Design and Fabrication of Energy Harvester using VIVACE (Vortex Induced Vibrations Aquatic Clean Energy)

Ashok B C, Akshay B L, Akshatha H, Akash D L, Bharath Yogendra

ABSTRACT--- Massive industrialization and population explosion have led to an increase in demand for energy across the globe in recent years. Electricity is the latest currency and developing countries are in desperate need of insatiable units of electricity. There is so much potential in Hydropower which when harnessed efficiently can show a phenomenal way in addressing the energy crisis. The conventional methods of harnessing the hydropower like generating electricity by damming, etc. have many limitations concerning environmental concerns, aquatic ecological imbalance and other issues. The paper is on Vortex Induced Vibrations Aquatic Clean Energy (VIVACE). It focuses on Clean Energy by making use of Vortex Induced Vibrations (VIV) to generate electricity. This paper describes the design and fabrication process related to energy harvester to harness VIVACE. CFD simulations done to obtain the feasible values of some important parameters involved in VIVACE are also discussed.

Keywords: Hydropower, Vortex shedding, Vortex Induced Vibrations (VIV), Vortex Induced Vibrations Aquatic Clean Energy (VIVACE), Energy Harvester, CFD simulations.

I. INTRODUCTION

India, being a Growth engine, plays a crucial role in the world energy trends. There has been an unremitting growth in the electricity production in India from Financial Year (FY) 2010 to 2018(figure 1). 1201.5 billion units (BU) of electricity has been produced in FY 2018 in India [1]. The Indian government has shifted its focus on clean energy as it has ratified the Paris Agreement in October 2016 [2]. The Indian government is all set for boosting investment in renewable energy. In an annual ranking of top 40 renewable energy markets conducted by EY, a UK accountancy firm, renewable energy sector of India is the second best country in attracting investors in renewable energy market in the world.

According to India Brand Equity Foundation (IBEF), India is all set to meet its requirements, which is predicted to attain 15,820 TWh (Terawatt hour) by the year 2040. Therefore renewable energy will take the center stage in the coming years.

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Dr. Ashok B C, Visvesvaraya Technological University (bcashok@vvce.ac.in)
Akshay B L, Visvesvaraya Technological University (akshaybl001@gmail.com)
Akshatha H, Visvesvaraya Technological University, (akshuakshatha0@gmail.com)
Akash D L, Visvesvaraya Technological University (akashdlbenakanahalli@gmail.com)
Bharath Yogendra, Visvesvaraya Technological University (yogibharath106@gmail.com)

The ramifications of conventional hydropower generation due to damming of water, change in flow of water, construction of roads and setting up of power lines are disastrous to aquatic ecosystem. How can engineers develop an energy harvester without unbalancing the aquatic ecosystem? Millions of units of power is frittered away as water flows incessantly down the streams, rivers and join the oceans. This poses an immense challenge to utilize this restless resource. Can engineers think of harnessing this huge, restive energy to generate clean sustainable energy?

The answer to above two questions is Clean and sustainable energy making use of Vortex Induced Vibrations. Energy crisis can be mitigated by utilizing the unused flow energy of water and producing electricity even in small scales. Using the principle of VIVACE, we can produce clean and renewable energy. During this era of depleting energy, we can obtain considerable amount of electricity. By incorporating VIVACE, areas having flowing water like streams, rivulets, rivers, etc. can extract energy and generate electricity.

This paper focuses on design and fabrication of energy harvester using VIV, familiarization with the vibration phenomenon of the bluff body (cylindrical object) and understanding the flow around the bluff body (cylindrical object), investigation of the lift force v/s flow time simulation in transient flow using CFD.

