International Journal of Innovative Research in Computer Science and Technology (IJIRCST)
ISSN (Online): 2347-5552, Volume-13, Issue-3, May 2025
https:/doi.org/10.55524/ijircst.2025.13.3.27
Article ID IJIRE-1408, Pages 197-204
www.ijircst.org

Integrated Framework for Design & Testing of a Low-Solidity Vertical Axis Water Turbine for Renewable Micro-Hydro Applications

Dr. Saba Irum[1], Saram Abbas[2], and Muhammad Ibraheem[3]

[1]Department of Mathematics, TU Dortmund University, Germany
[2]Doctoral Student, Department of Electrical & Electronics Engineering, Newcastle University, UK
[3]Department of Materials & Surface Engineering, SCME, NUST, Pakistan

Correspondence should be addressed to Dr. Saba Irum; Saba.irum@lums.edu.pk

Received 29 April 2025; Revised 15 May 2025; Accepted 30 May 2025

ABSTRACT- With fast growing requirements of energy, discovery and using innovative and non-conventional energy sources are necessary. Hydro power is major source of substitute energy which would go unexploited otherwise if not extracted though some mechanical means. Pakistan is rich in shallow and high velocity stream water channels which carry significant energy potential. Lift based vertical axis water turbines such as Darrieus turbines are capable of generating large amount of energy with much simpler mechanism than conventional horizontal axis water turbines making it cost effective just by placing them in flowing water with substantial potential. However, low solidity vertical axis water turbines absence self-start capability due to low lift and higher required torque at beginning. Designed configuration was analysed by DMS theory in QBlade software and was then tested in actual water passage after fabrication.

KEYWORDS- Integrated Framework, Low-Solidity, Vertical Axis Water Turbine, Renewable Micro-Hydro Applications

I. INTRODUCTION

Human is reliant on energy, which is vital for his speedy industrialized development and technical progress. The speed of improvement subsequent to commercial up rise is extraordinary. Simply two hundred years in the past, the world has seen energy revolution that released the industrialized era. The promoter to this exchange became normal coal - an energy wealthy hydrocarbon [1]. A century later, oil and gas had been delivered to satiate the thirst of industry. Men still are based in particular on these fossil fuels.

Though many other assets of electricity: hydro, solar, nuclear, wind, geothermal, biogas and wave had been taped. Those assets of power are not most effective renewable but easy as nicely. Since the hydrocarbons are exhaustible and their use additionally threatens human health and environment; this reality has necessitated transformation from non-renewable electricity sources to renewable and smooth electricity assets in order that financial boom will be sustained and environmental degradation could be avoided. Following diagram indicates international's dependence on strength sources.

Electricity isn't always most effective critical for the enterprise however it's also the lifestyles blood of our everyday existence. The intake of fossil fuels has amplified because of rapid industrialization of developing countries like China and India [2]. However, the fundamental proportion of hydrocarbon is fed on through already advanced countries like the US, Japan and Western au states. The hydrocarbons also are the primary source of strength for heating of homes and running motor automobiles and technology of electricity. Because the need has been extended far greater than the increase within the production of fossil fuels, a disparity between the demand and deliver has been created which has led to strength disaster.

Water flowing in the rivers has kinetic energy. As soon as they are used to force the mechanism and bring energy electricity produced as Hydel energy. Power generated by using the turbines relies upon on mass flow rate of water and the quantity of water available [3]. Generally, river runs by means of melting ice on mountains. As soon as the water start flowing down to the sea level it carries huge kinetic energy. This energy may be transformed into electrical power.

Ever-increasing requirements of the world for energy and the depletion of the fossil fuel reservoirs have encouraged man to search for the renewable energy sources which do not have health and environmental aspects like the fossil fuels.

Two methods are normally used for power extraction through hide means: -

- Dams
- Run of River projects

In situation of Dams the water flow is restrained means of creating a large garage device and the pinnacle of water is extended, the water then is authorized to waft by gates and bypass thru the generators, the head of reservoir stage is maintained to provide uniform power, and the water saved in height season additionally is used for irrigation functions in dry seasons.

Run-of-the-river hydroelectricity (ROR) is a kind of hydroelectric generation plant wherein little or no water storage is furnished. Run-of-the-river electricity flora may also haven't any water garage in any respect or a restrained quantity of garage, wherein case the storage reservoir is known as poundage. A plant without poundage has no water storage and is, consequently, situation to seasonal river flows. In above mentioned projects the flow is distracted over the subways and once it gains the head allowed to fall and pass through the turbines and returns to river. The water in such schemes is constantly flowing and not being stored. Run-of-the-river or ROR hydroelectricity is considered perfect for streams or rivers that can withstand a minimum flow or those delimited by a lake or reservoir upstream.

