BIO - INSPIRED FLAPPING WING ENERGY HARVESTER

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ABSTRACT

In order to generate clean and green energy through water resources as an alternative to large rotary turbine-based dams, an oscillating hydrofoil turbine is proposed in this project that seeks to utilize shallow flowing waters of rivers and streams to ostensibly generate a minimum of 1 kilowatt of power.

The project employs oscillating motion caused by the water flow field and converts it to rotary motion through a four-bar mechanism, that is in turn connected to a generator to produce electricity. The final results indicate a power generation of 1.089 kW for 1.5 m/s of water flow and oscillation frequency of 1.375 Hz. A hydrodynamic efficiency of 32.9% is achieved.

ACKNOWLEDGMENTS

We are extremely grateful to Allah Almighty for satisfactory progress in our Final Year Project. We have, till now, learnt significantly about project management, analytical and critical problem solving, engineering analysis, and other aspects important while progressing in an FYP. We are also thankful to our supervisor Dr. Aamir Mubashar who provided us an opportunity to learn and gain practical knowledge. We are also very thankful to Dr. Emad-Ud-Din and other faculty members for guiding and helping us. We hope this fruitful project will enable us to apply our skills and knowledge to polish ourselves as good mechanical engineers.

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ABBREVIATION

RPM	Revolutions per Minute
AOA	Angle of Attack
FOS	Factor of Safety

NOMENCLATURE

h_o	Heaving Amplitude (m)
c	Chord length (m)
b	Hydrofoil Span (m)
w(t)	Angular Velocity (rad/s)
M(t)	Torque (N.m)
U	Free Stream Velocity (m/s)
θ	Pitching Amplitude (°)
Y_p	Swept Area (m)
F_b	Buoyant Force (N)
P_o	Power Output (W)
P_a	Available Power (W)
C_L	Coefficient of Lift
C_D	Coefficient of Drag

CHAPTER 1: INTRODUCTION

Throughout the journey of technological advancements, humans have found ways to improvise and adapt to new solutions whenever the need arises. Given the current situation of greenhouse gases, fossil fuel depletion and air pollution, researchers all around the world are trying to switch to environment friendly sources to produce energy. Flowing water being an ancient source of extracting energy is also being used as an alternative energy source in a lot of different ways even today. Around 70% of the world is covered with oceans and given the tidal effects and many other phenomena that cause the water to flow, extracting green energy from water sources is a lot easier than other sources. One of the leading effects of air pollution and global warming is glacier loss. The rate of glacier loss accelerated from 9 inches per year in 1980 to 3 feet per year in 2020. Where, on one side melting glaciers are an immense issue for scientists and researchers to deal with, it can also provide us with the opportunity to extract energy in huge capacities.

Conventionally, Dams and Hydel power plants have been extracting energy from water for decades, using rotary turbines. These turbines use the kinetic energy of fast flowing or falling water to drive generators which generate electricity. But there are many limitations and disadvantages associated with these. Dams require a certain topography to ensure there is sufficient water head and falling velocity to be commercially viable. As a result, they are very expensive to build and maintain, huge area is required for reservoirs, spillways and the structure itself. For small scale rotary turbines energy harvesters, there are other problems. Either vertical or horizontal axis blades, they require excessive space and flow velocities ranging from 2.5m/s to 3.2m/s [5]. Aquatic animals have a very different kinematic locomotion to rotary turbines, which means that the unnatural movement of the blades compared to its surroundings means that marine life is severely affected.

While conventional rotary turbines are being used widely across the globe, the oscillatory hydrofoil systems are gradually making space for themselves in the modern-day picture of green energy sources. In 1981, McKinney and DeLaurier were the first researchers to present the phenomena of extracting energy from flow using an oscillating airfoil shaped wing/blade [3]. Although they based their research on wind energy, the same concept can be applied for water flows which is a much better alternative due to the high density of water. Additional work was done by Jones and Platzer who investigated the feasibility of energy extraction from fluid flow.

The use of rectangular oscillating hydrofoil blades offers an interesting alternative to the conventional rotary turbines. This new concept explores the hugely untapped potential of extracting energy from slow flowing waters even at shallow sites in water bodies. This offers an obvious advantage as compared to rotary turbines which requires a very specific topography for energy generation. Hydrofoil systems with oscillatory motion have certain advantages over rotary turbines:

- Easier to manufacture because of geometry (Hydrofoil)
- Cheaper installation of power generation system
- Can be deployed in shallow waters near metropolitan areas
- Easily scale – able
- Natural motion means less environmental footprint
- Less susceptible to debris

1.1 Problem Statement

To develop an efficient Oscillating Hydro-foil Energy Harvester capable of generating 1KW electricity from tidal rivers motions and shallow water streams.

1.2 Objectives

The main objective of this project is to design an oscillating hydrofoil energy harvester which uses a fluid flow of 1.5m/s to efficiently harvest 1 kW of energy. The system design and configuration should be viable enough to be used in shallow water stream and should be agile enough to handle varying fluid flow. The lift-drag combination should meet the need for producing the aforementioned wattage. The system configuration should have the minimum possible maintenance cost.

1.3 Motivation

Over the past few decades, modernization and technological advancements have done great favors to the human race but the use of non-renewable fuel sources has also posed a great threat to our environment. According to a report, average temperature has risen by 2.3 degree Celsius in the past century, the ozone layer has depleted significantly at various points over the globe causing diseases and hazards, glaciers have been melting rapidly and the sea levels are rising. With all this, we need efficient and green energy sources which do not harm the environment any further and also meets our need of the energy production.

While researchers all around the world are taking steps to shift to green sources, there has not been much work on alternate sources of energy in Pakistan. There are a few pre-installed green energies producing setup in Pakistan including some of the major dams but there is no work being done on hydrofoils-based energy producing systems. But the efficiency and adaptability of hydrofoil systems suggest installing such systems in Pakistan can help cater the energy losses in northern rural areas.

All the above-mentioned reasons add to our motivation to work on this project. Our objective is to create a successful design that could cater the needs of the local market. We are determined to work on this project, not only as an FYP, but also to explore its potential of being a successful product in the market.

CHAPTER 2: LITERATURE REVIEW

Oscillating Hydrofoil energy harvesting systems started to originate in the late 1930s when researchers thought of extracting energy from low-flow, shallow water streams where conventional rotary turbines could not be used. A lot of proposals based on configuration, dimensions and setup of hydrofoils were made. Further analysis based on Computational Fluid Dynamics was done which provided with more possible combinations of hydrofoil profiles and configuration. Certain hydrofoil parameters such as chord length, aspect ratio, foil span, tip clearance, and angle of attack of the hydrofoil motion affects the efficiency of system.

2.1 Origin of Hydrofoil Systems

Birnbaun pioneered the work on the flapping foil energy harvesting systems in 1920s. several researchers have done work on hydrofoil systems since then, with McKinney and DeLaurier (1981) making analytical and experiment work showing that these systems can be effective in comparison to rotary systems. Jones and Platzer (1997) studied motions of hydrofoil separately using heaving only, pitching only and combined effect of these two motions over a broad spectrum of parameters.

2.2 Hydrokinetic Turbines versus Hydrofoils.

The first hydrokinetic turbines were modeled after wind turbines and many radial turbines contain the same designs to this day. They are very expensive to fabricate and install and are very location specific. A hydrokinetic turbine’s placement is limited by their required flow speeds, their large size and the shallowness of waterways. Radial turbines can also restrict access to open water; they can change tidal levels, negatively impact the marine life and environment, and capture debris drifting in waterways.

Other hydrokinetic turbines include the Gorlov helical turbine, which utilizes curved foil blades mounted longitudinally to a rotating shaft as shown in figure 1 below. There have also been many attempts to recreate the Savonius turbine (figure 2) for tidal energy extraction. This turbine is a drag-type device, which utilizes two scooped blades rotating about a central rotating shaft.

Another hydrokinetic turbine design (figure 3) is called the Flipwing pivoting turbine. This device uses pivoting foil blades that revolve around individual axles of rotation, which all revolve about a central rotating shaft. Each of these turbines exhibits the same problematic chopping motion and placement issues as described for the common radial turbine. More importantly, the most prominent issue that all of these hydrokinetic devices have is the fact that they are all based on wind turbine designs. Water is 1000 times denser than air; therefore, the same turbine designs are plausible but raise a more difficult engineering feat for tidal wave energy extraction.

Figure 1: Traditional Radial Water Turbine

Figure 2: Gorlov Turbine

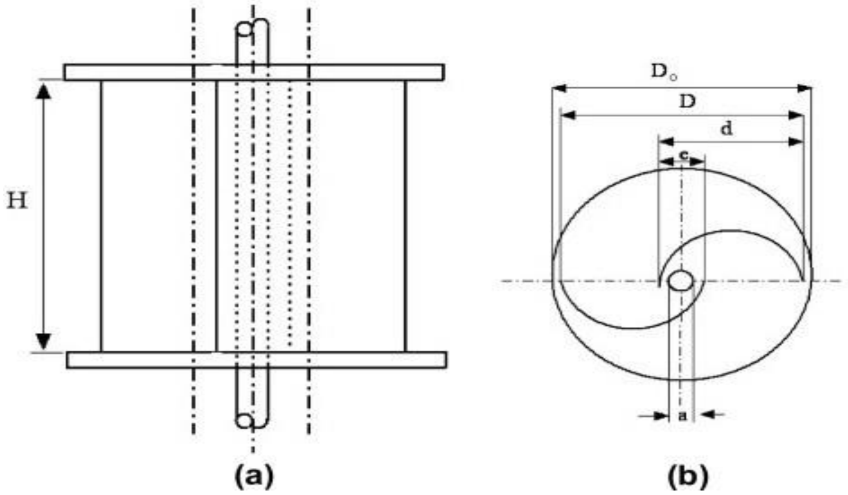

Figure 3: Savonius single-stage turbine scheme: a) elevation view and (b) plane view

As an alternative to the rotation-based turbine, oscillating hydrofoil turbines utilize hydrofoils, which undergo a combined heave-pitch motion about their individual pitching axis. This thesis explores the efficiency and performance of an oscillating hydrofoil turbine. An oscillating hydrofoil turbine has a very different motion when compared to traditional radial turbines. Radial turbines consist of foils originating at one point then protruding radially outward (figure 1). However, oscillating hydro- foil turbines consist of foils that periodically pitch and heave resulting in an upstroke and downstroke (figure 3). This motion is represented as:

$$H(t) = h \sin(\omega t)$$

$$\theta(t) = \alpha \cos(\omega t)$$

Where;

h and α are the heave and pitch amplitudes respectively and ω is the oscillation frequency.

2.3 Power Extraction

In order to generate power, the device's hydrofoils must have positive lift forces, which contribute to the power of the overall system. Torque forces can also contribute to the power, however, harnessing the power from torque is more challenging from a design perspective. Optimizing these forces lead to optimal power extraction. The instantaneous power equation for a single hydrofoil is expressed as:

$$P(t) = P_y(t) + P_\theta(t) = Y(t)V_y(t) + M(t)\Omega(t)$$

Where;

P_y and P_θ depict the heave and pitch power contributions, respectively. Y represents the lift force exerted on the hydrofoil, and V_y is the instantaneous heaving velocity. M is the torque about the pitching axis and Ω represents the instantaneous pitching angular velocity. The overall efficiency of a single hydrofoil can be calculated using the equation below:

$$\eta = \bar{P}/0.5\rho U^3 A$$

Where;

$\bar{P}$ is the average power for the cycle, ρ is the density of the water, U is the free stream velocity, and A is the area swept by the foil.

This sinusoidal pitching and heaving motion of amplitude 0-90° and where c is the chord length of the foil, combined with a $\pi/2$ phase difference has been previously validated to obtain the most optimal maximal power-extraction efficiency for a low velocity oscillating foil based on a study performed by McKinney and DeLaurier [8]. This study investigated the influence of the pitch and heave phase difference with respect to power extraction from an airflow. An analytical and experimental study was conducted on a windmill which utilized a harmonically oscillating wing. The analytical case study was performed using unsteady-wing aerodynamics from aeroelasticity and the results were used to aid in the design of an experimental model. The results concluded that the wing mill was capable of efficiencies comparable to traditional radial turbines.

McKinney's and DeLaurier's investigation were later supported by Shah, K.N. & Dutt, B. & Ahir, A. [5] who conducted numerical simulations (panel-code and Navier-Stokes's simulations) on cases of single oscillation airfoil operation in the power-extraction regime. This study also consisted of experimental components. The modeled generator consisted of tandem wings that oscillated in a combined pitch- plunge motion with a 90° phase difference. Two-dimensional inviscid and viscous flow models were used to predict the flow fields and power transfer in the analytical studies.

2.4 Hydrofoil Geometry

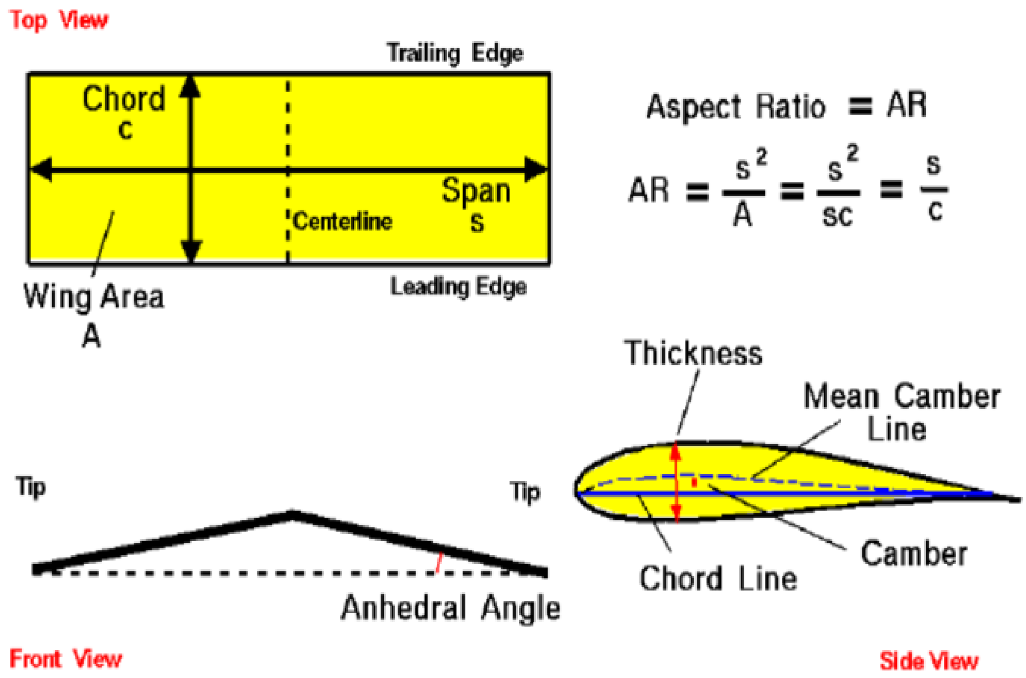

Figure 4: Parameters and Basic Geometry of Hydrofoil

Hydrofoils have specialized terms for their dimensions. The leading edge of a foil is the first part to interact with the flow. The trailing edge is the last to interact with the flow. The chord is the width of the foil from the leading edge to the trailing edge and the imaginary line this creates is called the chord line. The span is the length of the foil. From a top view, the span is seen left to right. The aspect ratio of a foil is the ratio of the span to the chord. The camber of the foil is the maximum distance between the chord line and the top of the foil. The mean camber line is a curve that follows the halfway points between the upper and lower surfaces of the foil. These dimensions along with the anhedral angle are shown in the diagram above.