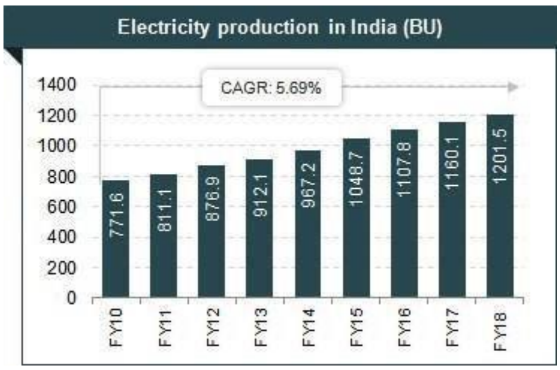

Figure 1: Electricity Production in India in each Financial Year (FY) from 2010 to 2018.[3]

II. DESIGN METHODOLOGY

- Background study
- Principle
- Principle parts
- Working Principle

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The design of our Project goes as follows:

A. Background study

1. Flow Regimes

Reynolds number (Re) is one of the non-dimensionless numbers that is used to instantiate the flow around a bluff body (cylindrical object). Reynolds number is the ratio of the inertia forces to viscous forces. Huge changes in the Reynold number bring about regimes of flow. Vortices are formed due to the separation in the region of wake of the bluff body (cylindrical object). This separation in the wake region is caused due to changes in the Reynolds number. Separation does not occur at meagre values of Re (Re < 5). When the Reynolds number is increased to greater extent (Re > 40) is further increased, the occurrence of separation takes place which becomes unstable, and actuates the phenomenon of vortex shedding at a particular frequency. [4]

2. Vortex Shedding

When Re is more than 40, the phenomenon of Vortex shedding (Fig 2.1) occurs. Vortex shedding takes place when a set of two stable vortices are susceptible to small disturbances and become unstable for Re values more than 40 as the boundary layer over the bluff body will separate due to the pressure gradient forced by the divergent profile of the flow territory behind the bluff body. Vortex shedding manifests at a particular frequency called as vortex shedding frequency (f_v).

Flow velocity (U) normalized for this frequency and the bluff body diameter (D) are function of the Reynolds number [4]. Moreover, the vortex-shedding frequency which is normalized is known as Strouhal number (St).The relationship between Re in x- axis and St in y-axis is seen in Figure 2.2.

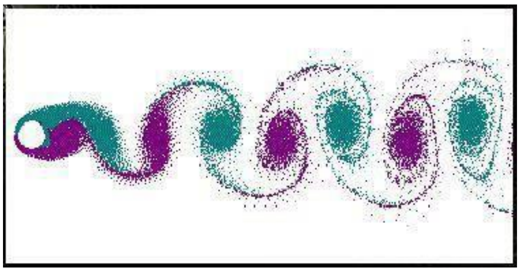

Figure 2.1: Vortex shedding

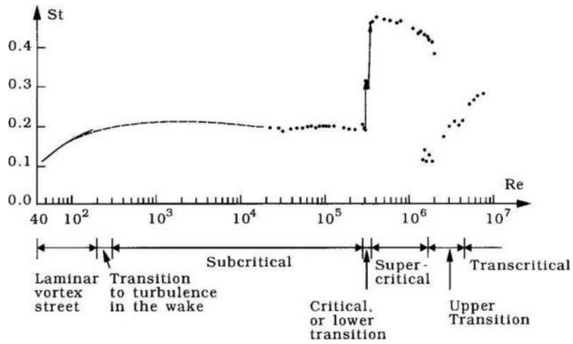

Figure 2.2: Graph of Reynolds number v/s Strouhal number for bluff body

3.Drag and Lift Forces

Due to cyclical change of the vortex shedding, distribution of pressure around the bluff body will change periodically. This results in cyclical variation in the force components in the bluff body. Cross-flow and in-line directions are the force components. The lift force (F_L) is in the cross-flow direction and the drag force (F_D) is in the inline direction. The lift force develops when the vortex shedding begins and it varies at the vortex shedding frequency. Correspondingly, the drag force also has the oscillating part due to the vortex shedding. Additionally, because of friction and difference in pressure, drag force also has a small force called the mean drag [5].