II. LITERATURE REVIEW

The exploration of vertical axis water turbines (VAWTs) as a viable solution for shallow and fast-flowing stream environments has received increasing attention due to their structural simplicity, adaptability, and compatibility with low-head water sources. However, challenges such as self-start limitations, sub-optimal power output under fluctuating flow conditions, and blade inefficiencies continue to hinder their widespread application. A review of relevant interdisciplinary literature—ranging from passive flow control techniques to AI-augmented optimization frameworks—reveals multiple avenues for enhancing the performance and design robustness of VAWTs suited to such conditions.

Initial focus has been directed toward improving lift and flow stability through passive geometric modifications. One study demonstrated the effectiveness of integrating an optimum trapped vortex cavity (OTVC) within a turbine blade profile, resulting in a 31.8% improvement in aerodynamic efficiency near stall conditions [4]. Using a hybrid Gaussian Process Regression (GPR) and Genetic Algorithm (GA) strategy, only 80 CFD simulations were required—reducing computational cost by 97% while maintaining a 0.5% deviation from full-model predictions. The success of this method suggests it can be repurposed in our water turbine design to mitigate performance losses at low tip-speed ratios by stabilizing boundary layer behavior in the presence of unsteady shallow flows.

Further geometric innovation was explored through the implementation of bio-inspired leading-edge tubercles, where the sinusoidal modification led to a 55% performance enhancement under off-design conditions [5]. The design, optimized using Response Surface Methodology (RSM) and Design of Experiments (DoE), promoted smoother pressure recovery and delayed flow separation. Applying similar tubercle geometry in water turbine blades is expected to improve self-start behavior and ensure stable torque generation in low-head, highly variable stream environments—particularly during the critical early phases of blade rotation.

Accurate prediction of hydrodynamic performance is essential for guiding such design innovations. The use of the Vortex Lattice Method (VLM), when compared against high-fidelity CFD tools, was shown to offer a reliable, lower-cost modeling alternative [6]. For small-scale turbines operating in dynamic water conditions, where repeated performance evaluations are required across varied configurations, this method serves as a rapid and sufficiently accurate analytical foundation. Building on this, a potential flow-based framework using VLM coupled with Polhamus suction analogy was developed for high-lift devices, yielding 80–90% accuracy at one-third of the computational cost compared to CFD [7]. This trade-off between fidelity and efficiency is mirrored in our use of QBlade's Double Multiple Stream Tube (DMST) model to simulate the water turbine's real-time performance across a range of tip-speed ratios.

The reliability of numerical models ultimately hinges on the geometric accuracy of the physical prototypes used for testing. To this end, subsonic wind tunnel experiments employing 3D-printed models demonstrated the viability of low-cost experimental validation for complex aerodynamic geometries [8]. Transferring this concept to the water turbine domain, a similar rapid prototyping approach enables pre-deployment validation of blade designs fabricated for flow channel testing. Moreover, a detailed surface deviation analysis using point cloud comparison against CAD references was employed to quantify the manufacturing accuracy of wings fabricated through casting techniques [11]. Such methods are directly applicable to water turbine fabrication quality assurance, helping to correlate geometric fidelity with observed performance during experimental trials.

Parallel to geometric and modeling improvements, artificial intelligence (AI) and machine learning (ML) are increasingly being used to augment and accelerate flow simulation and design optimization. An AI-augmented framework incorporating Physics-Informed Neural Networks (PINNs) was proposed to accelerate high-fidelity CFD simulations, resulting in a 70% reduction in computational time while maintaining precision [9]. Applying this to water turbine modeling, PINNs could replace conventional Navier–Stokes solvers for faster parametric sweeps across different stream velocities or blade geometries. A complementary study introduced a generative AI-based aerodynamic shape optimization framework using GANs and variational autoencoders (VAEs), capable of automatically generating and refining shape profiles that outperformed adjoint-based solvers in both accuracy and efficiency [10]. In our case, such AI-driven tools can be employed to generate optimized CAD geometries of turbine blades, which can then be validated within the QBlade environment or through experimental trials.

Beyond generative design, direct performance optimization was achieved using adjoint-based shape optimization frameworks. Employing both Hicks-Henne and Free-Form Deformation (FFD) techniques, the study reported a 67% drag reduction and a threefold increase in aerodynamic efficiency [12]. These multi-parameterization methods, when applied to turbine blades, offer precision control over profile shaping—particularly beneficial in scenarios where blade-solidity tuning and angle-of-attack control can influence torque smoothness and power capture in varying flow regimes.

Design and operation of wind turbines have been transformed by the introduction of AI,which has increased their effectiveness, resilience, and viability. As per a recent study [13], predictive maintenance based on AI can decrease the time for troubleshooting manifold. AI enhances the design of wind farms, control of wake, and load balance to enhance the efficiency of wind electricity generation. Similar, techniques can be employed in design of vertical-axis water turbine effectively.