Hydrofoil geometry is an important aspect for oscillating hydrofoil energy harvesters. Research has shown bigger the camber of the hydrofoil, greater lift force it generates due to the pressure differential. But a larger camber also presents a downside that there is increased drag force which can hamper the performance of a hydrofoil wing. Symmetrical hydrofoils are necessary for energy harvesters with oscillating motion since the wings have to move in both directions. If unsymmetrical hydrofoils are used, there will be an imbalance in energy generation between upstroke and downstroke.

2.5 Existing Works

Iro E. Malefaki and Kostas A. Belibassakis used a single hydrofoil oscillating horizontally against the motion of water flow to harvest energy. While ***Zhen Liu, Heng liang Qu and Guoliang Zhang*** have used a system of two mechanically coupled hydrofoils at a phase difference of 180°. The two hydrofoils had a distance of four chord lengths between them, and the oscillatory motion caused vertical motion of the arm carrying the foils. The configuration is shown in the figure.

The device was designed to produce 1.29 kW of electricity against a flow velocity of 2 m/s at an angle of attack of 70^0. The foils have a chord c = 0.24m and effective span of b = 1.026m with the pitch axis located at (½)c so that the device could operate in a bidirectional flow, such as a tidal stream. The device implemented a gear box and wheel at the output shaft for electricity generation. The purpose of the gearbox in this design is to increase the output RPM to the rating of the generator that has been connected to the device. Flywheel conserves the torque and makes sure the output RPM and power is smooth.

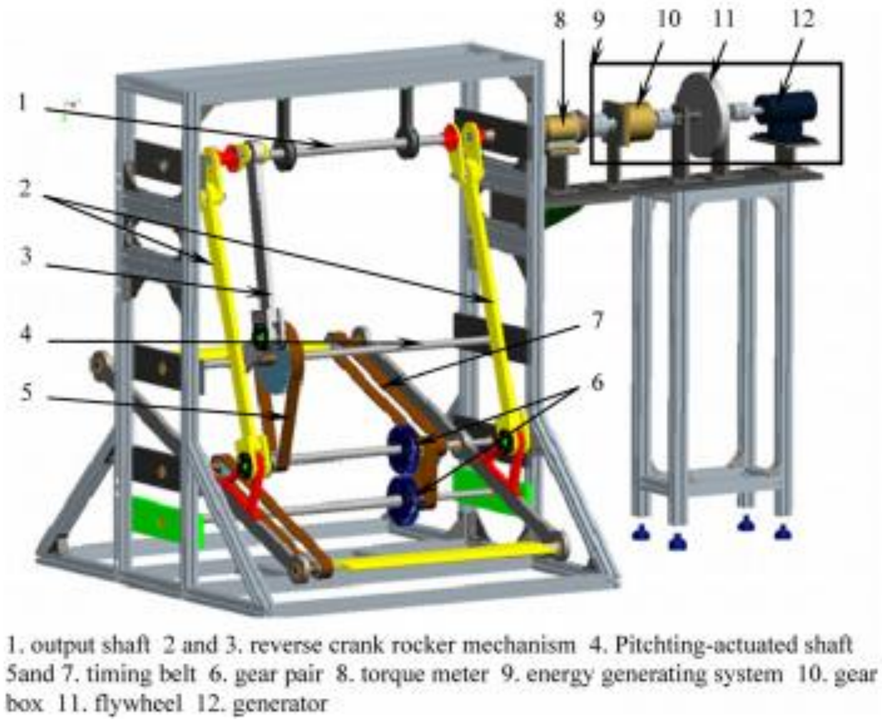

Figure 5: Oscillating Hydrofoil Energy Harvester 1

Sitorus, P., Won, B., & Ko, J. (2017, July 31) developed an energy harvester with oscillating hydrofoils as shown in the figure below. Two hydrofoils were used with an aspect ratio of 6 attached in a tandem configuration as can be seen in the figure below. To actuate the hydrofoil, the researched used a semi passive system where a pitch actuator has been used to change the pitching angle of the hydrofoil wings.

Although, the energy generation system was very similar to previous works in the field, an innovative technology and design was used. The device has an actuation system of the wings which can be used to change the orientation of the wing. Such a design can be used in both shallow and deeper waters, depending on the available space and topography.

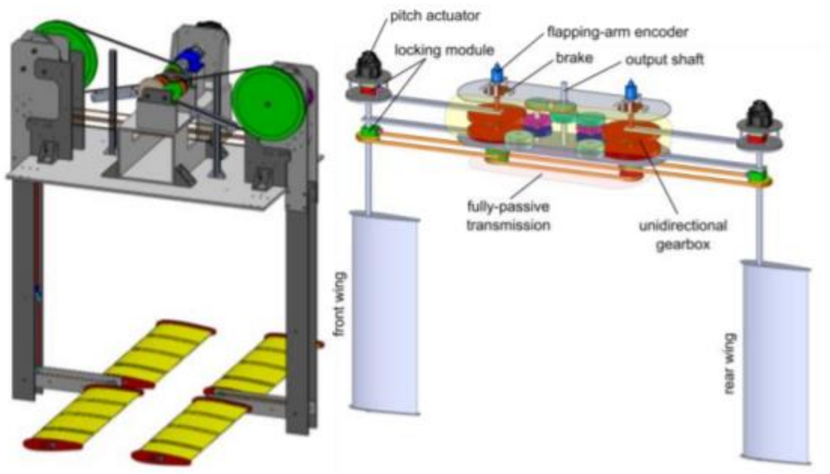

Figure 6: Oscillating Hydrofoil Energy Harvester 2

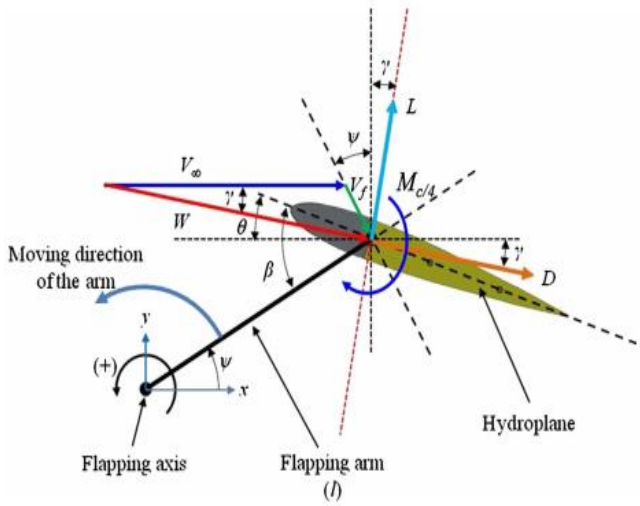

Figure 7: Hydrofoil Dynamics

2.6 Hydrofoil Configurations

Performance of hydrofoils were measured using both single and dual hydrofoils in tandem to evaluate the contribution of each hydrofoil to the total output. The results of single vs double hydrofoils are illustrated in the figures below. It's evident from these researches that a system of two or more hydrofoils used in one device is more efficient than a single hydrofoil.

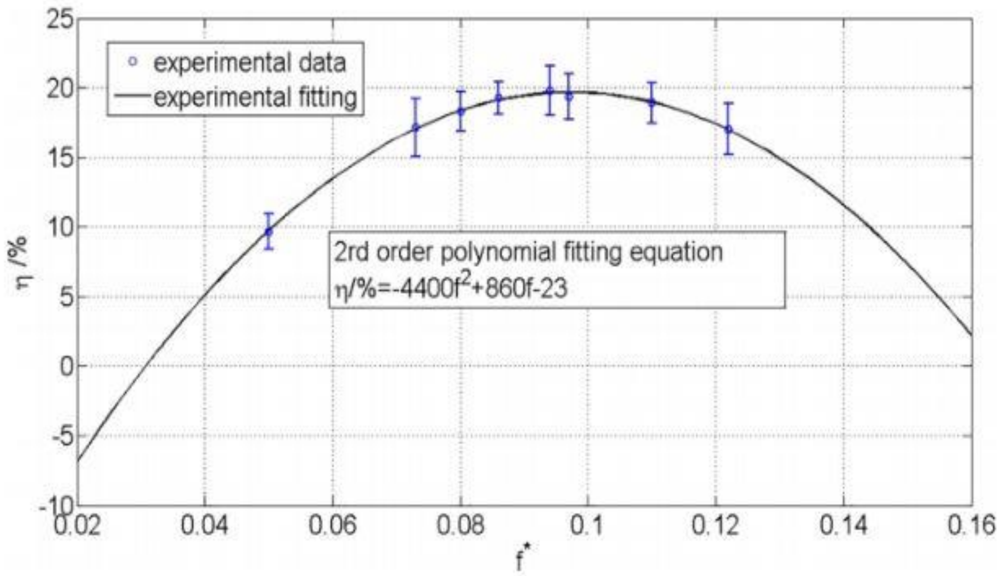

Figure 8: Single Hydrofoil Efficiency

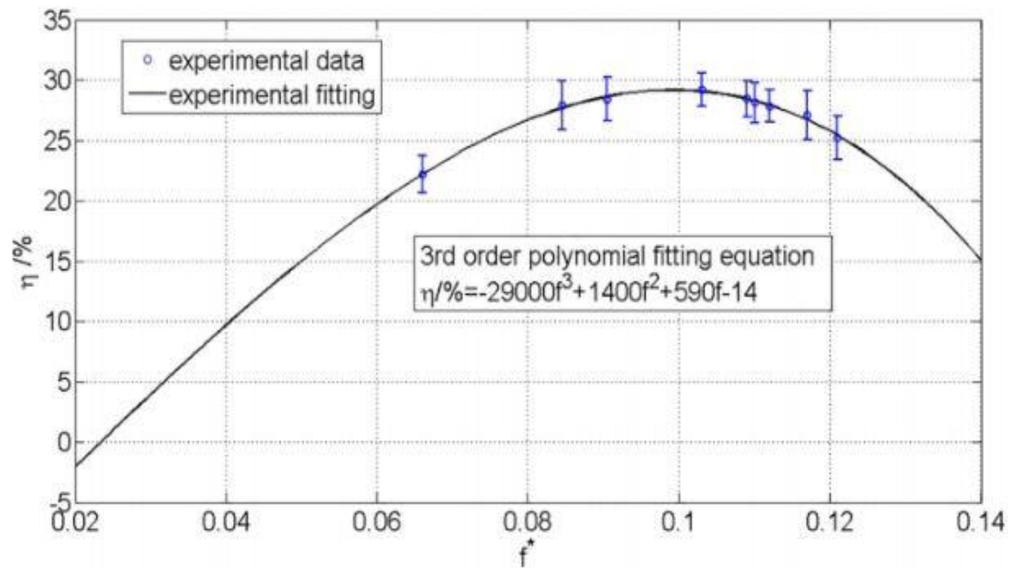

Figure 9: Tandem Hydrofoils Efficiency

2.7 Power Generation

Harnessing the power from our oscillating hydrofoil is a key consideration. There are many two main methods through which energy has been extracted from oscillating hydrofoil wings – Piezoelectric materials and Conventional generators.

Jianan Xu (2019) Used the phenomena of piezoelectricity to extract energy from oscillating systems. Piezoelectric materials are connected to the oscillating body the stress generated by the motion forces the piezoelectric material to generate electricity. But the main problem with such a method is that the volume of power that a piezoelectric can harness is significantly smaller than the power of a flapping hydrofoil, hence it’s not very efficient.

Conventional generators use the motion and the force from the water to drive the turbine which generates electricity. This is done using a linear generator, or through the use of a linkage to transform the linear oscillation into rotational motion to power a conventional generator. The most suitable method has been used by Kinsey (2011) who implemented a four-bar crank rocker linkage to drive the generator from the oscillating wings.

CHAPTER 3: METHODOLOGY

In view of the literature review it was evident that a robust design methodology must be setup subjected to desired deliverables. Referring to the stated design problem, the oscillating hydrofoil energy harvester must generate electricity when placed in a stream of water flowing at ≈ 1.0 m/s to 2.0 m/s. Such an energy harvester system is easier to manufacture because of the simple hydrofoil geometry involved in energy extraction mechanism. Not only is such a design easier to install in already existing topography, the unconventional technology of oscillating wings aims to minimize the damage to marine wildlife. The system can be used to generate renewable and consistent power in areas near flowing rivers in rural areas to provide auxiliary power.

3.1 Design Specification

In choosing our design, we determined the optimal parameters for our device to balance affordability, manufacturability and of course the most important aspect, which is performance. The optimal oscillating hydrofoil energy harvester that we design must fulfil certain requirements:

(i) Passive energy harvesting mechanism.

(ii) Self-start mechanism to ensure no external power is required.