4.Cross-Flow Vibrations and In-Line Vibrations of bluff body

Vibrations of bluff body materialise because of cyclical changes in the force components because of vortex shedding. Cross flow vibrations (Fig.2.3(a)) and in-line vibrations (Fig.2.3(b))) are the two types of Vortex Induced Vibrations. The lift force causes the cross-flow vibration while the drag force causes the in-line.

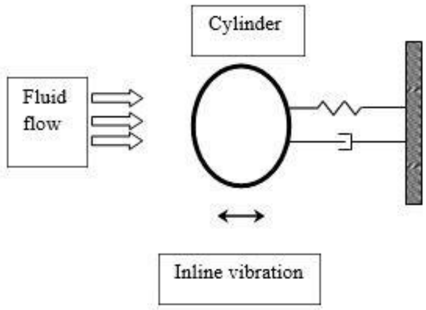

Figure 2.3(a): Sketch of Inline Vortex Induced Vibrations [7]

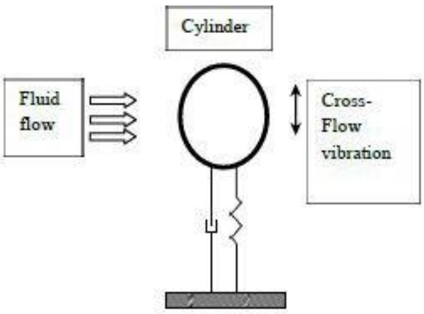

Figure 2.3(b): Sketch of Cross-Flow Vortex Induced Vibrations [7]

5.Vortex Induced Vibrations (VIV)

VIV occurs due to formation and shedding of vortices behind the bluff body in a water current. A vibration is created as vortex shedding alternates from one side to the other. The VIV is non-linear occurrence. This property of VIV has huge implication as it produces beneficial energy over a wide range of flow velocities at greater efficiency.

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6.Lock-in Frequency

The vortex shedding frequency (f_v) will be trailing the stationary-bluff body Strouhal frequency (f) till the reduced velocity (V_r) arrives at some value. When the flow speed increases, vortex shedding frequency (f_v) does not follow the Strouhal frequency (f) and begins to follow the natural frequency (f_n) of the system. This phenomenon takes place at a range. In this range, the vortex shedding frequency is locked into the natural frequency of the system. This phenomenon is known as the "lock-in'' phenomenon. At this range, f_v, f_n and f have the same values, therefore, the lift force oscillates with the bluff body motion resulting in large vibration amplitudes.

B Principle:

Vortex Induced Vibrations Aquatic Clean Energy (VIVACE)

Vortex Induced Vibration Aquatic Clean Energy (VIVACE) replicates the features of fish movements. By curving their bodies, fish shed vortices in front of them and glide between the vortices. They ride in each other's wake to propel them forward through the water at the speed they go as their muscle power alone cannot do it.[6][8]

Vortex induced vibrations are oscillations that a bluff body makes in a fluid flow(air or water). The presence of the bluff body puts twirls in the flow speed as it glides by which causes eddies or vortices that generate a pattern on either sides of the bluff body. The vortices push and pull the bluff body perpendicular to the flow, which is up and down in cross flow orientation, or, left and right in inline flow orientation. VIVACE works as the bluff body in the flow causes alternating vortices to form above and below the body. Mechanical energy i.e. vibrational energy is created by vortices pushing and pulling the bluff body. Later, this energy is converted into electricity. It is propounded that the this energy harvester would not harm aquatic life like how conventional hydro energy technologies would do as the oscillations of VIVACE would be slow.[9][10]

C. Principle Parts

- *Bluff Body (Cylinder)*
- *Rack*
- *Pinion*
- *Gear*
- *Gear Coupled with DC generator*

D. Working Principle

The Figure Below Shows the Working Principle of Our Project.