Taken collectively, these studies offer a rich methodological toolkit for addressing the unique design and performance challenges associated with vertical axis water turbines in shallow flow environments. By integrating bio-inspired design, lightweight modeling, high-fidelity simulations, AI-based optimization, and experimental validation, the current work builds a robust foundation for the development of an efficient, site-adaptable Darrieus-type water turbine. The approaches reviewed here not only inform the modeling and design steps of our turbine system but also point to future enhancements in control strategies and adaptive geometry via AI-augmented real-time optimization.

III. ANALYTICAL MODEL

Performance prediction for lift-based vertical axis water turbines (VAWTs) involves several theoretical and semi-empirical models developed to capture flow characteristics and estimate turbine output. Prominent among these are the Momentum Models, Cascade Models, Vortex Models, and the widely adopted Double Multiple Stream Tube (DMST) Model.

The DMST model, originally introduced by Ion Paraschivoiu, offers an effective way to simulate the turbine's interaction with upstream and downstream flows. Each turbine blade intersects the stream tube twice per rotation—once in the upwind and once in the downwind section. The model accounts for induced velocity variations and wake effects, providing improved accuracy in correlating computational and experimental results. Momentum conservation and lift-based force analysis are applied at each azimuthal position, with the induced velocity upstream calculated using actuator disk theory as:

$V=2V_a-V_\infty$

Where V is the velocity at the rotor plane, V_a is the average induced velocity and V_∞ is the free-stream velocity.

For the current study, the QBlade software was selected to carry out hydrodynamic performance analysis using the DMST model. QBlade supports user-defined rotor geometry and polar data (imported or generated via XFOIL), enabling performance computation across a range of tip-speed ratios (TSRs) and flow conditions. The software allows rapid iteration and graphical visualization of blade loading, torque, and power coefficients. Key features include:

- Integration with XFOIL for polar extrapolation
- Full definition of turbine and rotor control settings
- Streamlined DMST-based analysis over varying flow velocities.

This modeling framework laid the groundwork for the turbine design presented in this research, ensuring a computationally efficient yet accurate approach to performance estimation prior to physical testing.

IV. HYDRODYNAMIC ANALYSIS

The performance of a Vertical Axis Water Turbine (VAWT) is fundamentally governed by the flow dynamics around its blades and the configuration of key design parameters. The turbine extracts power from the kinetic energy of the flowing water, which is expressed as:

$$\mathbf{P = \tfrac{1}{2} \times \rho \times A \times V^3 \times C_p}$$

Where:

- **P** is the power extracted
- **ρ** is the density of water (kg/m³)
- **A** is the swept area of the turbine (m²)
- **V** is the free-stream velocity (m/s)
- $\mathbf{C_p}$ is the power coefficient, a measure of turbine efficiency

For Darrieus-type VAWTs, the swept area **A** is determined by:

$$\mathbf{A = 2 \times R \times H}$$

Where:

- **R** is the rotor radius (m)
- **H** is the blade height (m)

These turbines experience complex unsteady flow due to the blade's cyclic interaction with its own wake. At every azimuthal angle, the blade encounters a varying relative velocity vector, which can be described using velocity triangles. The relative velocity(V_r) experienced by the blade, considering free-stream velocity V_0 and tangential velocity $V\theta = \omega \times R$, is calculated as:

$$V_r = \sqrt{[(V_0 + V\theta \times \cos\theta)^2 + (V\theta \times \sin\theta)^2]}$$

Where:

- V_0 is the free-stream velocity
- $V\theta$ is the tangential velocity
- θ is the azimuthal angle

The **tip speed ratio** (TSR), denoted as **λ**, is a key parameter for efficiency and is defined as:

$$\mathbf{\lambda = (R \times \Omega) / V}$$

Where:

- **Ω** is the angular velocity (rad/s)
- **R** is rotor radius
- **V** is water velocity

The effective angle of attack, torque, and thus the power coefficient (C_p), vary with both azimuthal angle and tip speed ratio.

V. DESIGN PARAMETERS

Several geometrical and operational parameters define the hydrodynamic behavior and performance output of the turbine:

- Swept Area (A): The fluid area enclosed by the rotating blades. For straight-bladed VAWTs, it has a rectangular profile, calculated as:
  $\mathbf{A = 2 \times R \times L}$
  Where **L** is blade length (m).
- Power Coefficient (C_p)**:** This is the ratio of actual power extracted by the turbine to the total available kinetic power in the flow. It indicates the efficiency of energy capture.
- Tip Speed Ratio (λ)**:** The ratio of blade tip speed to free-stream flow speed. Optimal λ is essential for maximum energy conversion:
  $\mathbf{\lambda = (R \times \Omega) / V}$
- Blade Chord: The straight-line distance between the leading and trailing edges of a blade. Airfoil profiles like NACA are selected for defined aerodynamic performance based on thickness and shape.
- Number of Blades: Affects torque ripple and structural stability. For this study, 3, 4, and 5 blade configurations were considered, though wake

interference effects were excluded in performance calculation.