(iii) Efficient device to harvest flow energy from water

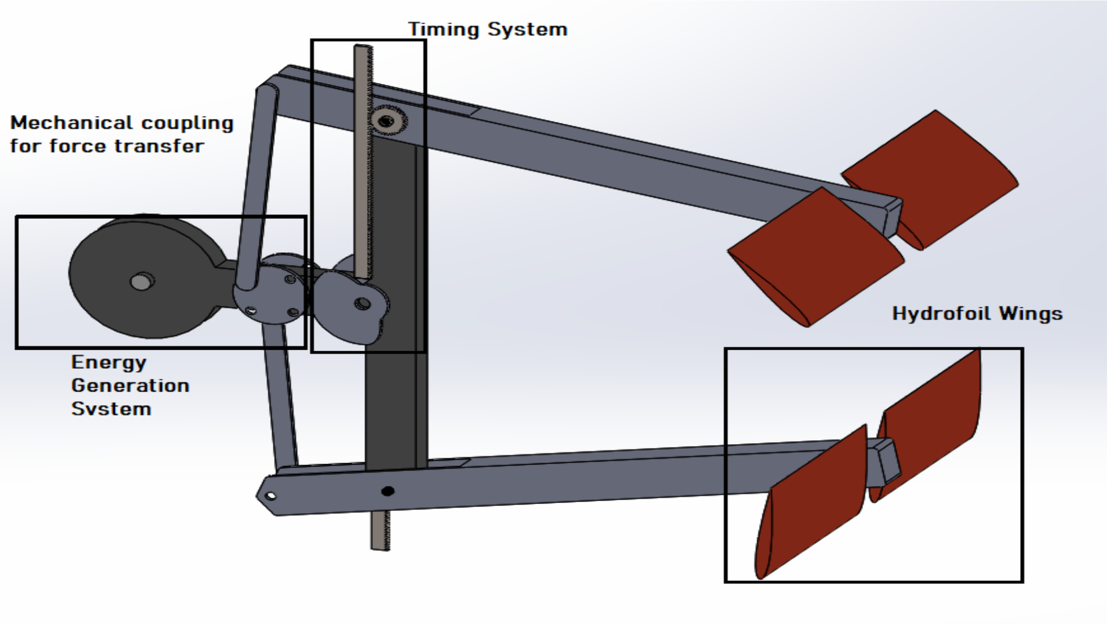

Figure 100: Oscillating Hydrfoil Energy Harvester

3.2 Power Generation

As shown in the figure above, the design prototype that we finalized has four main components in the mechanism of power generation. These components are:

(i) Oscillating hydrofoil wings
(ii) Mechanical coupling for force transfer
(iii) Timing Mechanism (Hydrofoil Actuation)
(iv) Energy generation system

Harnessing the power from the oscillating hydrofoil was the most important consideration in the design. Since the oscillating movement is a linear movement, two main options to harness the energy was either to use a linear generator or to use a linkage which would transform the linear movement into rotary movement to drive a conventional generator. A design with linear generator has fewer moving parts such as gears or chains, which would improve efficiency but a more comprehensive design was to use a design with four – bar crank rocker mechanism, which we implemented in our design. The device consists of two mechanically coupled hydrofoils with two simultaneous crank – rocker mechanism in single energy generation system. The two systems are 90° out of phase with each other. Such a system is important to ensure the device can self – start, unassisted, in any configuration and allows to overcome the dead spots in the power cycle located at bottom dead centre and top dead centre. The oscillating wing acts as the rocker arm of the four – bar mechanism and consequently drives the rotary crank.

The rotary motion of the crank, driven by the oscillation of the hydrofoil arms, is the prime moving mechanism for the energy generation. This rotary motion is used to drive a generator which produces energy. Because of the oscillatory motion, the power cycle is not constant, as there are dead zones in the cycle at bottom dead centre or top dead centre. To ensure a more uniform power output, a momentum flywheel is being implemented in the design and coupled with the crank using gear/belt system to drive it which in turn drives the generator.

The timing mechanism in the design prototype is an innovative design which is used to control the pitching of the hydrofoils which are pinned at the ends of the oscillating arms. The timing system is a passive system which uses the configuration of the oscillating arms at any given point in to time to constrict the pitching of the hydrofoil as desired by the design. The crank constantly drives a cam follower mechanism which is coupled with a rack and pinion gear system. The rack and pinion gear system are coupled with the hydrofoil shaft via a belt and controls the pitching of the hydrofoil at any given time. Through this mechanism, we ensure that the arms rise and fall through a set, pre – defined heaving amplitude.

3.3 Oscillating Hydrofoils Wings

3.3.1 Physical Arrangement

Energy extraction occurs as a result of the periodic heaving and pitching motions as shown in the 2 figures below. The heaving and the pitching motions, with a phase difference of 90° between them, are represented by the following equations:

$$H(t) = h \sin(wt)$$

$$\theta(t) = \alpha \cos(wt)$$

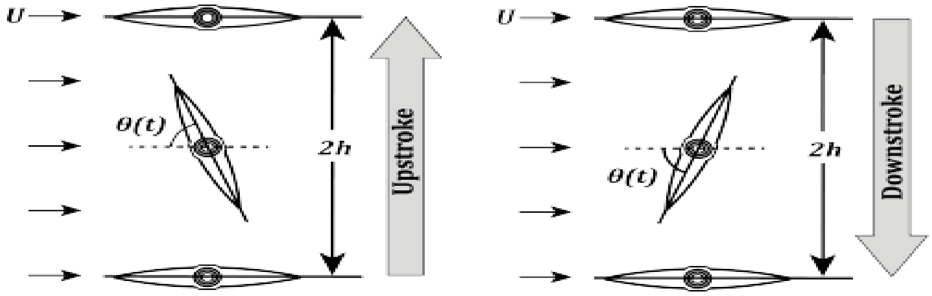

Figure 11: Oscillation of Hydrfoil wings

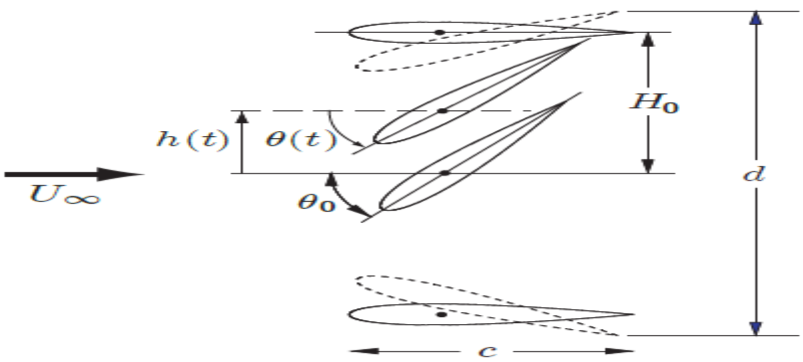

Figure 12: Oscillation of Hydrfoil wings

In our design, since the hydrofoil wing has to oscillate and move in both directions, the hydrofoil profiles best suited for the design are symmetric in nature. The hydrofoil profile we chose for our wing was NACA 0024 with a chord length of 0.24m and a span of 1.5m which gives an aspect ratio ≈ 6, optimum for energy harvesting [4]. The two hydrofoils have been arranged in a stacked configuration with spacing of 4c (0.96m) between them as shown in the figure below. Such an arrangement ensures that both hydrofoils are met with "clean" flow without any turbulence. The hydrofoils wings have an effective of 1.5m and are pinned at the centre with the oscillating arm. For optimal energy harvesting, $h_c/c = 1$ is most efficient 3] and hence the arm has been constrained which each hydrofoil moving up and down 0.24m from its mean position.

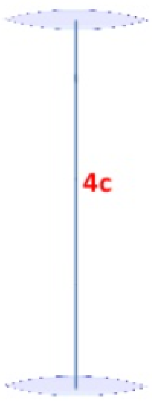

Figure 13: Paralelly Arranged Hydrofoil Wings

The table below shows the specifications of the hydrofoil wings:

Description	**Magnitude**
Hydrofoil Section	NACA 0024
Chord Length (c)	0.24m
Span (b)	1.5m
Pitching Axis	c/2
Heaving Amplitude (H_o)	2c
Pitching Amplitude (θ_o)	45^0
Inter Wing Phase Difference($\emptyset_{1-2}$)	90^0
Inter Wing Spacing (L_y)	4c

Table 1: Hydrfoil Wing Specifications

3.3.2 Hydrodynamic Power Extraction & Efficiency

When hydrofoils are placed in a uniform fluid flow field, the total instantaneous power available to the hydrofoil for extraction is given by the following equation:

$$P_a = \rho \frac{1}{2} U^3 b \sum Y_P$$

Where;

P_a = Total available power

U = Free stream velocity

b = Span of hydrofoil

$\sum Y_p$ = Total sum of swept length of each hydrofoil in the system (Figure 14)

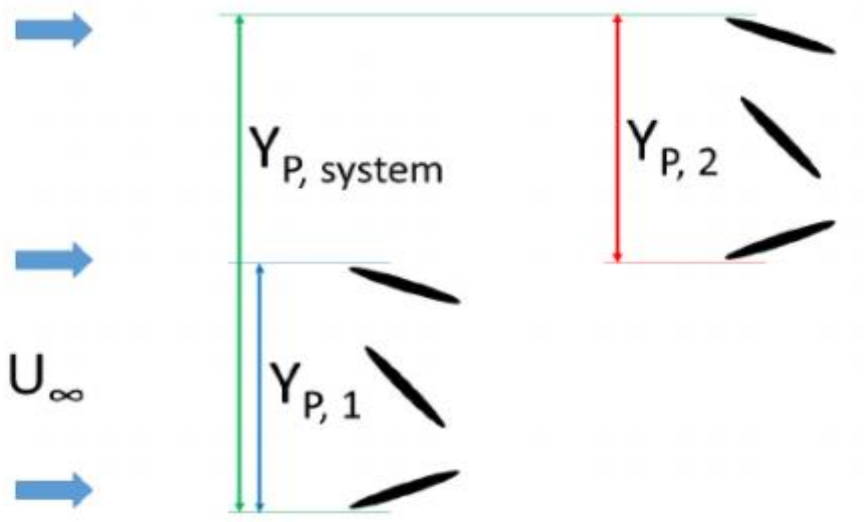

Figure 14: Area Swept by Hydrofoil Wings

Swept area for the system is the sum of the swept areas of all the oscillating hydrofoils. If the swept areas overlap for two or more hydrofoils, the total sum is less than sum of individual swept areas. For one of the hydrofoils can be determined using the following equation:

$$Y_P = 2(h_0 + \frac{1}{2} c\ sin\theta_0)$$

Power is transferred from the water flow to the hydrofoil wings, and consequently the power generation system, through the lift generated on the wings. The shape of the hydrofoils causes a pressure differential between the upper and lower surface of the wing which generates lift (pitched up) or downforce (pitched down). The lift or downforce on the wing is given by the following relation:

$$L = \frac{1}{2}\rho l A v^2$$

Where:

l is the dimensionless coefficient of lift

A is the effective area given by c*b in m^2

V is the velocity of incoming water flow in m/s

To measure the hydrodynamic (water to gearbox) efficiency of the oscillating hydrofoil energy harvesting system, it's important to determine the output power at crank output of the mechanism. The instantaneous mechanical power output at the crank before its transmitted to the gearbox and subsequently the generator is given by the following equation:

$$P_o = M(t)\,.\,\omega(t)$$

Where;

M(t) is the instantaneous torque at the output in N.m

w(t) is the instantaneous angular velocity of crank in rad/s

The dimensionless hydrodynamic efficiency of the device is determined from the following equation.

$$n = \frac{P_o}{P_a}$$

$$n = \frac{M(t)\,.\,\omega(t)}{\frac{1}{2}U^3 b \sum Y_P}$$

3.3.3 Materials and Manufacturing

In designing the hydrofoil shaped wing as shown in the figure below, mass and shape are the two most important factors. Since external lift and drag is to act on the wing due to the foil profile, buoyancy is a very important factor. If the hydrofoil tends to sink or float, in both cases that would mean that the design wasn't feasible as the wing would be unable to oscillate. For this purpose, it's in the best interest to keep the hydrofoil wing as close to neutrally buoyant condition as possible 7]. For best results, a very slightly negatively buoyant design is also workable.

Area of wing = 0.009478 m^2

Displaced volume of wing = 0.01425 m^3

$$F_b = \rho g V$$

$$F_b = 139.5$$

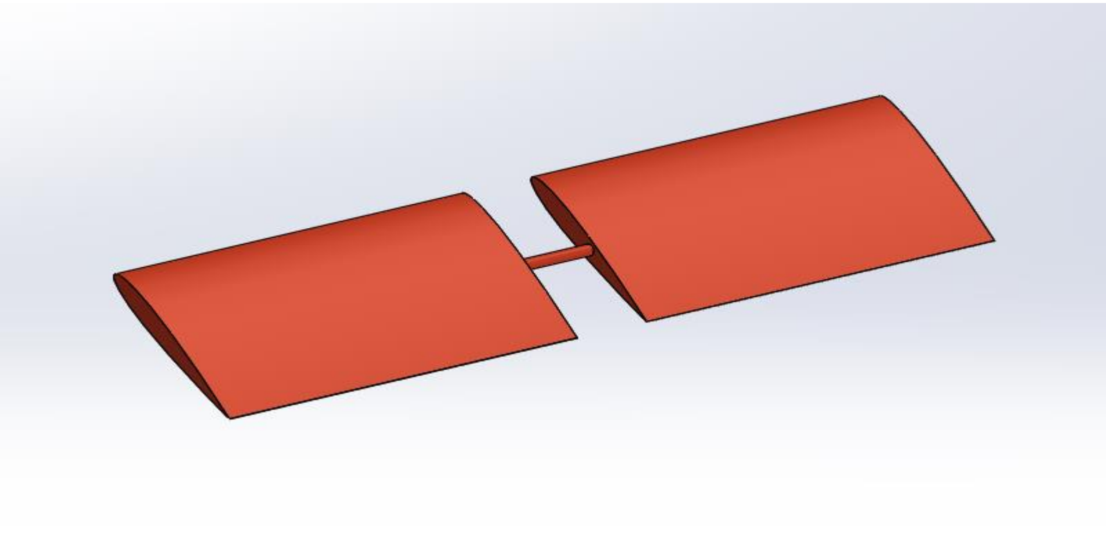

Figure 15: Hydrofoil Wing

We can see from the calculations above that the weight of the wing must be equal to 139.5 N or slightly more for negative buoyancy to ensure the oscillatory mechanism works perfectly. Underwater components are susceptible to rusting, therefore the chosen material for the wings is Aluminium 7075 alloy, which is not only used in airfoil applications in aircrafts, but also has significant corrosion resistance as compared to other alloys. Aluminium sheets are suitable for the design, as they can be easily molded to form the hydrofoil profile. Hollow wings are to be manufactured, completely sealed to avoid any water inside. Inside the channel, weights can be added along the length to increase the overall mass, to make the wing neutrally buoyant. These weights can be of several different materials e.g., wood, stainless steel, concrete foam etc. The internal material is only for the purpose of buoyancy, although homogeneity is not important, weights need to distributed in a balanced manner across the length. The properties of Aluminium sheet metal are given in the table below.

