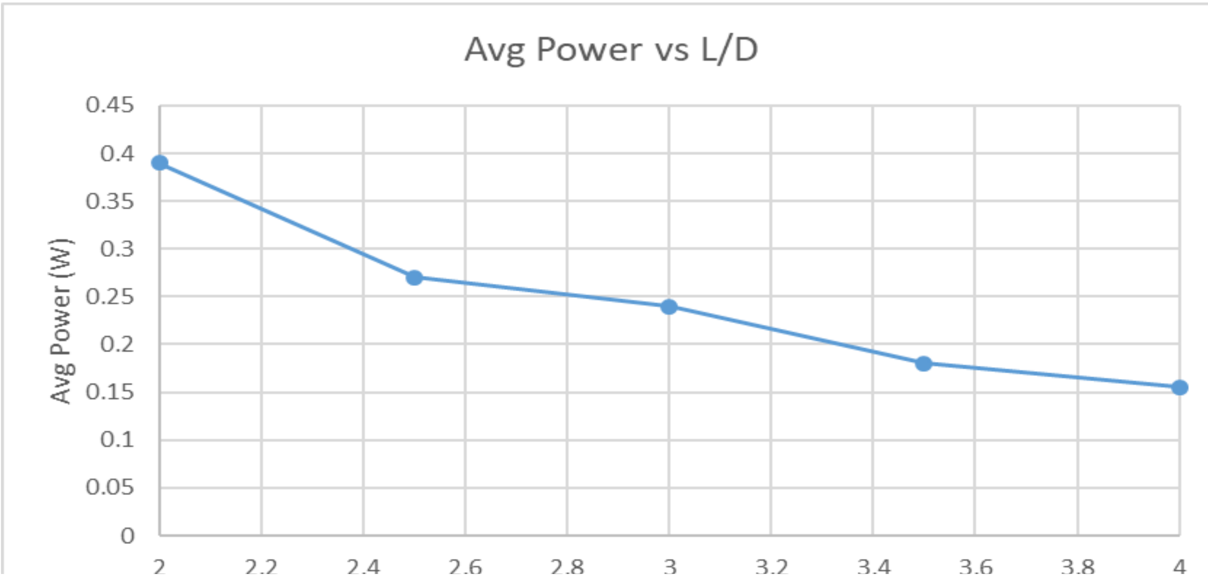

Figure 21: Average power vs L/D **(Simulated)**

As visible from the above graphs, the simulated power is 3 times the actual obtained power which is due to the following reasons:

1. Frictional losses between the bearings and the linear rail.
2. Minor misalignments between the rails.
3. Increased drag due to U-shaped supports and mounting mechanisms of the cylinders.
4. Non-linear behaviour of springs in actual conditions.

