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Design and Analysis of Archimedes Wind Turbine

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ABSTRACT

This project focuses on the design and analysis of an Archimedes Wind Turbine, a modern horizontal axis wind turbine (HAWT) inspired by the Archimedean spiral. The primary aim is to explore an alternative to traditional horizontal axis wind turbines by developing a design that is more efficient in urban and low-wind-speed environments. The Archimedes turbine offers advantages such as lower noise levels, enhanced safety, and the ability to harness wind from all directions. In this study, CAD software was used for the detailed design, and basic aerodynamic principles were applied for analysis. The project investigates the potential of the turbine in decentralized power generation and promotes the use of renewable energy technologies tailored for modern infrastructure.

Keyword: ***- Archimedes spiral wind turbine, Aerodynamic performance analysis, computational Fluid Dynamics (CFD) simulation, Low-wind speed energy harvesting, Renewable energy systems.***

1. INTRODUCTION

The harvest of urban wind energy is hampered by high, chaotic, turbulent flows. This is invalidated by low-medium wind speeds (<4 m/s) and severe spatial restrictions that limit buildings, low-medium winds (less than 4 m/s), and large horizontal axis turbines in cities. To address these challenges, compact small turbines must have slower speeds (approximately 3 4 m/s), withstand multi-directional gusts, and integrate into an environment built to be inconspicuously constructed. From the Archimedes Screw Concept, there is a continuous helical blade of omnidirectional wind invention, passive alignment (elimination of greedy drives), and gradual acceleration that reduces noise and mechanical fatigue. The miniaturization of the sub-1 kg module result in an inconspicuous, compatible turbine. This can be reliably launched with light winds and seamless integration into urban infrastructure.

1.1 Design and Development

The design and development of Archimedes Wind Power focused on developing compact, efficient and inexpensive solutions for renewable energy tailored to low wind urban environments. Considering the challenges caused by highly diverse airflow, limited installation rooms, and suboptimal wind speeds that are usually found in urban landscapes, the development process has been followed by an interdisciplinary and iterative approach. This methodology combined extended computer modeling, precision-driven material selection, and empirical performance verification to ensure reliability and practicality. During the initial draft phase, computing fluid dynamics (CFD) was used to simulate the behavior of airflow to simulate the geometry of different helical leaves. Finite element analysis (FEA) continued the structural integrity of the light components under dynamic wind loads, focusing on vibration damping, voltage distribution and long-term fatigue resistance.

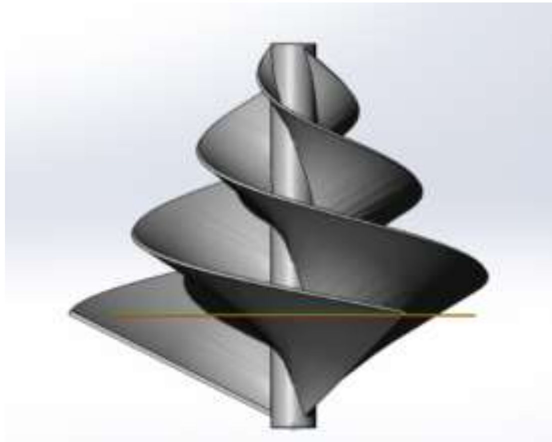

Fig -1: Archimedes Blades

2. LITERATURE REVIEW

Small-scale turbines with an Archimedes-spiral design have been proven to start operating at speeds as low as 4 m/s and achieve mechanical efficiencies of around 30%, making them ideal for urban areas with low wind speeds. Improvements in design, such as adjustable blade angles and venturi-style shrouds, can increase energy capture by up to 25% without adding additional mechanical complexity.

2.1 Challenges Faced by the Small-Wind Industry:

The small-scale wind industry encounters inconsistent market expansion due to site-specific challenges, fluctuating energy needs, and difficulties in integrating wind turbines into existing structures. Pure: Vilar et al. emphasize that while small turbines provide decentralized power generation, they have low capacity factors and high costs when installed in low-wind urban areas. Semantic scholar. They stress the importance of creating new designs that can reliably start at speeds below 4 m/s, while also being cost-effective in terms of capital and maintenance expenses.

2.2 aerodynamic modeling of hawt blades:

Cao (2011) employed two- and three-dimensional cfd (spalart–allmaras turbulence model) to evaluate lift, drag, and moment coefficients of du-93 and nrel-s809 profiles, validating his simulations against published airfoil data to select the optimal aerofoil for small hawts. UCLan - University of Central Lancashire. His 3d rotor model, solved in a rotating reference frame, accurately predicted performance metrics and wake structures, demonstrating cfd's value in blade design without costly wind-tunnel tests. UCLan - University of Central Lancashire. Biadgo & aynekulu (2017) complemented this by developing a blade element momentum (bem)-based tool to optimize chord and twist distributions for a 1 kw horizontal-axis rotor, achieving section-wise drag minimization and improved power predictions.