Description	Magnitude
Alloy	7075-T6 Alclad
Thickness	1.6002 mm
Density	2750 Kg/m^3
Ultimate Strength	524 MPa
Yield Strength	462 MPa

Table 2: Properties of Aluminium 7075-T6

3.4 Mechanical Coupling for Force Transfer

The oscillating hydrofoil wings have a rocking movement, through which energy needs to be harvested. To produce electricity from a conventional generator, the linear motion of the hydrofoil wings needs to be transformed into a continuous rotary motion to drive the generator. For this purpose, a 4 – bar, rocker – crank linkage mechanism has been implemented. The rocker is connected to the hydrofoil wings and follows the linear oscillation of the wings. This drives the crank which is directly connected to the energy generation system.

3.4.1 Four – Bar Linkage Synthesis

Oscillating hydrofoil wing is attached to a freely rotating arm which follows the motion of the wing. This arm has been pivoted on the frame of the protype at a length of L/5 as shown below in figure (highlighted in red). The longer side of the oscillating arm is connected to the hydrofoil wings while the shorter side is connected to the four – bar linkage and acts as the rocker in the rocker – crank mechanism. The crank is coupled with the crank through a coupler which transmits the linear motion of the crank into a rotary motion of the crank wheel. Twin four – bar mechanisms are being used, with a phase difference of 90 degrees to drive the generator.

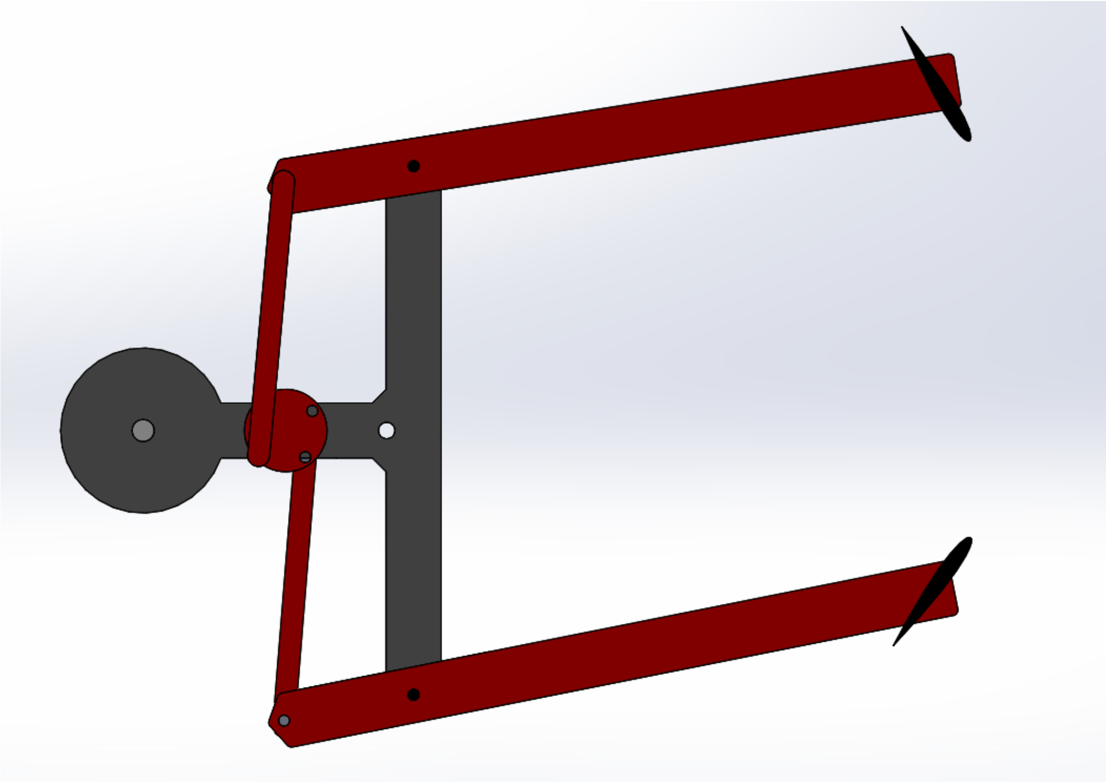

Figure 16: Four-Bar Linkage (Front View)

A simplified drawing of the rocker – crank mechanism is displayed in the figure below. This mechanism was designed to transform the linear motion of the hydrofoil wing into a 360-degree rotation of the crank in each cycle. As shown in the figure below, blue link is the rocker, green link is the coupler while the red link is the crank. An imaginary link between the two pivots is the fixed ground link of the system. It's important to fulfil the criterion of the Grashof's condition to ensure the crank completes a full rotation in every cycle, otherwise the design cannot work smoothly. Grashof's condition states that for the rocker – crank mechanism to work, the sum of the shortest and longest link must be less than the sum of the other two links.

S = 60mm

L = 428mm

P = 360mm

Q = 240mm

$S + L < P + Q$

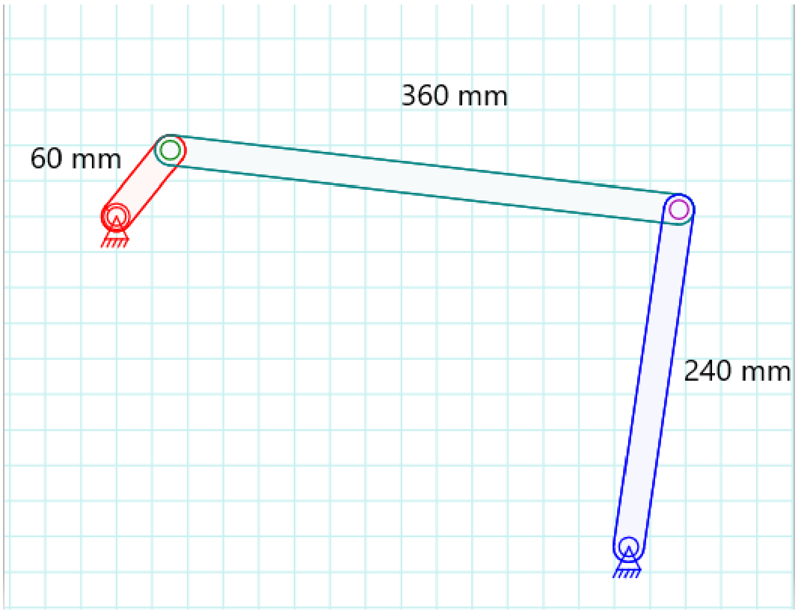

Figure 17: Schematics of Four – Bar Linkage

3.4.2 Kinematic Analysis

As stated in the previous section, for the most efficient performance, the oscillating hydrofoil wing has been designed with a heaving amplitude of 1c. Depicted previously in figure, the oscillating arm is pivoted at L/5. Since the deflection is proportional to the length, the rocker arm will have a heaving amplitude of c/4 and overall deflection of c/2 as shown in the figure below.

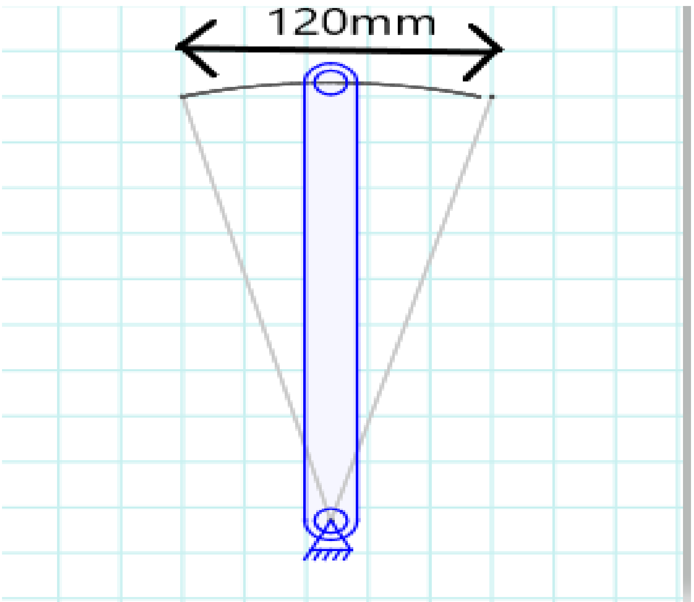

Figure 18: Heaving Amplitude of Rocker

The displacement, angular velocity and angular acceleration of the crank link at all times depends on the position, velocity and acceleration of the rocker, which is being driven by the flow of water acting on the hydrofoil wings. Figure below shows the general graphical representation of a simple rocker – crank mechanism. R4 is the input rocker, R3 is the coupler, R2 is the output crank and R1 is the ground link.

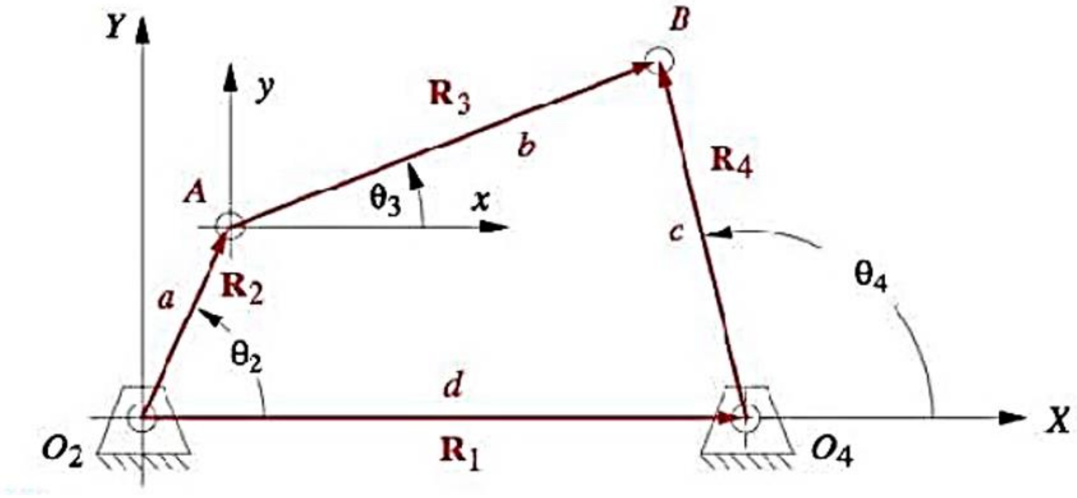

Figure 19: General Four – Bar Linkage

For the purpose of design of hydrofoil wing energy harvester, as stated in previous sections, output angular velocity of the crank (R2) needs to be determined to calculate the power output of the system. Following equations are necessary to calculate the output angular velocity of the crank link, dependent on the motion of the rocker link with known displacement (θ4) and angular velocity (ω4).

$$\theta 2 = Tan^{-1}(\frac{A_y}{A_x})$$

$$\theta 3 = Tan^{-1}(\frac{B_y - A_y}{B_x - A_x})$$

$$\omega 2 = \frac{c\ \omega 4 \sin(\theta 4 - \theta 3)}{a \sin(\theta 2 - \theta 3)}$$

$$\omega 3 = \frac{a\ \omega 2 \sin(\theta 4 - \theta 2)}{b \sin(\theta 3 - \theta 4)}$$

3.4.3 Kinetic Analysis

Lift and down force from the water flow acts on the hydrofoil wings which results in the oscillation of the arm. The force and torque generated on the wings is transmitted through the four – bar linkage. At all times in the cycle of the oscillation, an output instantaneous torque act on the crank. For the purpose of design of hydrofoil wing energy harvester, as stated in previous sections, output torque of the crank (τ2) needs to be determined to calculate the power output of the system.

During one cycle of complete oscillation of the hydrofoil wings (one complete revolution of the crank), the output instantaneous output torque depends on the force acting on the rocker and the orientation of the linkage at that particular instant. As a result, the output torque will vary across one cycle depending on the input. Force acting on the crank (blue link) is shown below in figure where F is the force acting on the wing. The direction of this force depends on the orientation of the wing and will change after each half cycle of oscillation. This force will be transferred across the linkage and an output torque will act on the crank (red link).

Graphical method has been implemented, along with use of software to calculate the output torque at all instants in one cycle of oscillation of the hydrofoil wings. These calculations/derivations are discussed in detail in Appendix II.

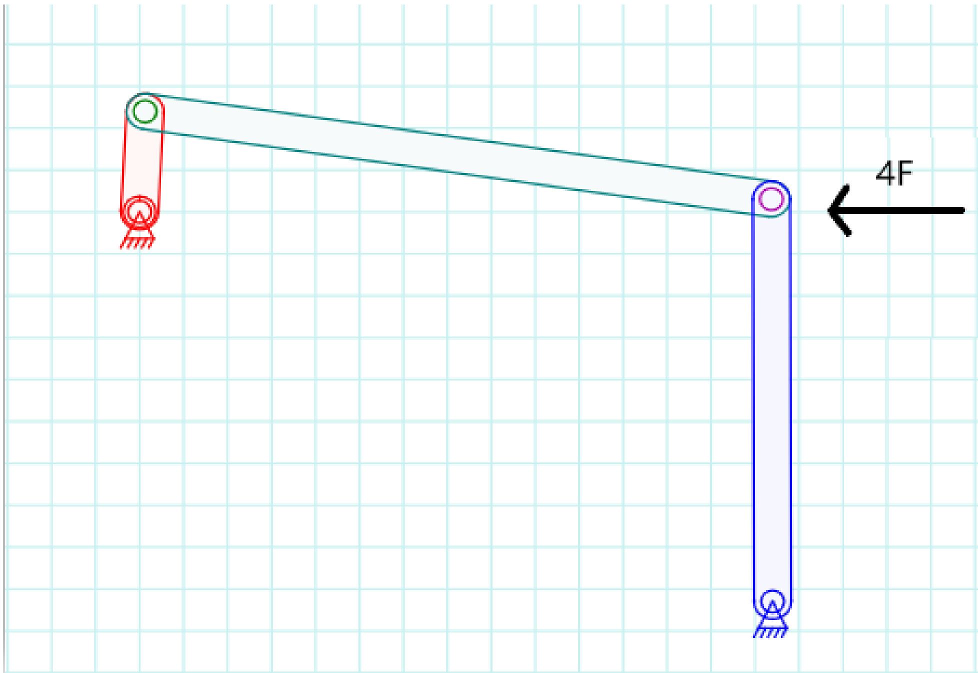

Figure 20: Force Acting on Four – Bar Linkage

3.4.4 Materials and Manufacturing

Rocker Arm

The rocker arm, which is connected to the wing and oscillates during the motion, is shown below in figure. Since this arm also needs to oscillate with the wing, buoyancy is a very important factor. If the arm tends to sink or float, in both cases that would mean that the design wasn't feasible as the wing would be unable to oscillate. For this purpose, it's in the best interest to keep the hydrofoil wing as close to neutrally buoyant condition as possible.