- Solidity (σ)**:** Solidity is a non-dimensional parameter reflecting the ratio of blade area to the turbine's swept area. For straight-bladed VAWTs:

  σ = (N × c) / (2π × R)

  Where:
  - **N** is the number of blades
  - **c** is the blade chord
  - **R** is the rotor radius
- Initial Angle of Attack**:** The preset angle between the blade chord line and its motion path. Affects startup behavior and flow alignment. Typically selected based on experimental tuning or CFD optimization.

This analytical and parametric formulation provided the foundation for the simulation studies performed using QBlade and informed the physical design of the turbine prototype tested in flowing water conditions.

VI. CALCULATION OF DESIGN VARIABLES

Darrieus turbines of low velocity for river packages is designed by means of Q Blade. Wind power institution of Berlin Technical University which is branch of Experimental Fluid Mechanics department developed Q Blade software under the supervision of Prof. Dr. Christian Oliver Paschereit. This software calculates the performance parameters of turbine which is built in airfoil design and analysis application. Both Horizontal and vertical axis turbines can be designed by QBlade software. Two sub –modules are functioned by QBlade. HAWT design is one of them which is entirely based on Blade Element Model. VAWT design is the other one primarily dependent upon Double Multiple Stream tube Model which was introduced by ION Paraschivoiu [14]. Airfoils can be designed in XFoil without any difficulty besides computing and integrating polar facts and extrapolating them to the range of 360º. Feature of design process have been enlisted down.

- Airfoil designing by using XFOIL.
- Computing and extrapolating polar data to 360º angle of attack.
- Turbine rotor configurations using created airfoil.
- Performance calculation of turbine for tip speed ratios based upon extrapolated statistics.

Swept Area is a part of fluid that encircles the mechanism during its rotation. Rotor configuration of turbine determines the shape of swept area. Therefore, swept area of vertical axis turbine having straight blades looks rectangular while that of horizontal axis rotor is like circular [15].

S=2RL

S represents swept area [m2], rotor radius by R [m] and L shows blade length [m].Swept area was calculated according to power required. 300 watts of power was assumed to be enough for the experimental purpose. So, 300w was inserted in the following relation with

1000 kg/m^3 water density and 1.5 m/s of assumed water velocity. Calculations were carried out by assuming turbine as 30% efficient.

P=0.5ρv3A 300w=0.5*1000*1.53*0.3*A

A=0.625$m2$

Hence, swept area came out to be as .625 m^2

Commonly used airfoils in Darrieus rotors are chosen for analysis for selection of optimum airfoil for turbine blades. Three different airfoils NACA 0018, NACA 0020 and NACA 0021 were opted for comparison. During the performance analysis solidity ratio was assumed to be 1 for being typical value for VAWT. One out of three airfoils were selected based upon the following analysis. NACA 0021 airfoil was selected for turbine blades since it provides overall maximum power coefficient[16]. For the selection of suitable solidity ratio for airfoil selected for further analysis, further analysis was done at three different solidity ratios by inserting their corresponding chord lengths in the analysis.Results show that maximum power coefficient is achieved at C=.125 which corresponds to solidity ratio 1. So, solidity ratio 1 has been selected[17]. The selection of no of blades is based on the maximum power coefficient achieved. Different configurations selected for evaluation are 3, 4, 5 and 6 blade configurations. The performance analysis of these four configurations is carried out & maximum Cp is achieved at 6 blade configurations but 5 blade configuration is selected to reduce weight of turbine[18].

VII. PERFORMANCE ANALYSIS

Different performance parameters for the final design were obtained by using QBlade software. Following figure shows the deviation of the coefficient of power with the Tip Speed Ratio.

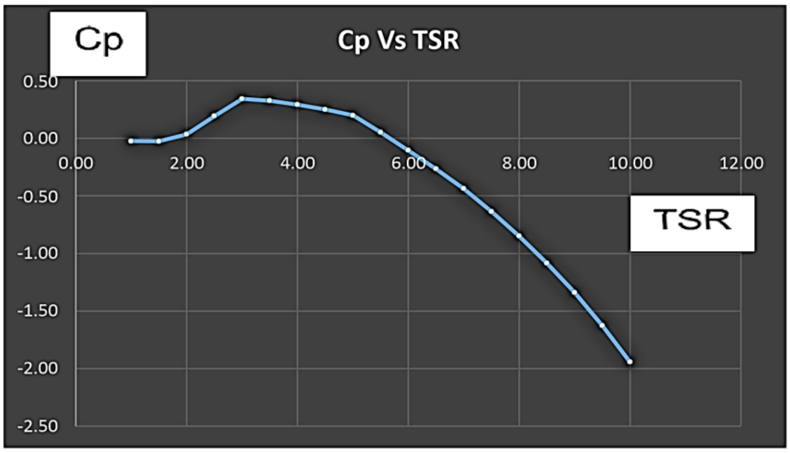

Figure 1: Cp Vs TSR

Cp max is .4 at TSR of 3 which means that the designed model is efficient up to 40% according to analytical results.Rottor Torque Vs Azimuthal Location is shown by each curve in graph in figure 2 below:

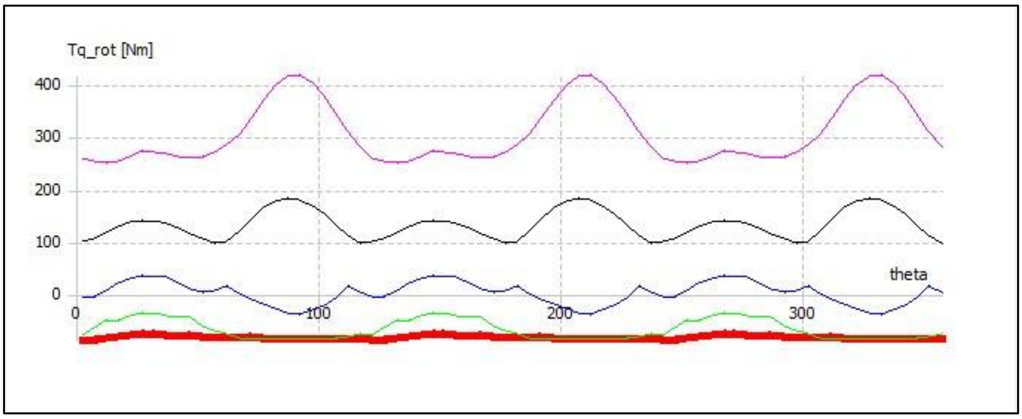

Figure 2: Rotor Torque Vs Azimuthal Position

Whereas, Power Vs TSR is shown in figure 3 which depicts the expected power which can be obtained out of turbine.

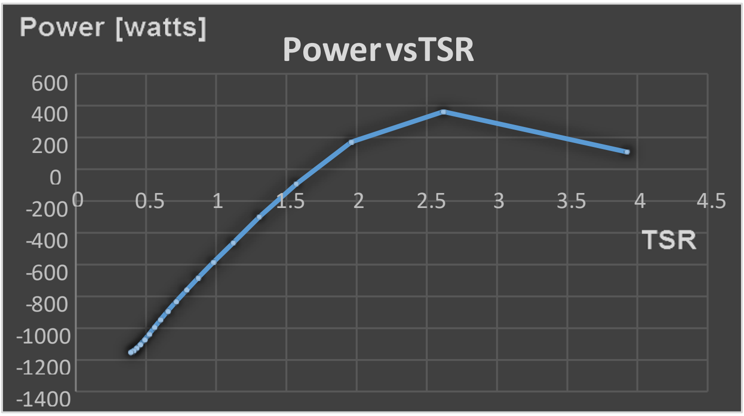

Figure 3: Power Vs TSR

Maximum power generated by the turbine is up to 400 watts according to DMS model.

VIII. CAD MODELLING

After finalizing the design variables according to requirement. CAD was drawn of the whole assembly[19]. First of all, turbine blade of NACA0021 airfoil was drawn through parametric modelling by inserting airfoil coordinates in Microsoft Excel and linking them to CATIA®. Figure below shows turbine blade.

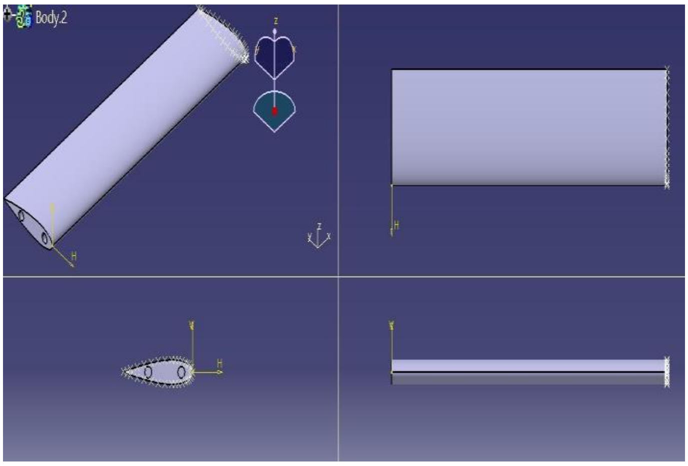

Figure 4: NACA0021 Airfoil Blades

CAD of rotor was prepared separately which is attached to central rotating shaft with the help of supports. Circular plates have also been drawn on the top of blades which are used to avoid vortex shedding in physical model.