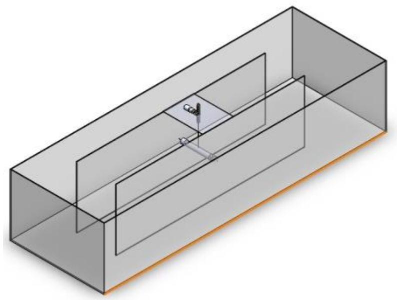

Figure 2.4: CAD model of experimental set-up

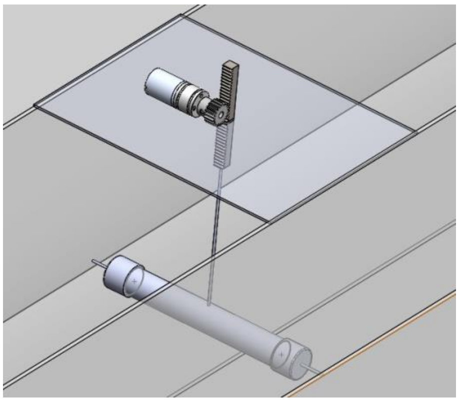

Figure 2.5: Enlarged view of gear coupled with Generator

The main principle behind this project is the conversion of linear oscillation of bluff body to rotational motion of the pinion. As the Bluff body (cylindrical object) is subjected to hydro-energy, it tends to oscillate due to the vortices formed around the structure of the bluff body, which can be converted to rotational energy to generate electricity. In this configuration, the bluff body is fixed axially and cross flow Vortex Induced Vibrations takes place. A rack and pinion arrangement is used for converting linear motion to rotational motion. As the bluff body reciprocates, the rack's movement rotates the pinion attached to it. The pinion drives the shaft which in turn rotates the alternator to generate power. Thus, electrical energy is obtained by continuous oscillation of the bluff body and DC output voltage is obtained.

III. DESIGN SPECIFICATIONS

A. Formulae

1. Reynolds number

Reynolds number (Re) is dimensionless hydrodynamic number. It describes the flow around a bluff body. Reynolds number is the ratio of the inertia forces to viscous forces and formulated as:

$$R_e = {}^{DU}/_{v}$$

in which *D* is the diameter of the bluff body, *U* is the flow velocity and *v* is the kinematic of the fluid.

2.Vortex shedding

Vortex shedding occurs at a certain frequency, which is called as vortex shedding frequency (f_v). This frequency normalized with the flow velocity U and the bluff body diameter *D*, can be seen as a function of the Reynolds number:

$$f_v = {}^{S_t U}/_{D}$$

Furthermore, the normalized vortex- shedding frequency is called Strouhal number (St) and the empirical formulae is:

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$$S_t = 0.198\left(1 - \frac{19.7}{R_e}\right)$$

3. Lift Force

Lift force is formulated as follows:

$F_L = \hat{F}_L \sin(\omega_S t + \emptyset_S)$. $\hat{F}_L$ is the amplitude of the oscillation lift. The Vortex Shedding is represented by $\omega_s = {2\pi}/{f_v}$ and $\emptyset_s$ is the phase angle between oscillating force and vortex shedding. C_L are the dimensionless parameters for lift force and can be calculated using:

$$\hat{F}_L = 0.5 \times \rho_{fluid} L D U^2 \times C_L$$

where L, D and U are the bluff body length, bluff body diameter and flow velocity respectively.[12]

4. Apparent mass

$$m_{app} = m_{pipe} + m_{dis} \text{ where}$$

$$m_{pipe} = (\rho_{cyl} \times L) + m_{add}$$

$$m_{dis} = \rho_{fluid} \times Vol$$

$$Vol = \frac{\pi}{4}(D^2 \times L)$$

Where Vol is Volume of the bluff body, m_{dis} is mass of fluid displaced by the bluff body, ρ_{fluid} is water density, mass m_{add} is additional mass added to the bluff body, which will be assumed as 0. Based on unit length density of bluff body (ρ_{cyl}) i.e. 0.64kg/m mass m_{pipe} was determined.