Displaced volume of rocker arm = 0.00758 m^3

$$F_b = \rho g V$$

$$F_b = 74.2$$

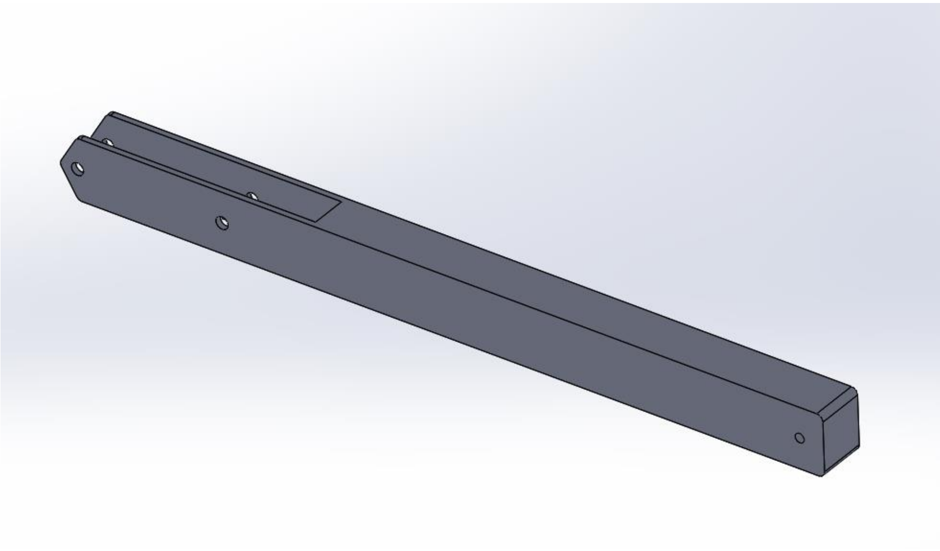

Figure 21: Rocker Arm

We can see from the calculations above that the weight of the rocker arm must be equal to 74.2 N or slightly more for negative buoyancy to ensure the oscillatory mechanism works perfectly. Underwater components are susceptible to rusting, therefore the chosen material for the wings is Aluminium 6082 alloy. Aluminium plates are suitable for the design, as they can be easily molded to form the hollow channel and welded. Inside the channel, weights can be added along the length to increase the overall mass, to make the wing neutrally buoyant. The properties of Aluminium plate are given in the table below.

Description	**Magnitude**
Alloy	6082 T6/T651
Thickness	10 mm
Density	2700 Kg/m^3
Ultimate Strength	280 MPa
Yield Strength	240 MPa

Table 3: Properties of Aluminium 6082-T6

Crank and Coupler

In the design prototype, the crank link is two circular disks. each of which is connected to one of the oscillating hydrofoil wings. Coupler is a simple solid link with holes drilled on each end to connect the crank with the rocker. Both are pin joints to ensure the rocker – crank mechanism can operate seamlessly. Figure 22 and 23 show the 3D models of the crank and coupler respectively. Each of these are manufactures using Aluminium 6082 plates whose specifications are detailed in the table below.

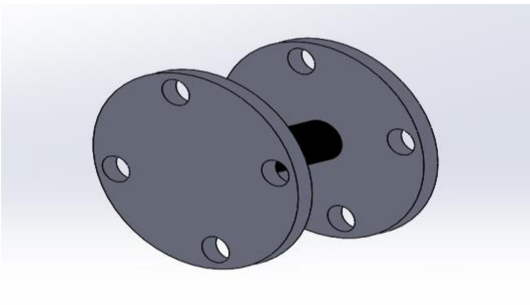

Figure 22: Crank Link

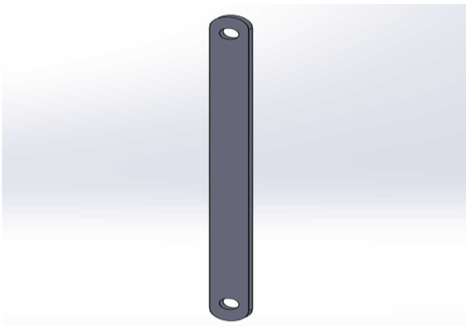

Figure 23: Coupler Link

Description	**Magnitude**
Alloy	6082 T6/T651
Thickness	10 mm
Density	2700 Kg/m^3
Ultimate Strength	280 MPa
Yield Strength	240 MPa

Table 4: Properties of Aluminium 6082-T6

3.5 Timing Mechanism (Hydrofoil Actuation)

The main source for harvesting the power from the flowing water is the oscillating hydrofoil mechanism, which is consequently used to drive a generator. Since the direction of water flow on the leading edge of the hydrofoil is constant, the pitching of the hydrofoil wing determines whether there's lift or downforce, and consequently whether the rocker arm moves up or down at any given time. To ensure this constant oscillating motion, the pitching of the hydrofoil wing needs to controlled. An actuation method needed to be designed which would keep the hydrofoil pitching up to move the rocker arm and then reverse the direction of the pitching at the top of the oscillation to move the rocker arm down in the next half cycle. It was important to minimize the power loss in actuating the hydrofoil, hence the most suitable solution was to design a passive, self – powered timing mechanism. Cam – follower mechanism driven by the crank has been implemented.

3.5.1 Working Principle

The working principle of the passive timing (actuation) mechanism is shown in the figure below. During the normal operation of the energy harvester under constant water flow, the crank is being rotated through the four – bar linkage. The axis of the crank is the connected to the axis of the cam which consequently rotates in the opposite direction. The diameters of both axes have been kept same to ensure the cam rotates at the same rotational speed as the crank link. Same rotational speed is also important since we need to make sure both cam and crank follow the same cycle since the cam has to be timed according to the position of the crank at all times in the cycle. The cam is mechanically coupled with a cam follower.

The follower has been manufactured such that it serves as the rack in the rack & pinion gear system. The teeth have been machined on one side of the follower which is then coupled with the pinion gear. Up and down displacement of the rack drives the rotation of the pinion gear. The pinion gear's rotation is connected to the hydrofoil wing which is pinned at the centre, through a belt. The specification of the gears are as follows:

Rack: Metric - Rack-spur - rectangular 2M 20PA 10FW 30PH 600L

Pinion: Metric - Spur gear - 2M 35T 20PA 10FW

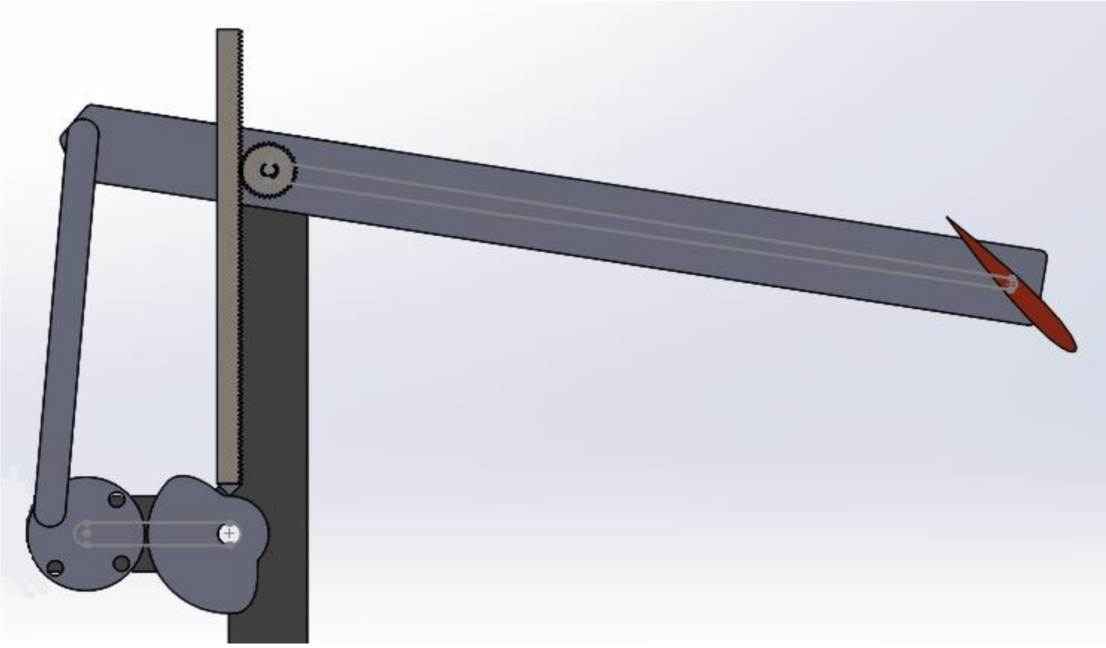

Figure 24: Timing Mechanism

3.5.2 Cam Design

The profile of the Cam is the most important factor in this timing mechanism as it controls the actuation of the hydrofoil wing at all times. The profile needs to be designed according to the pre – defined conditions and specifications. Since the rocking arm needs to oscillate up and down between the TDC and BDC, the wing needs to pitch up when it moves up and pitch down when it needs to move down. TDC and BDC are the neutral positions where the pitching angle is 0 degrees. Through each cycle, the dwell period of the cam is the motion where the pitching angle of the wing is constant. Rise period of the cam profile is when the wing changes its pitching angle from maximum negative pitching angle to maximum positive pitching angle. Opposite happens in the fall period when the wing changes its pitching angle from maximum positive pitching angle to maximum negative pitching angle.

Motion	**Period**
Harmonic Rise	45°
Dwell	135°
Harmonic Fall	45°
Dwell	135°

Table 5: Motion of Cam

Physical design parameters of the cam follower mechanism have been assumed as follows:

Parameter	Magnitude
Base Circle Radius (D_c)	30mm
Rise/Fall (H_o)	55mm
Follower Type	Knife Edge Follower
Arbitrary RPM	20

Table 6: Design Parameters of Cam Follower

To design the profile of the cam, we need values of displacement, velocity and acceleration of the cam at all times through one 360° cycle. We need values for all time periods, dwells, rises and falls. Following equations have been used for these calculations.

	Rise	Fall
Displacement	$d = \frac{H_o}{2}\left[1 - \cos\left(\frac{\pi t}{T_i}\right)\right]$	$d = \frac{H_o}{2}\left[1 + \cos\left(\frac{\pi t}{T_i}\right)\right]$
Velocity	$v = \frac{\pi H_o}{2T_i}\left[\sin\left(\frac{\pi t}{T_i}\right)\right]$	$v = -\frac{\pi H_o}{2T_i}\left[\sin\left(\frac{\pi t}{T_i}\right)\right]$
Acceleration	$a = \frac{\pi^2 H_o}{2{T_i}^2}\left[\cos\left(\frac{\pi t}{T_i}\right)\right]$	$a = -\frac{\pi^2 H_o}{2{T_i}^2}\left[\cos\left(\frac{\pi t}{T_i}\right)\right]$

Table 7: Cam Motion Equations

Where; t = time, T_i = Arbitrary time taken for fall/rise assuming RPM.

Using the values calculated above, we have to find the x and y coordinates of the cam profile to plot. The plotted shape on a x-y plane is the profile of the cam.

$$x = (D_c + d)\,(Sin\,\theta)$$

$$y = (D_c + d)\,(cos\,\theta)$$

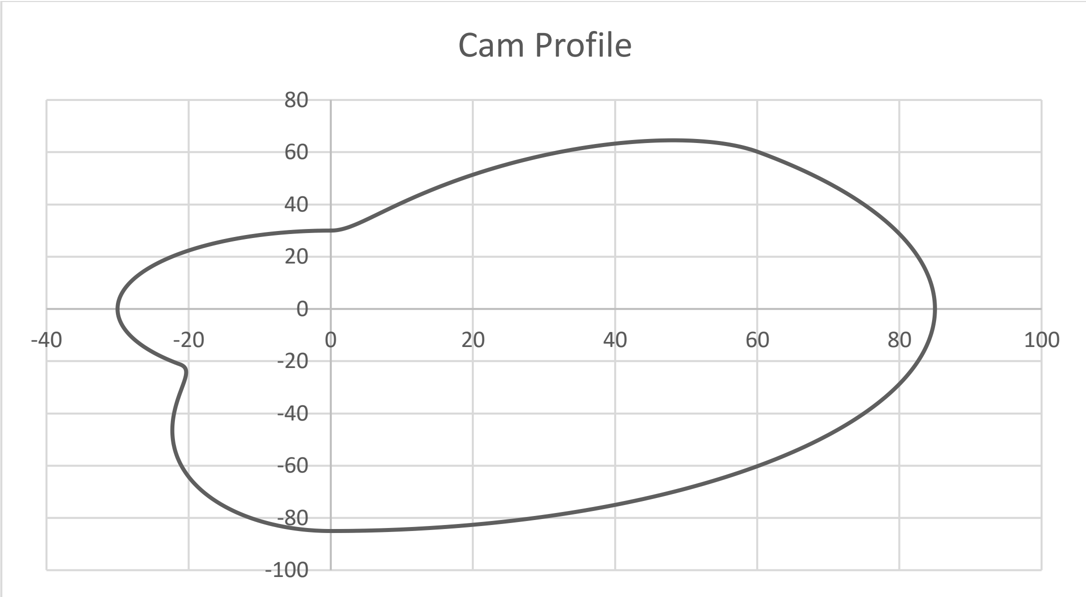

Figure 25: Cam Profile

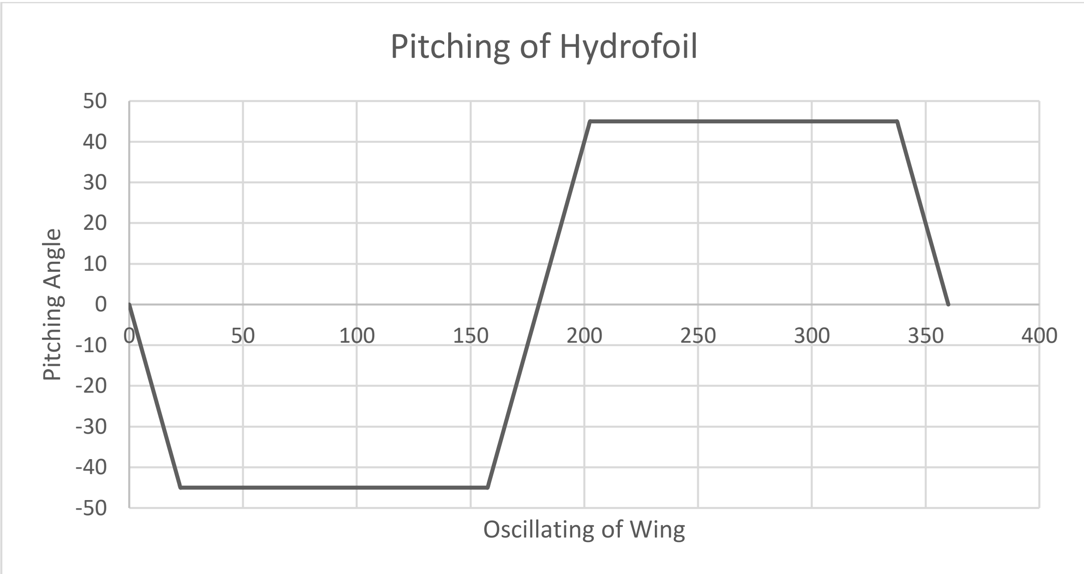

Figure 26: Hydrofoil Pitching Angle

Figure 25 above shows the profile of the cam while figure 26 shows how the cam controls the pitching of the hydrofoil wing across each 360-degree cycle. Detailed calculations can be found in Appendix I.