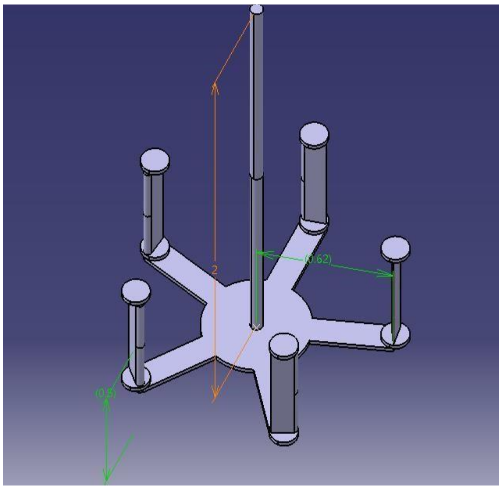

Figure 5: CAD of Rotor

Turbine was designed so that it holds its balance in the flow[20]. It may not be flowing away with in actual testing. Keeping in mind this point, a stand to support the turbine was designed. CAD of stand with exact dimensions is depicted in figure below:-

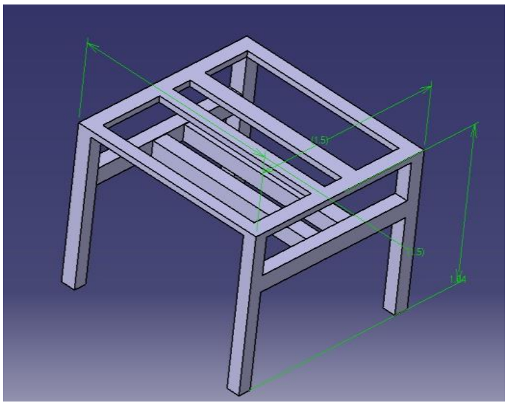

Figure 6: Turbine Stand

After drawing all parts of turbine, they were assembled in Assembly Design feature.Complete assembled turbine is shown below.

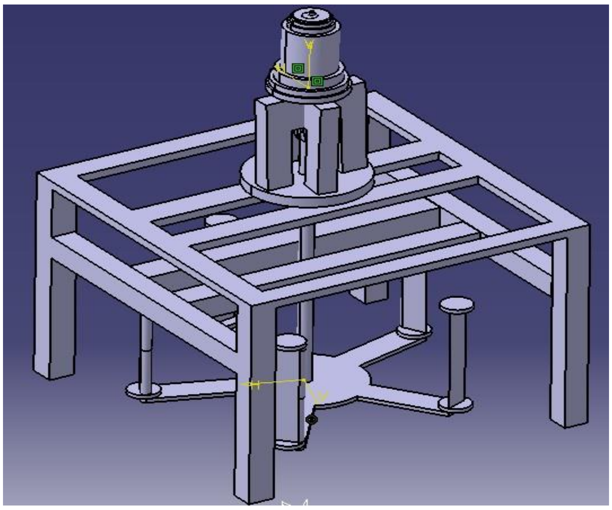

Figure 7: CAD of complete assembled Vertical Axis Water Turbine

IX. FABRICATION OF VERTICAL AXIS WATER TURBINE

Finally obtained design of the VAWT rotor was fabricated for the experimental validation of the process followed. Multiple materials were used for the fabrication of the various parts, following is list of the materials used for the fabrication

- Mild Steel
- Angle Iron
- Stainless Steel
- Poly urethane
- Polystyrene
- Bearings
- Aluminium
- Nut Bolts

The following figure shows the VAWT rotor blade of NACA 0021 made from the polyurethane with the coating of polystyrene. Total five blades were fabricated each having height of .5m.

Figure 8: Rotor Blades of Vertical Axis Water Turbine after Fabrication

Following figure will show the bolts inserted in the blade to join it with the rotor supports. Four bolts were inserted in each blade, two on either side. The bolts on the side facing support have diameter of 3/8 inch and length of 8 inch, whereas bolts on the side facing upward have diameter of 1/8 inch and length of 4 inch.

Figure 9: Bolts Inserted in Blades

Aluminum supports of 25-inch length, 5-inch width and .5 inches of thickness originating from centre of the rotor to which turbine blades would be joined were used. Two bearings have been used in the rotor assembly for smooth working of shaft and to avoid turbulence. They have inner diameter of 2 inches and outer of 4.5 inches. Aluminium circular plates of 5-inch diameter were mounted on top of each blade in order to avoid vortex shedding[21].

After getting every part fabricated in the workshop, all were assembled to give model a final shape. Final assembled model prepared for testing is shown in the following figure 10.