5. Spring stiffness

Stiffness is a measure of the resistance offered by an elastic body to deformation. Spring stiffness (k) is the force required to cause unit deflection. It is given by:

$$k = (2\pi f_v)^2 \times m_{app}$$

Where f_v is vortex shedding frequency and m_{app} is apparent mass.

IV. ANALYTICAL CALCULATIONS

These are the known values:

Property	Parameter	Values
Bluff body material	M	PVC
Bluff body Diameter	D	25.4 mm
Bluff body Length	L	200 mm
Water density	ρ_{fluid}	998 kg/m^3
Bluff body density	ρ_{cyl}	0.64 kg/m
Water temperature	T	25^o C
Water Kinematic Density	v	0.89 e^{-6} m^2/s
Maximum Flow speed	U	1 m/s

Calculations:

1. Reynolds Number (Re):

$$R_e = {DU}/{v} = 25.4 \times 10^{-3} \times {1}/{0.89\ e^{-6}}$$

$$R_e = 28539.32$$

2. Strouhal Number (S_t):

$$S_t = 0.198\left(1 - \frac{19.7}{R_e}\right) = 0.198\left(1 - \frac{19.7}{28539.32}\right)$$

$$S_t = 0.1978$$

3. Vortex Shedding Frequency (f_V):

$$f_v = {S_t U}/{D} = 0.1978 \times {1}/{25.4 \times 10^{-3}}$$

$$f_v = 7.787\ Hz$$

4. Lift force ($\hat{F}_L$):

$$\hat{F}_L = 0.5 \times \rho_{fluid} L D U^2 \times C_L$$

$= 0.5 \times 998 \times 200\ e^{-3} \times 25.4 e^{-3} \times 1^2 \times 0.8$

= 2.027 N

Coefficient of lift C_L is assumed as 0.8 based on literature survey. In actual practise , C_L varies with displacement of the bluff body, so this value is a mean.

5. Apparent mass (m_{app}):

$$Vol = \frac{\pi}{4}(D^2 \times L)$$

$$= \frac{\pi}{4}\left((25.4 \times 10^{-3})^2 \times (200 \times 10^{-3})\right)$$

$$= 1.0134 \times 10^{-4}\ m^3$$

$$m_{dis} = \rho_{fluid} \times Vol = 998 \times 1.0134 \times 10^{-4}$$

$$= 0.10114 \text{ kg}$$

$$m_{add} = 0 \text{ kg}$$

$$m_{pipe} = (\rho_{cyl} \times L) + m_{add}$$

$$m_{pipe} = (0.64 \times 200 \times 10^{-3}) + 0$$

$$= 0.128 \text{ kg}$$

$$m_{app} = m_{pipe} + m_{dis} = 0.22914 \text{ kg}$$

6. Spring Stiffness (k):

$$k = (2\pi f_v)^2 \times m_{app} = (2 \times \pi \times 7.787)^2 \times 0.22914$$

$$= 548.53 \text{ kg/m} = 548.53 \times 9.81$$

$$k = 5381.09 \text{ N/m}$$

V. CFD SIMULATION RESULT

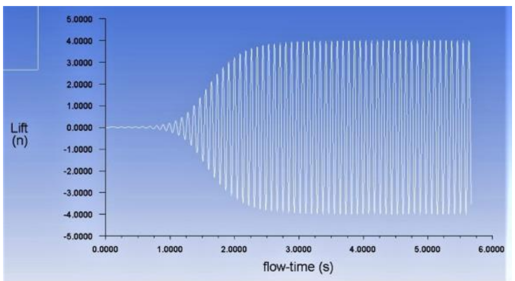

Figure 4.1: CFD Simulation of Lift v/s Flow-time

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The turbulent analysis is used in the CFD simulation as the Reynolds number is in turbulent region. K-omega (due to transient flow) type of turbulence model is chosen. In Figure 4.1, the displacement graph of the freely vibrating bluff body at Re = 25000 is shown. The flow time of the simulation is for 6 seconds. The vertical axis indicate the lift force in Newton and the horizontal axis is the flow duration in second. From the graph, it is observed that the response of bluff body rises after a second. Between the time value of 1 second to 2.5 seconds, the lift force is constantly rising. After 2.5 seconds, the lift force is constant and measures around 4N.