3.5.3 Materials and Manufacturing

Rack and pinion gear is the most sensitive component of the entire timing mechanism. This is because the gears need to survive the torsional stresses generated in its teeth when it forces the wing to reverse direction against the direction of the lift/down force. The material chosen for the manufacturing of gears is **Aluminium 7075-T6 Alloy.**

3.6 Energy Generation System

Energy generation system is the ultimate part of the design since it converts the power extracted from the flow of water into usable electric power. Using the four-bar linkage, the power available from the water flow is transferred to the crank. This mechanical power needs to be converted into electrical power using a DC generator. The rotary motion of the crank and the mechanical power is transmitted into the generator using a belt as show below in figure.

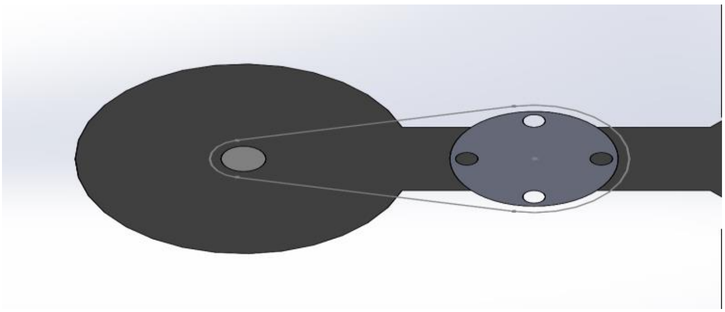

Figure 27: Energy Generation System

3.6.1 Working Principle

At slow flow speeds, the output speed of the crank will generally be rather slow, in the order of 50 – 100 RPM. For most off the shelf DC generators, this RPM is very slow as they usually are rated for 1000 – 2000 revolutions per minute. Therefore, we need to increase the output RPM using a gearbox with a ratio in the order 1:15 to 1:25. Any off the shelf efficient DC generator can be used in this design as there are no limitations. The generator must be rated such that it can easily generate electric power with a magnitude of around 1kW. Since the output power is sinusoidal due to the constant change in orientation of the four-bar linkage, output power will not be constant. To ensure smoother output from the crank into generator, flywheel will be used.

3.6.2 Component Specifications

Component	Specifications
Generator	DC motor Baldor CDP-3605
Gearbox	20:1 gearbox (Boston Gear 652B-20)

Table 8: Energy Generation System Components

CHAPTER 4: RESULTS AND DISCUSSIONS

After the design of the oscillating hydrofoil energy harvester was finalized, to ensure it would operate perfectly, we to need analyze performance and results. Power output is obviously the most important parameter here, and calculation/analysis needs to be done to determine the output power results. For the calculations and analysis of power extraction from flowing water, CFD analysis needs to be performed on the hydrofoil wings. We need to scrutinize whether our design would deliver the established 1kW power output from a 1.5m/s water flow.

However, before the parametric analysis of power, it needs to be ensured that our design prototype would survive in working conditions. Structural integrity of the prototype needs to be scrutinized and stress analysis performed on all components, most importantly on the sensitive moving components susceptible to failure under stress.

4.1 Computational Fluid Dynamic Analysis

There are two major results from the CFD analysis on the hydrofoil wing, namely, force and pressure. Force is directly related to the pressure differential created between the top and bottom surface of the hydrofoil. Force included both the normal lift force acting and the drag force acting on the hydrofoil. In our device, force acts on the hydrofoil wing which is then transferred along the four-bar linkage to crank link and consequently the generator. However, since the orientation of the four-bar linkage is constantly changing, the force is not constant, it varies from zero to a maximum value and then back to zero when oscillating between TDC and BDC.

4.1.1 Parameters

Firstly, we need to establish the optimum pitching angle of the hydrofoil wing, which would extract the maximum force and power from the water flow. The lift force on the NACA 0015 hydrofoil is analyzed for different angles of attacks. Therefore, we set up a *Flow Simulation* study in SOLIDWORKS for the static lift force acting on the hydrofoil wing. Static analysis is chosen to reduce the computational requirements of dynamic analysis and also because the static results are consistently accurate with dynamic results under low velocity flows.

The table below shows the experimental parameters that were assumed or decided. Under a flow speed of 1.5m/s acting on a hydrofoil with a chord length of 240mm, the flow regime is turbulent. Surface roughness was assumed to 0.5 micrometer.

Parameter	**Magnitude**
Fluid	Water
Fluid Speed (x)	1.5 m/s
Type of flow	Laminar and Turbulent
Type of Analysis	External
Surface Roughness	0.5 micrometer
Fluid Flow Axis	X - Axis

Table 9: Parameters of CFD Analysis

4.1.2 Force Results

With the chosen parameters, the lift force acting on the NACA 0015 hydrofoil wing for angles varying from 0 to 90°, with increments of 5°, is shown below in the table. The effects of water flow on the hydrofoil are shown in the figures below.

Angle of Attack (°)	**Lift Coefficient**	**Force(N)**
0	0	0
5	0.550	222.3
10	0.944	381.6
15	0.635	256.7
20	0.525	212.1
25	0.751	303.6
30	0.855	345.5
35	0.980	396.1
40	1.035	418.3
45	1.050	424.4
50	1.020	412.7
55	0.956	386.2
60	0.875	353.7
65	0.76	307.2
70	0.63	254.6
75	0.500	202.1
80	0.365	147.5
85	0.230	93.1
90	0.090	36.1

Table 10: Hydrofoil Lift Force

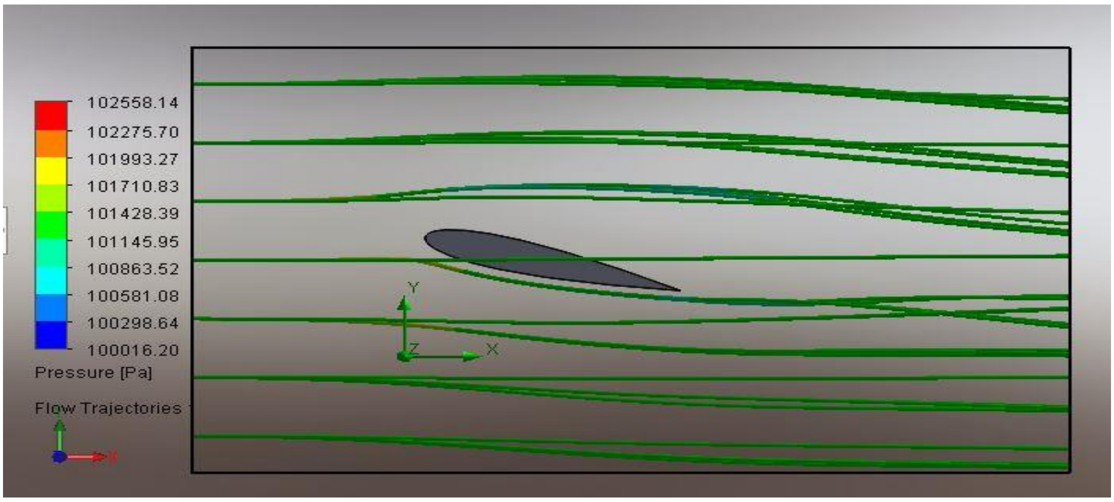

Figure 28: Hydrfoil Under Water Flow (15° AOA)

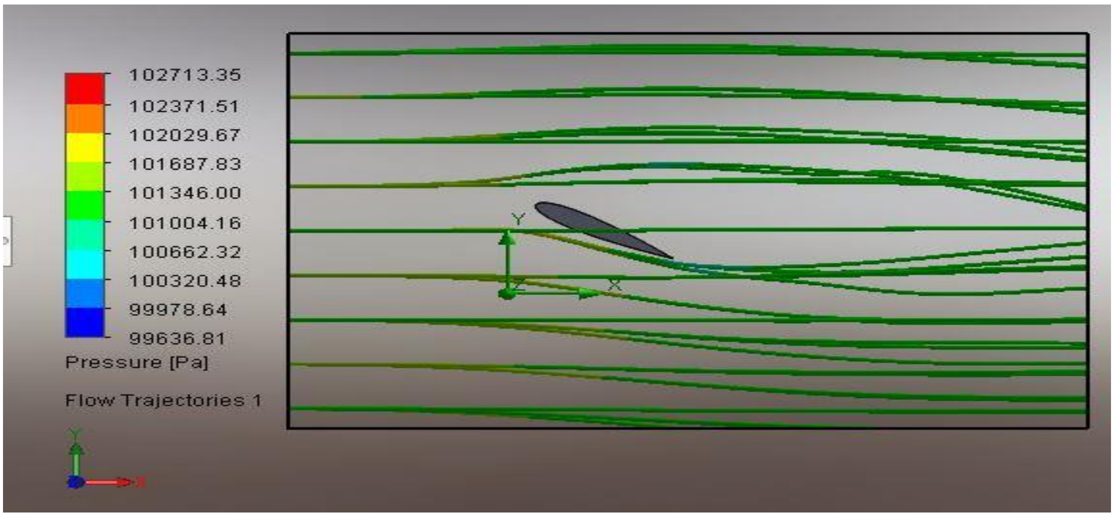

Figure 29: Hydrfoil Under Water Flow (30° AOA)

Figure 30: Hydrfoil Under Water Flow (45° AOA)

Figure 31: Hydrfoil Under Water Flow (60° AOA)

Figure 32: Hydrfoil Under Water Flow (75° AOA)

From the results obtained from the CFD analysis, two very important observations can be made. Firstly, the lift force, which is the most important output of the analysis, increases with the angle of attack to a certain point and then decreases. From the five angles of attack used in the analysis, it can be seen that the maximum was at 45 degrees, hence this will be the most optimum angle which can be used in the design. Secondly, the flow trajectories show that the fluid flow becomes turbulent and causes the formation of vortices at the edges of the hydrofoil in high angles of attack, specifically 60 and 75 degrees. These vortices induce drag force and reduce the effectiveness of the hydrofoil. This further solidifies the decision that 45 degrees should be used as the optimum angle in the design.

4.2 Stress Analysis

For the energy harvester to operate perfectly for the purpose it has been designed, it's very important to ensure it will be able to survive in actual working conditions. Submerged under water with numerous moving parts in the design, there are lots of different forces acting on the device due to the flow of water. If the device cannot maintain its structural integrity under these conditions, it will obviously fail during operation.

The three most susceptible parts of the energy harvester are the fixture, hydrofoil wings and the rack & pinion gear system.

4.2.1 Fixture

The fixture is the base frame of the entire energy harvester. It's fixed on the bottom of the riverbed or seabed and all other components are attached on the frame. Under the constant flow of 1.5 m/s there is a constant drag force acting on its surface perpendicular to the flow of water. This force induces stress all over the fixture specially in corners and the 'pivot' point.

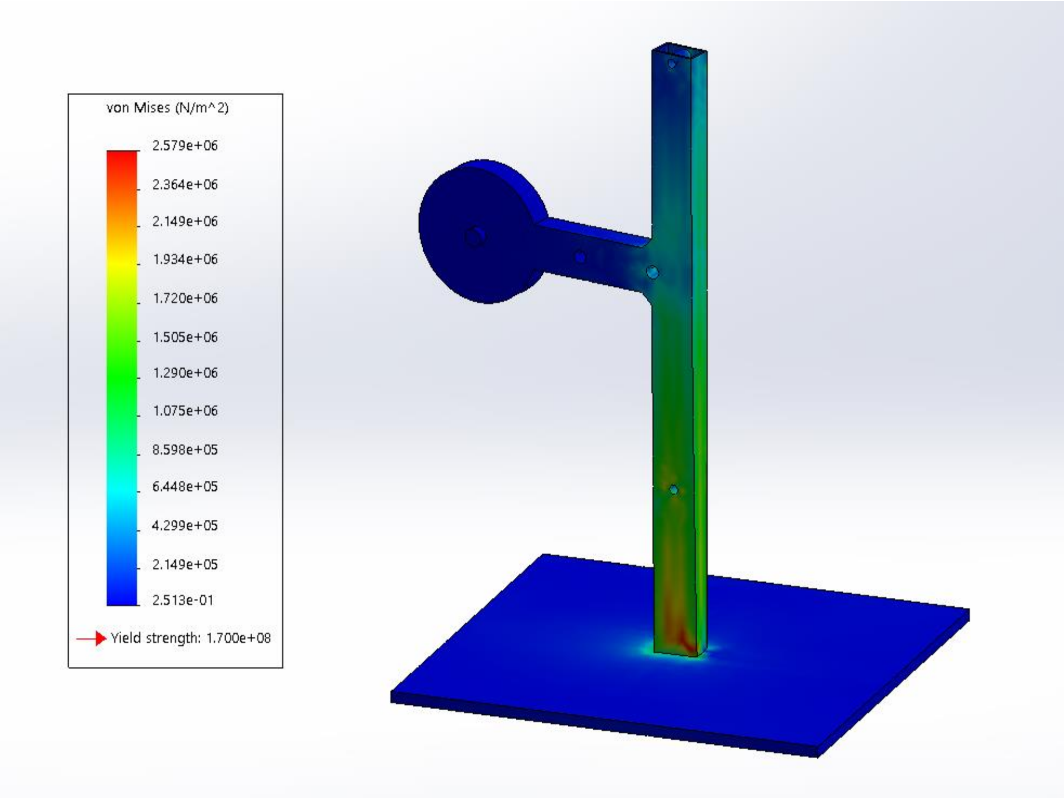

Figure 33: Von Mises Stress (Fixture)