7.2 Power Output of each cylinder against Reynolds number in the sub-critical regime comparison with simulation results:

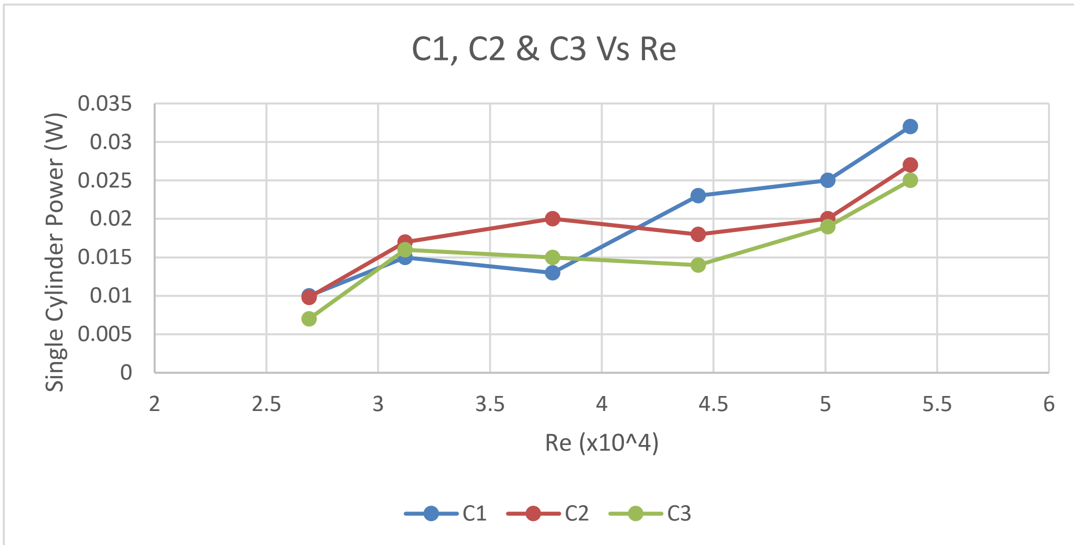

Figure 22: Single cylinder power vs Reynolds number **(Actual)**

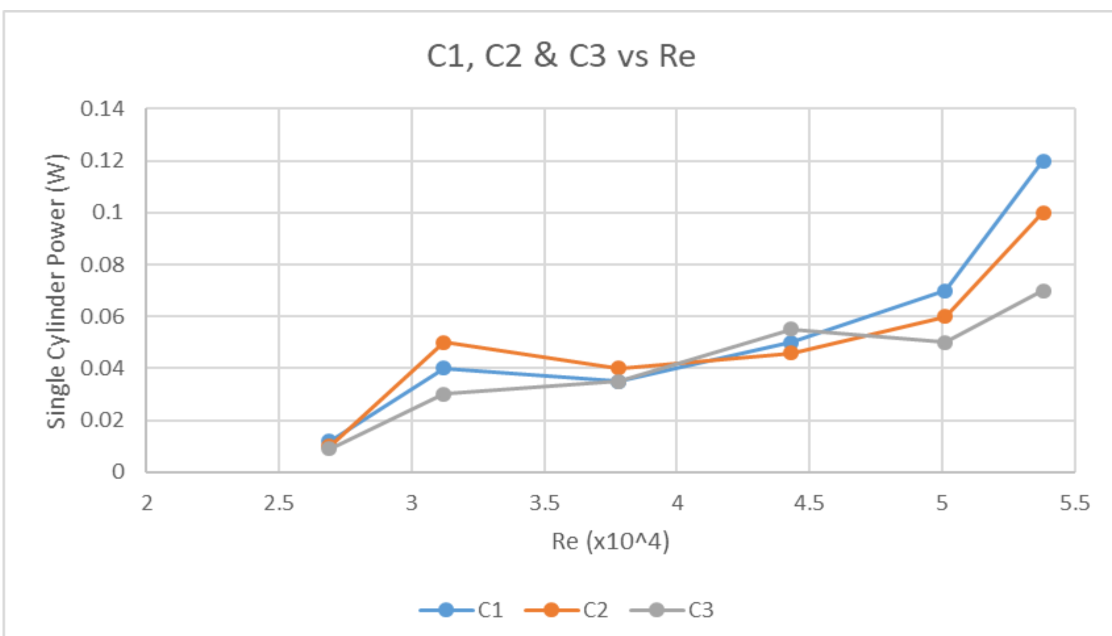

Figure 23: Single cylinder power vs Reynolds number **(Simulated)**

The above comparison showcases the affect of synchronization without the influence of other bluff bodies in the flow regime. This gives us a more accurate result for a single bluff body as it is not affected by drag from the neighbouring bluff bodies and the synchronization range (lock-in regime) can be examined explicitly. The influence of Renaults number against the power produced by each cylinder was verified in both the cases. The experimental and simulated results validate that as we increase the Renaults number the power production of each cylinder increases linearly.

7.3 Findings

The trend of Reynold’s number vs power generated by each cylinder is similar in nature, but with a lower power produced in experimental results due to frictional losses and low impedance of the alternator.

The optimum centre-to-centre distance between actual and numerical results conclude that a distance greater 2D is ideal, but in experimental data it concludes that an optimum centre-to-centre distance should be around 3D.

The analytical model's predictions are consistent with the results obtained through numerical simulations and real-world experiments, hence demonstrating their mutual validation.

8 CONCLUSION

A new concept for generation of clean and renewable energy from ocean/river currents has been introduced. An energy converter has been designed and tested. It extracts energy successfully by strengthening rather than spoiling vortex shedding, enhancing rather than suppressing VIV, and harnessing rather than mitigating VIV. It is unobtrusive to navigation, the marine life, and coastal real estate; it is simple with all mechanical and electrical components sealed from the water environment; it is based on readily available offshore technology implying robustness and it has high energy density. Additional advantages include consistency of current flow and its availability all year round, grid compatibility, broad range of synchronization, which allows efficient extraction of energy with minor and slow adjustment of basic design parameters such as the spring stiffness and induced damping, its ability to generate energy with high power conversion ratio even at speeds as low as 0.8 m/s, and ability to extract even more energy even in the case of velocity surge to 2.5 m/s and higher. Finally, its scalability, modularity, and design flexibility allow for a broad range of applications.

8.1 Way Forward

This project is an energy harvesting device representing a groundbreaking innovation in renewable energy technology. By harnessing the high energy density of vortex shedding, it generates small yet significant amounts of electricity, perfect for powering offshore sensors and low-powered electronics in remote or challenging environments.

Reliable: Its potential impact is vast, offering reliable energy solutions for marine research, environmental monitoring, and even offshore infrastructure maintenance. As technology advances, it can contribute to sustainable development and the advancement of renewable energy sources.

There is plenty of room for improvement in this model. There are three areas of promising improvement at the module level:

- optimization of the hydrodynamics of VIV including vortex shedding mode under high damping and vortex strengthening and shedding timing,
- optimization of the range of synchronization and the amplitude of VIV under high damping.

9 REFERENCES

[1] C. Feng, "The Measurement of Vortex-Induced Effects in Flow Past a Stationary and Oscillating Circular Cylinder and d-Section Cylinders.," *Masters Thesis, University of British Columbia,* 1968.

[2] Raghavan and Bernitsas, "Experimental investigation of Reynolds number effect on vortex induced vibration of rigid circular cylinder on elastic supports,," vol. 38, no. 5-6, pp. 719-731, 2011.

[3] R. Govardhan and C. Williamson, "Vortex-induced vibrations," *Annual Review of Fluid Mechanics,* vol. 36, pp. 431-455, 2004.

[4] C. Feng, "The measurement of vortex induced effects in flow past stationary and oscillating cylinders and D-section cylinders.," *PhD thesis, University of British Columbia,* 1968.

[5] Lefebure, D. &. Dellinger, N. &. François, P. &. Mose and Robert, "Analytical and CFD study of the influence of control parameters on the maximum efficiency of a hydro-power conversion system based on vortex-induced vibrations," 2020.

[6] R. Mahmood, N. Kousar, K. Usman and A. Mehmood, "Finite element simulations for stationary bingham fluid flow past a circular cylinder.," 2013.