Figure 10: Final Assembled Turbine

X. TESTING

The turbine was designed for water channels that have significant velocities but don't have prominent depth. For the designed actual testing was carried out in such a water channel as shown in figure below:-

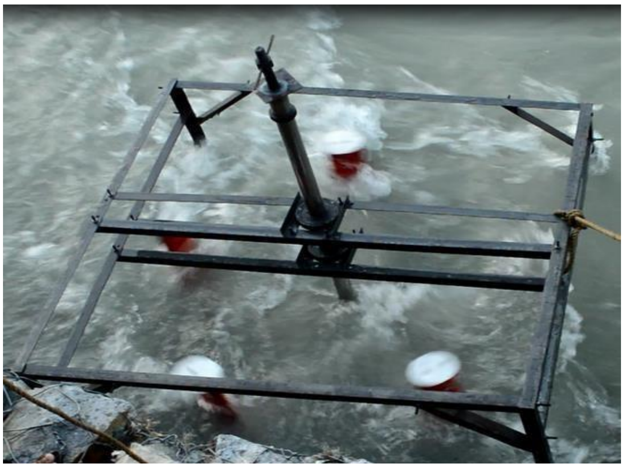

Figure 11: Testing of VAWT in shallow water channel

XI. EXPERIMENTAL RESULTS

First of all, water velocity was calculated by throwing a floating body in water and noting the time it took to cover 10m distance. So, the velocity was calculated from the relation.

S=Vt 10m=V(6sec) V=1.67m/s

Where "s" is the distance in meters, "V" is the velocity of water and "t" is time taken.

Then most important performance parameter i.e. RPM was calculated. As turbine started rotation, its rounds were counted for one minute which came out to be as following:-

Table 1: Calculation of RPM

No of Rotations in 5 Minutes	**220**
Rotations Per Minutes (RPM)	44
Radian Per Second	4.6

For the torque calculations, spring balance was attached to the rotorin order to calculate force applied to stop the rotation. Force was multiplied with moment arm to measure torque produced by the turbine.

Table 2: Calculation of Torque

Torque	T=F.d
Spring Balance Reading	3.5kg
Force	F=ma
F(Force applied to stop rotation)	(3.5kg)(9.8ms^{-2})=34N
D	Perpendicular distance=.625m
T	(34)(.625m)=21.5N.m

Power calculations for the turbine are shown in the table 3 below:-

Table 3: Calculation of Power

Power (Generated)	**Tw**
RPM	44
w (Angular Velocity)	RPM ∗ 2¶/60 = 44∗6.28/60 =4.6rad/s
P	(21.5N.m)(4.6rad/s)=100W

XII. COMPARISON OF ANALYTICAL AND EXPERIMENTAL VALUES

Comparison is presented in the table 4 below:-

Table 4: Calculation of Power

Parametres	Analytical Results	Experimental Results
Flow Velocity	1.5 m/s	1.67 m/s
RPM	66	44
Torque	28 N.m	21.5 N.m
Power	140 Watts	100 tts

XIII. CONCLUSION

Despite of the simplicity of the design in vertical axis water turbines, their performance analysis is a challenging task. Historical trends show that lift based VAWTs lack the self- start capability but this drawback was not found during experimental testing. VAWT is a better choice in comparison to the HAWTs when efficiency is not a prime concern, because it requires less space as compared to HAWT. Moreover, the diameter for the same power output is less for VAWT.

XIV. RECOMMENDATIONS

Venture at the inlet of the turbine may be installed in order to boost flow velocity for better results & effect of the variable pitch may be studied on the efficiency of the turbine performance.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

REFERENCES

[1] Planetforlife.com, *World Energy Crisis*, 2015. Available from: http://planetforlife.com

[2] S. Kuchibhatla, *United Nation Energy Program - Study Guide*, 1st ed., 2014. https://doi.org/10.1146/annurev-matsci-070813-113627

[3] G. Tverberg and V., *Don't count on natural gas to solve US energy problems*, Our Finite World, 2011. Available from: https://tinyurl.com/2r98x9yk

[4] D. Paraschivoiu, *Windturbine Design*, Montréal: Polytechnic International Press, 2002. Offshore Wind, *Workshop on New Wind Farm Software to Be Held in Den Helder*, 2014. Available from: https://tinyurl.com/2kd35ep3

[5] M. T. Javaid et al., "Power enhancement of vertical axis wind turbine using optimum trapped vortex cavity," *Energy*, vol. 278, p. 127808, 2023. Available from: https://doi.org/10.1016/j.energy.2023.127808

[6] S. S. ul Hassan et al., "Systematic investigation of power enhancement of Vertical Axis Wind Turbines using bio-inspired leading-edge tubercles," *Energy*, vol. 270, p. 126978, 2023. Available from: https://doi.org/10.1016/j.energy.2023.126978

[7] S. Nasir et al., "Applicability of Vortex Lattice Method and its Comparison with High Fidelity Tools," *Pakistan Journal of Engineering and Technology*, vol. 4, no. 1, pp. 207–211, 2021. Available from: https://doi.org/10.51846/vol4iss1pp207-211