We set up the simulation analysis in SOLIDWORKS on the 3D model of the fixture. Parameters and boundary conditions were defined according to the operating conditions of the energy harvester. Simulation was then and the results obtained are shown in the figure above. The figure shows the equivalent Von Mises stresses acting on the fixture frame. As expected, the stresses are concentrated on the incident surface of the fixture and the point where it's fixed to the seabed (riverbed). The maximum stress value on the fixture is 2.5 MPA which is well within the safe limits of the material **Stainless Steel 304.**

4.2.2 Hydrofoil Wings

Hydrofoil wings are constantly under dynamic loading due to the lift/down force acting on the wing at all times. The wing needs to be structurally strong enough to withstand these forces. Different magnitude of forces acts on the wing depending on the pitching angle at any given point in time. SOLIDWORKS simulation was set up for the maximum possible force that can act on the wing at any given time, The results are in the figure below. Highest stress concentration is where the wing is pivoted on the rocking arm. Maximum stress generated is 50 MPA which is well within the safe range of **Aluminium 7075-T6 Alclad**

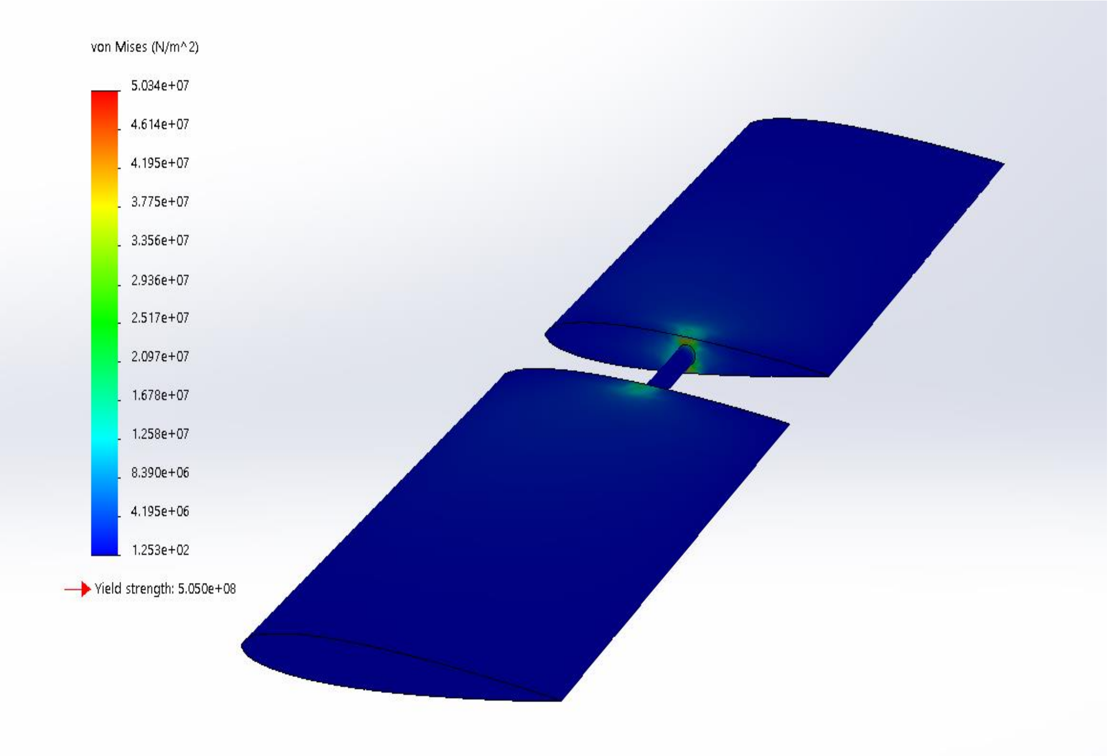

Figure 34: Von Mises Stress (Hydrofoil Wing)

4.2.3 Rack & Pinion Gear

The gear pairing has to transmit enough force to actuate the wing which is subjected to great hydrodynamic forces; thus, gears are under stress during the operation. The gears were subjected to maximum static loading condition and were analyzed for the equivalent stresses developed. Pinion gear among the gear pair was subjected to maximum a torque of 14.85 N.m with a frictionless support at the rotational axis whereas the rack gear was jointed as a fixed support.

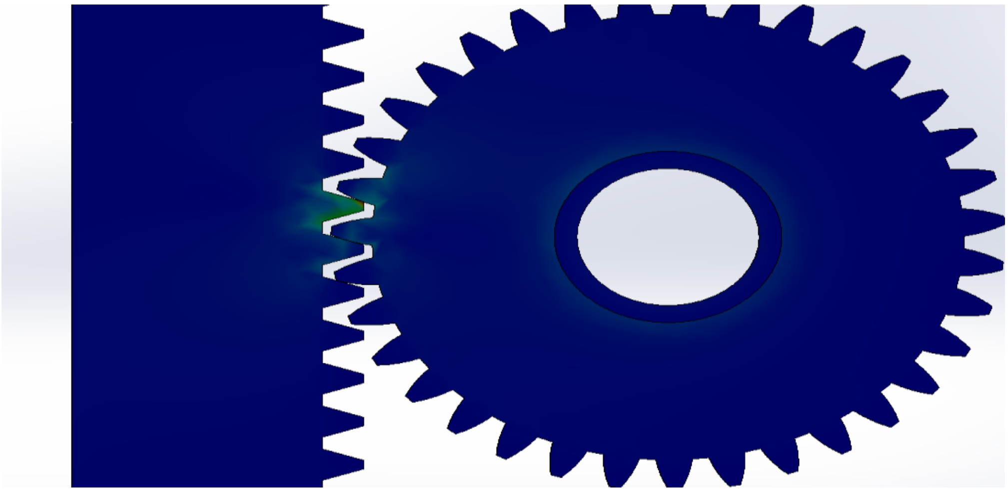

Figure 35: Von Mises Stress (Rack & Pinion 1)

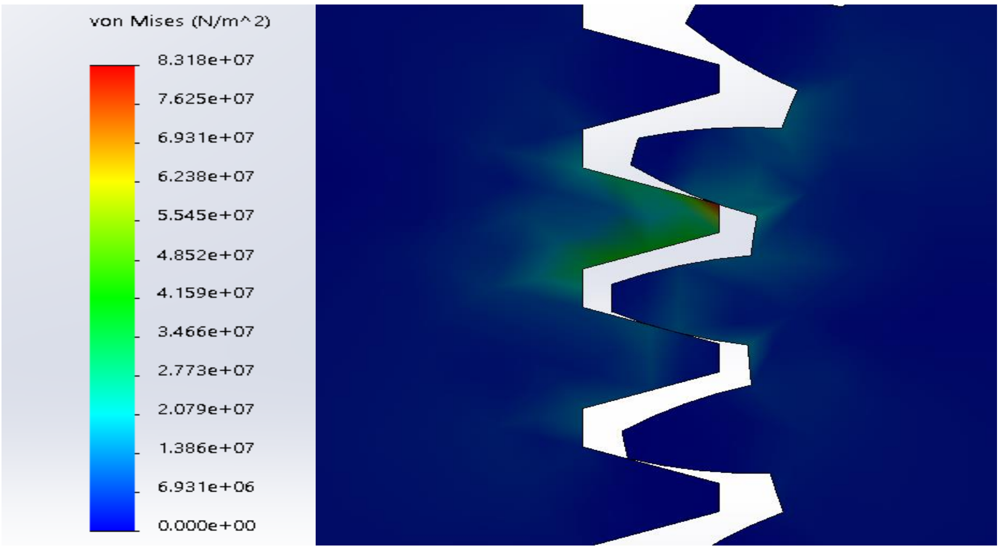

Figure 36: Von Mises Stress (Rack & Pinion 2)

The figures above show that the equivalent stresses (von-mises) developed under the maximum static loading condition of 14.85 N.m, are well within the safe limits of the material chosen.

4.3 Power Calculations

After it has been satisfied that the device would function perfectly under practical conditions and will not fail, we use the CFD analysis results to calculate the power output of the energy harvester. The power out of the energy harvester is given by the following equation:

$$P_o = M(t)\,.\,\omega(t)$$

Where;

M(t) is the instantaneous torque at the output in N.m

w(t) is the instantaneous angular velocity of crank in rad/s

4.3.1 Analysis of Four Bar Linkage – Torque

Instantaneous torque of the crank depends on the oscillation of the hydrofoil wings. Force from the lift of the hydrofoils is transmitted through the four-bar linkage to the crank output. The torque output is calculated on both the wings, each of which is at a phase difference of 90°. The results of the force transfer, over one cycle of crank rotation, have been calculated using MechAnalyzer and graphical methods are displayed in the figures below. Detailed calculations can be found in Appendix II.

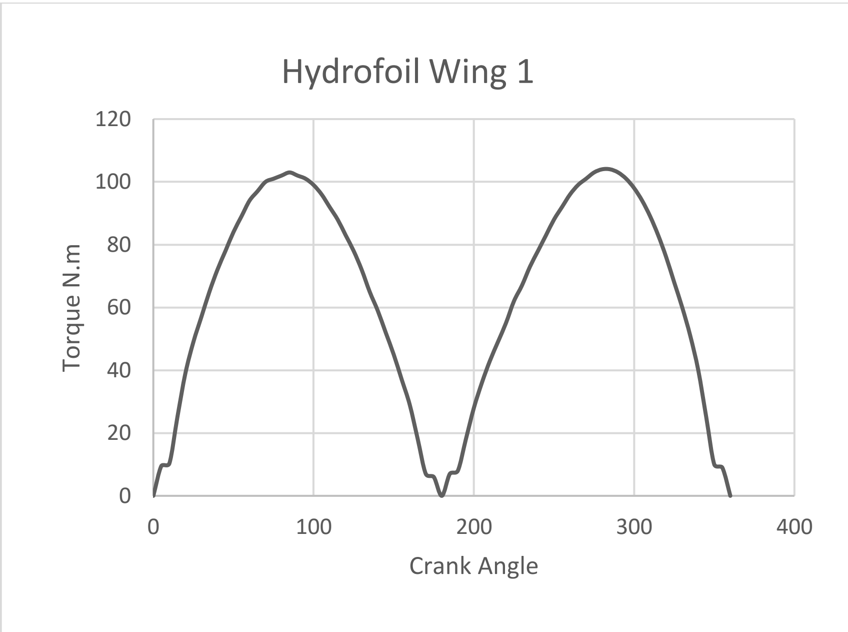

Figure 37: Torque from Hydrfoil Wing No. 1

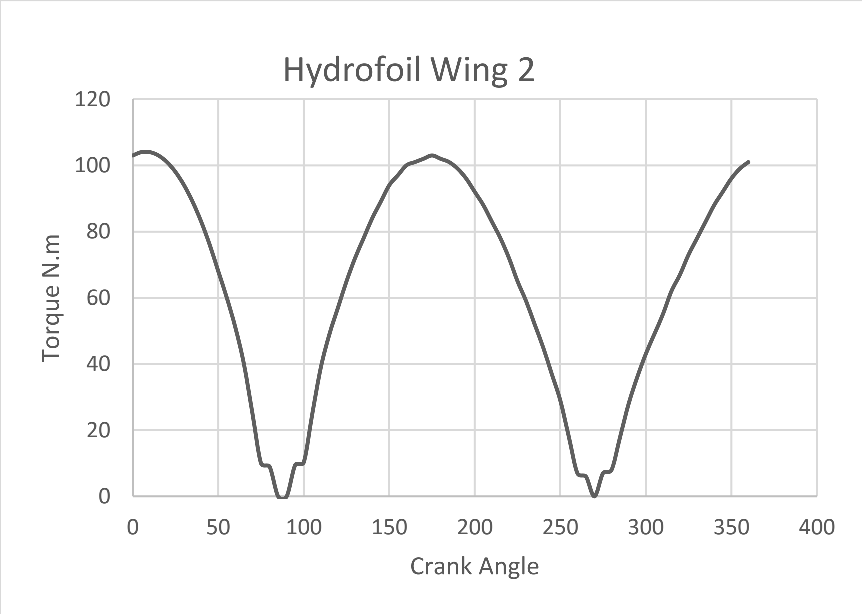

Figure 38: Torque from HydrfoilWing No. 2

Net torque output at the crank, due to both wings has been calculated and shown in the figure below.

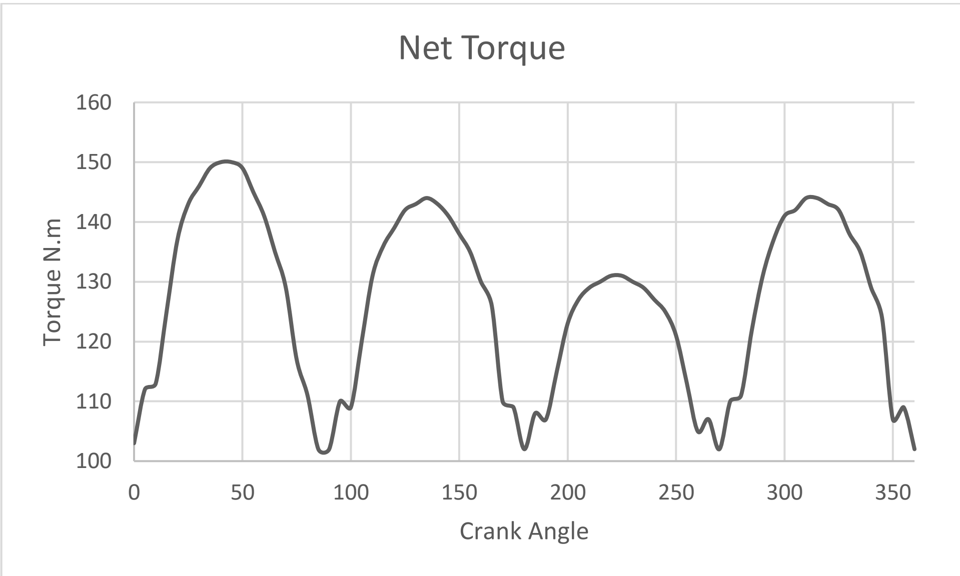

Figure 39: Net Torque

It's evident from the results that the torque output is not constant over one cycle. For each wing the torque out varies sinusoidally between a maximum value and zero. Net torque output of the system varies from a minimum torque of 102 N.m and a maximum torque of 150 N.m. The cycle averaged torque output over one cycle is calculated to be **126.1589 N.m.**

4.3.2 Analysis of Four Bar Linkage – Angular Velocity

Angular velocity of the crank link depends directly on the averaged oscillation frequency of the hydrofoil wings. Assuming a Strouhal number of 0.22 and a flow velocity, oscillating frequency can be calculated by the following formula:

$$S = \frac{fh}{V}$$

Where; S is the Strouhal Number, f is the oscillating frequency, h is the oscillating amplitude and V is the velocity of water.