VI. CONCLUSION

In this paper the VIV experiment on the energy harvesting device with a bluff body, rack and pinion and generator was done. Through mathematical calculations, CFD modelling and experiments, the possibility of Vortex Induced Vibrations (VIV) as an energy source was studied. Literature survey was done initially on the theory of VIV and other technologies pertaining to aquatic energies. Based on the literature survey, mathematical calculations were done in order to establish the relationship between experimental parameters and bluff body response. Based on the mathematical calculations, CFD modelling was done to obtain few key parameters involved to predict and establish the viability of experiments involving VIV.

Overall, this paper demonstrated the power generation at small scale. The output DC Voltage obtained lights up the LED in our case. Therefore, there is a bright prospective for Vortex Induced Vibrations (VIV) as a source of renewable energy.

VII. SCOPE FOR FUTURE WORK

The tests were conducted at low velocity. Speeds found in streams and rivers are much more greater than the experimental speed. The tests were conducted for sub-critical value of the Reynolds number. By increasing the

Reynolds number to the range of critical and super critical regions, more tangible results can be obtained which would further consolidate the feasibility of this technology in realistic conditions. Because of the low velocity for the water in the experiment, the lift force of the water acting on the bluff body was also small.

For large-scale generation of energy, bluff body made of piezoelectric material can be used. As vibrations increases on the piezoelectric bluff body, the stresses induced in piezoelectric bluff body also increases. This enables for producing electricity more efficiently. AC generators can be used in case of high flow speeds. At low flow speeds, AC generators are not feasible as some energy generated will be wasted for the conversion of direct current to alternating current. But when velocity increases, load on piezoelectric bluff body also increases and use of AC generator is feasible.

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About Authors

Dr. Ashok B.C is an Associate Professor in Mechanical Department and is the Accreditation & Assessment Coordinator in Vidyavardhaka college of Engineering, Mysuru, Karnataka ,India. He is a graduate from N.I.E, Mysuru under Mysore University in Mechanical Engineering, M.Tech in Maintenance Engineering and Ph.D under V.T.U, Belgaum. His research interests are

Maintenance and Production Management. He has guided many projects and funded by KSCST. He is a lifetime member of Indian Society for Technical Education (ISTE) and Indian Institution of Production Engineers (IIPE). Coordinator for NBA and NAAC and has delivered talk on NBA in several Engineering colleges. He has published papers in International journals and presently working as Associate professor in Department of Mechanical Engineering, Vidyavardhaka College of Engineering, Mysuru, Karnataka, India.

Mr Akshay B L is a young and enthusiastic student from Vidyavardhaka College of Engineering, Mysuru, Karnataka, India. He is currently pursuing eighth semester in mechanical engineering. He is a neoteric person and likes to think out of the box. He aspires to make a mark as an ingenious Engineer in the realm of Mechanical Engineering.

Ms Akshatha H is a young and enthusiastic student from Vidyavardhaka College of Engineering, Mysuru, Karnataka, India. She is currently pursuing eighth semester in mechanical engineering. She is a dedicated, hard working person and motivated towards goal. She has good leadership skills and would like to contribute good to society as a person and also an engineer.

Mr Akash D L is a young and enthusiastic student from Vidyavardhaka College of Engineering, Mysuru, Karnataka, India. He is currently pursuing eighth semester in mechanical engineering. He wants to carve a niche for myself in the field of Mechanical Engineering.

Mr Bharath Yogendra is a young and enthusiastic student from Vidyavardhaka College of Engineering, Mysuru, Karnataka, India. He is currently pursuing eighth semester in mechanical engineering. He is a person with high ambitions and various skill sets.

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