[8] M. U. Shahid et al., "Development and Fidelity Assessment of Potential Flow based Framework for Aerodynamic Modeling of High Lift Devices," *Pakistan Journal of Engineering and Technology*, vol. 5, no. 2, pp. 104–111, 2022. Available from: https://doi.org/10.51846/vol5iss2pp104-111

[9] Raza et al., "Applicability of 3D printed fighter aircraft model for subsonic wind tunnel," in *Proc. 2021 Int. Bhurban Conf. Applied Sciences and Technologies (IBCAST)*, 2021, pp. 730–735. Available from: https://ieeexplore.ieee.org/abstract/document/9393214

[10] S. Sahibzada, F. S. Malik, S. Nasir, and S. K. Lodhi, "AI-Augmented Turbulence and Aerodynamic Modelling: Accelerating High-Fidelity CFD Simulations with Physics-informed Neural Networks," *Int. J. Innovative Res. Computer Science and Technology*, vol. 13, no. 1, pp. 91–97, 2025. Available from: https://tinyurl.com/4fhhhpht

[11] S. Sahibzada, F. S. Malik, S. Nasir, and S. K. Lodhi, "Generative AI Driven Aerodynamic Shape Optimization: A Neural Network-Based Framework for Enhancing Performance and Efficiency," *Int. J. Innovative Res. Computer Science and Technology*, vol. 13, no. 1, pp. 98–105, 2025. Available from: https://tinyurl.com/3v4cv2xj

[12] M. Ahmad et al., "Experimental Investigation of Wing Accuracy Quantification using Point Cloud and Surface Deviation," *Pakistan Journal of Engineering and Technology*, vol. 4, no. 2, pp. 13–20, 2021. Available from: https://doi.org/10.51846/vol4iss2pp13-20

[13] S. Nasir, S. Sahibzada, and F. S. Malik, "Adjoint-Based Optimization for Enhanced Aerodynamic Performance Using Multi-Parameterization Techniques," *Int. J. Innovative Res. Computer Science and Technology*, vol. 13, no. 2, 2025. Available from: https://tinyurl.com/jantwtxn

[14] *Artificial-Intelligence Aerodynamics for Efficient Energy Systems: The Focus on Wind Turbines*, *BULLET: Jurnal Multidisiplin Ilmu*, vol. 3, no. 5, pp. 648–659. Available from: https://tinyurl.com/45u7m3xu

[15] M. M. A. Bhutta et al., "Vertical axis wind turbine–A review of various configurations and design techniques," *Renewable and Sustainable Energy Reviews*, vol. 16, pp. 1926–1939, 2012. Available from: https://doi.org/10.1016/j.rser.2011.12.004

[16] Fieldlines.com, *Three Blade Darrieus*, 2015. Available from: http://www.fieldlines.com/index.php?topic=127798.0

[17] H. Raza, *Hydrodynamic design and optimization of vertical axis cycloidal water turbine for shallow and high velocity water turbines*, Institute of Aeronautics and Astronautics, Air University, Islamabad, 2015. Available from: https://tinyurl.com/4uywnfkj

[18] D. P. Raymer, *Aircraft Design: A Conceptual Approach*, American Institute of Aeronautics and Astronautics, Reston, VA, 1999. Available from: https://doi.org/10.2514/4.869112

[19] D. Martin, *Qblade Short Manual*, TU Berlin, Berlin, 2012. Available from: https://doi.org/10.1016/j.jweia.2013.09.008

[20] M. A. Kamoji, S. B. Kedare, and S. V. Prabhu, "Experimental investigations on single stage, two stage and three stage conventional Savonius rotor," *Int. J. Energy Res.*, vol. 32, no. 10, pp. 877–895, 2008. Available from: https://doi.org/10.1002/er.1399

[21] B. D. Altan, M. Atılgan, and A. Özdamar, "An experimental study on improvement of a Savonius rotor performance with curtaining," *Experimental Thermal and Fluid Science*, vol. 32, pp. 1673–1678, 2008. Available from: https://doi.org/10.1016/j.expthermflusci.2008.06.006

[22] G. Bianchini, G. Ferrara, and L. Ferrari, "Design guidelines for H-Darrieus wind turbines: Optimization of the annual energy yield," *Energy Conversion and Management*, vol. 89, pp. 690–707, 2015. Available from: https://doi.org/10.1016/j.enconman.2014.10.038

[23] R. Dominy, P. Lunt, A. Bickerdyke, and J. Dominy, "Self-starting capability of a Darrieus turbine," *Proc. Inst. Mech. Eng. A: Journal of Power and Energy*, vol. 221, pp. 111–120, 2007. Available from: https://doi.org/10.1243/09576509JPE340