Oscillating frequency is found out to be **≈ 1.375 Hz** which results in average output angular velocity of **≈ 8.639 Rad/s.**

4.3.3 Power Output

Mechanical power output of the energy harvester is given by the product of instantaneous torque and instantaneous angular velocity. Average power output over a 360-degree cycle of the crank is shown in the figure below.

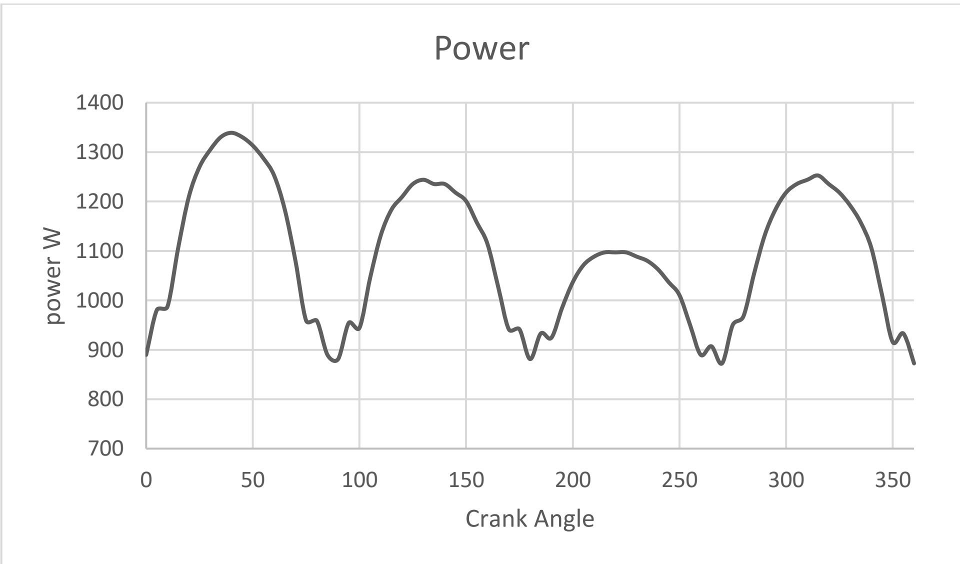

Figure 40: Power Output

Since the torque output varies greatly across the cycle, power out of the energy harvester also varies. Net power output of the system varies from a minimum value of 881 W and a maximum value of 1296 W. The cycle averaged power output over one cycle is calculated to be **1089.935 W.**

4.3.4 Efficiency Parameter

The dimensionless hydrodynamic efficiency of the device is determined from the following equation.

$$n = \frac{P_o}{P_a}$$

$$n = \frac{M(t)\,.\,\omega(t)}{\frac{1}{2}U^3 b \sum Y_P}$$

$$n = \frac{1089.935}{3282.556}$$

Hydrodynamic (water to gearbox) efficiency of the oscillating hydrofoil energy harvester is determined to be **32.9 %.**

CHAPTER 5: CONCLUSION AND RECCOMENDATION

The previous chapters of this report have explained the design of the oscillating hydrofoil energy harvester in detail along with calculations and analysis. From Methodology Chapter it is evident that the energy harvester is fulfilling the design and functionality requirements that were expected from it. Whereas, in the result section, various components of the design were tested for their strength and ability to withstand the stresses they would undergo using FEA, CFD and other analysis. The results verify both the design feasibility and durability of the energy harvester to fulfill the tasks that were required of it. Further, testing and analysis can only be done using a manufactured prototype of the energy harvester in future endeavors of this project.

5.1 Manufacturing

Manufacturing of this oscillating energy harvester is a relatively simple process, considering common materials are being used and no complex geometry is involved in the device.

Precision is important, especially in the four – bar linkage, since any deviation in lengths could result in crank link not rotating completely, which renders the device useless. Hydrofoil profile is the most complicated geometry or part in the entire device, which can be manufactured by rolling Aluminium sheets into the required profile. Cam profile needs to be made on a CNC with the given inputs of the coordinates while the rest of the components (links, fixtures, pins etc.) can be machined on lathe/milling.

Flywheel, generator, battery and gearbox are off the shelf components.

5.2 Applications and Prospects

Lack of electricity is a major issue in Pakistan, especially in the rural areas up north. The complex and harsh topography of these remote areas means that national grids and substations cannot be installed there. Although work is being done, it will take lots of years before proper electrical systems can be established in these areas.

To counter this problem, our energy harvester can be used to generate electricity at a smaller scale for small communities in these remote areas. There is an abundance of fast flowing waters in these areas from rivers, streams, waterfalls etc. which provides a huge potential for energy generation which is yet to be tapped. Our oscillating energy harvester can be installed in these waters and connected to a battery which can power a few houses nonstop. To power more houses or even entire villages, the device can be easily scaled to generate more power or a system of multiple devices can be used.

5.3 Recommendations

Although all the deliverables and objectives of the project were achieved with an acceptable level of accuracy and effectiveness, there are some improvements that could be made for this subject area in general and for this project in the future. For this, several recommendations are suggested which can be applied to the design and analysis of the oscillating hydrofoil energy harvester. Firstly, the oscillating frequency used in the design phase of the project was obtained from literature review. Previous work similar to this project was observed and considering the use of similar conditions, a general value for the oscillating frequency was selected and was used in several calculations and analysis. While this value did serve the intended purpose to a suitable level of effectiveness, for the future, it is recommended to design and manufacture a prototype of the energy harvester and test it in a controlled environment such as a hydro tunnel where the oscillating frequency and other such parameters can be determined experimentally.

Secondly, in this project, a crank rocker mechanism was selected and used for the purpose of power transmission. The main goal of the mechanism was to convert the oscillating motion of the hydrofoils to rotational motion for the generation of power. This mechanism was selected due to the fact that it was the most commonly used in previous literature without any further research into its efficiency and the alternatives which could be used. Hence, for the future, further research should be done in the form of a comparative study between the crank rocker and other mechanisms to evaluate which one has better efficiency and a greater mechanical advantage.

Thirdly, a relatively common material was selected for the body of the energy harvester. There is ongoing research and development in the field of material science which can be looked into in order to obtain materials which are better fitted for this project. The goals to be achieved through the material are to make it weigh less but also to maximize its strength. Such materials can be researched upon and their use and feasibility for this project can be evaluated.

Finally, the main objectives of the project were related to the mechanical design and analysis of the energy harvester without any great focus on the electrical components, such as electrical circuits, actuation or the electrical components to be used. For the potential manufacturing of this project in the future, focus should be put on all parts of the project including electrical in order to holistically fulfill the need for which this project was initiated. Hence, a detailed circuit diagram should be made, specifications of the electrical components used should be discussed and the use of any off the shelf components for actuation should also be mentioned.

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APPENDIX I: CAM PROFILE

Cam Motion:

Motion	Period
Harmonic Rise	45°
Dwell	135°
Harmonic Fall	45°
Dwell	135°

Parameters of Cam – Follwer:

Parameter	Magnitude
Base Circle Radius (D_c)	30mm
Rise/Fall (H_o)	55mm
Follower Type	Knife Edge Follower
Arbitrary RPM	20

Cam Profile equations:

	Rise	Fall
Displacement	$d = \frac{H_o}{2}\left[1 - \cos\left(\frac{\pi t}{T_i}\right)\right]$	$d = \frac{H_o}{2}\left[1 + \cos\left(\frac{\pi t}{T_i}\right)\right]$
Velocity	$v = \frac{\pi H_o}{2T_i}\left[\sin\left(\frac{\pi t}{T_i}\right)\right]$	$v = -\frac{\pi H_o}{2T_i}\left[\sin\left(\frac{\pi t}{T_i}\right)\right]$
Acceleration	$a = \frac{\pi^2 H_o}{2{T_i}^2}\left[\cos\left(\frac{\pi t}{T_i}\right)\right]$	$a = -\frac{\pi^2 H_o}{2{T_i}^2}\left[\cos\left(\frac{\pi t}{T_i}\right)\right]$

Where; t = time, T_i = Arbitrary time taken for fall/rise assuming RPM.

Using the values calculated above, we have to find the x and y coordinates of the cam profile to plot. The plotted shape on a x-y plane is the profile of the cam.

$$x = (D_c + d)\ (Sin\ \theta)$$

$$y = (D_c + d)\ (cos\ \theta)$$

Where, θ is the angle of cam in radians.

Cam profile calculations:

(Calculations were performed for each increment of 1° between 0 and 360° for high accuracy. Results displayed here are for increments of 10° for simplicity.)

Time	Angle (Degrees)	Angle (Radians)	Displacement	Velocity	Acceleration	X - Coordinate	Y- Coordinate
0	0	0	0	0	2382.78515	0	30
0.075	10	0.174533	6.433777814	164.5418	1825.319324	6.326659123	35.8802669
0.15	20	0.349066	22.72467511	252.0927	413.7662991	18.03290094	49.5449881
0.225	30	0.523599	41.25	221.6866	-1191.392575	35.625	61.70431
0.3	40	0.698132	53.34154707	87.55087	-2239.085623	53.57091383	63.843329
0.375	50	0.872665	55	0	0	65.11377767	54.6369468
0.45	60	1.047198	55	0	0	73.61215932	42.5
0.525	70	1.22173	55	0	0	79.87387277	29.0717122
0.6	80	1.396263	55	0	0	83.70865901	14.7600951
0.675	90	1.570796	55	0	0	85	5.2069E-15
0.75	100	1.745329	55	0	0	83.70865901	-14.7600951
0.825	110	1.919862	55	0	0	79.87387277	-29.0717122
0.9	120	2.094395	55	0	0	73.61215932	-42.5
0.975	130	2.268928	55	0	0	65.11377767	-54.6369468
1.05	140	2.443461	55	0	0	54.63694682	-65.1137777
1.125	150	2.617994	55	0	0	42.5	-73.6121593
1.2	160	2.792527	55	0	0	29.07171218	-79.8738728
1.275	170	2.96706	55	0	0	14.7600951	-83.708659
1.35	180	3.141593	55	0	0	1.04138E-14	-85
1.425	190	3.316126	48.56622219	-164.5418	-1825.319324	-13.6428813	-77.3726247
1.5	200	3.490659	32.27532489	-252.0927	-413.7662991	-21.2994155	-58.5196633
1.575	210	3.665191	13.75	-221.6866	1191.392575	-21.875	-37.8886114
1.65	220	3.839724	1.658452928	-87.55087	2239.085623	-20.3496613	-24.2517819
1.725	230	4.014257	1.658452928	87.55087	2239.085623	-24.2517819	-20.3496613
1.8	240	4.18879	0	0	0	-25.9807621	-15
1.875	250	4.363323	0	0	0	-28.1907786	-10.2606043
1.95	260	4.537856	0	0	0	-29.5442326	-5.20944533
2.025	270	4.712389	0	0	0	-30	-5.5132E-15
2.1	280	4.886922	0	0	0	-29.5442326	5.20944533
2.175	290	5.061455	0	0	0	-28.1907786	10.2606043
2.25	300	5.235988	0	0	0	-25.9807621	15
2.325	310	5.410521	0	0	0	-22.9813333	19.2836283
2.4	320	5.585054	0	0	0	-19.2836283	22.9813333
2.475	330	5.759587	0	0	0	-15	25.9807621
2.55	340	5.934119	0	0	0	-10.2606043	28.1907786
2.625	350	6.108652	0	0	0	-5.20944533	29.5442326
2.7	360	6.283185	0	0	0	-7.3509E-15	30

APPENDIX II: FORCE ANALYSIS OF 4 – BAR MECHANISM

Torque output on the four-bar mechanism has been done using MechAnalyzer software and graphical method. The results for the torque output are shown in the excel sheet below. (Analysis was performed for each increment of 0.25° between 0 and 360° for high accuracy. Results displayed here are for increments of 10° for simplicity.)

Angle	Force (N)	Torque Wing 1 (N.m)	Torque Wing 2 (N.m	Net Torque (N.m)	Power Output (W)
0	0	0	103	103	889.8561191
10	848.35	10.3	104	114.3	987.4811108
20	1673.347	39	101	140	1209.513172
30	1697.598	57	94	151	1304.546349
40	1697.598	72	83	155	1339.103869
50	1697.598	84	68	152	1313.185729
60	1697.598	94	51	145	1252.710071
70	1697.598	100	25	125	1079.922475
80	1697.598	102	9	111	958.9711575
90	1697.598	102	0	102	881.2167393
100	1697.598	99	10.3	109.3	944.2842119
110	1697.598	92	39	131	1131.758753
120	1697.598	83	57	140	1209.513172
130	1697.598	72	72	144	1244.070691
140	1697.598	59	84	143	1235.431311
150	1697.598	45	94	139	1200.873792
160	1673.347	29	100	129	1114.479994
170	848.35	7	102	109	941.6923979
180	0	0	102	102	881.2167393
190	848.35	8	99	107	924.4136383
200	1673.347	28	92	120	1036.725576
210	1697.598	43	83	126	1088.561854
220	1697.598	55	72	127	1097.201234
230	1697.598	67	59	126	1088.561854
240	1697.598	78	45	123	1062.643715
250	1697.598	88	29	117	1010.807436
260	1697.598	96	7	103	889.8561191
270	1697.598	101	0	101	872.5773595
280	1697.598	104	8	112	967.6105373
290	1697.598	103	28	131	1131.758753
300	1697.598	98	43	141	1218.152551
310	1697.598	89	55	144	1244.070691
320	1697.598	76	67	143	1235.431311
330	1697.598	60	78	138	1192.234412
340	1673.347	40	88	128	1105.840614
350	848.35	10	96	106	915.7742585
360	0	0	101	101	872.5773595