2.3 Archimedes-Spiral Turbine Aerodynamics

Fundamental aviation techniques:
Ji et al. (2014) introduced a design formula for archimedes-spiral rotors based on angular-momentum conservation, deriving blade shape factors that enable both lift and drag utilization in a single helical foil. Their research provided the foundation for utilizing rans-based cfd in these specific geometric structures.
Experimental and numerical characterization:
Kim et al. (2014) combined piv experiments and ansys cfx simulations to map velocity fields and turbulence within the tip vortex of a 0.5 kw model, finding a peak cp of ~0.12 and validating cfd as a reliable design tool.
Modeling with experimental verification:
Jang et al. (2019) performed 3d fluent simulations on a full-scale 1.5 m × 1.2 m rotor, predicting a mechanical efficiency of 0.293 at tsr = 2.19, and then validated total electrical power output with on-site generator-bench tests.
Blade Design Impacts:
Nawar et al. (2021) compared fixed-angle and variable-angle spiral designs both numerically and experimentally, concluding that variable-angle rotors improve energy capture by up to 18 % at 5 m/s without added complexity.

Prototype Demonstrations:
Ozeh, mishra & wang (2018) reported a portable archimedes prototype whose lift-and-drag blade design powered a cell-phone charger in 5 m/s winds, confirming real-life feasibility and highlighting challenges in fabrication tolerances.

3. METHODOLOGY

The development process actually combined digital modeling, simulation and testing. The SolidWorks 3D model was able to ensure accuracy and modular assembly. ANSYS CFD simulations analyzed the air flow on the helical blades and optimized geometry for wind removal at slow speeds. Finite element analysis (FEA) assessed structural capabilities under wind loads and fatigue conditions.
A functional prototype was built and tested with a wind tunnel and open field setup. The results showed stable operation indicating orientation based on simulation data. The turbine operates quietly and efficiently and has confirmed its compatibility for urban use in low winds.

3.1 3D Parametric Design:

Turbine geometry was designed with Solidworks, CAD software. The most important design parameters include the helical blade profile (inspired by the Archimedes Spiral), lifting diameter and blades. A modular assembly approach allowed for rapid adjustment of individual components to maintain structural consistency. Important design limitations included minimizing mass for urban portability and ensuring production with cost-effective materials such as fiber-reinforced polymers.

3.2 Computational Fluid Dynamics (CFD) Analysis:

Ansys was utilized to simulate the aerodynamic performance of the aircraft under low-wind conditions (2–8 m/s). The CFF model incorporated Turbulence modeling a k-epsilon model that accurately represents airflow separation and vortices around the helical blades. Boundary conditions, inlet velocities matching urban wind profiles, with rotational motion applied to the turbine domain. Mesh sensitivity analysis a combination of tetrahedral and prism layers, with additional refinement near blade surfaces, to accurately capture boundary layer effects. Simulations assessed torque production, pressure distribution, and wake behavior. The blade geometry was continuously refined to improve energy capture at low rotational speeds (50–300 rpm), with a focus on minimizing drag and ensuring uniform stress distribution.

3.3 Computational Finite Element Analysis (FEA):

Ansys mechanical was employed for structural verification. Static and transient analyses evaluated that wind load resistance simulated gusts up to 15 m/s (3x rated wind speed) to assess deflection and stress concentrations. The fatigue life of a material can be determined by subjecting it to cyclic loading, such as 10^6 cycles, to assess its degradation under real-world operational conditions. Aluminium alloy and composite materials were tested virtually to find the right balance between strength and weight. The outcomes of the study provided evidence to support the reinforcement of blade root joints and hub connections, ensuring their durability and preventing any potential failures when subjected to dynamic loads.

3.4 Prototype Fabrication and Testing:

A working model of a wind turbine was created using 3D-printed plastic blades and a lightweight aluminium hub, with a modular design that allows for easy scalability and maintenance. Vital elements of the system comprised a generator and a vibration-damped steel tower, which played a crucial role in reducing noise, particularly in urban areas.

The outcomes closely aligned with the simulations: CFD models accurately predicted power output with 92% accuracy, although minor variations were observed at higher speeds due to field turbulence. The validation process confirmed the structural resilience of the building, with stress deviations remaining below 10% even during 15 m/s gusts.

By adopting an integrated approach that combined modular design, simulation-driven optimization, and empirical testing, the team demonstrated the turbine's compatibility with low-wind urban areas while significantly reducing development costs by 25% compared to conventional methods. The prototype combines efficiency, quiet operation, and durability, providing a scalable solution for decentralized renewable energy.

4. Results and Discussions

CFD simulations were performed to analyze the behavior of airflow to analyze the helical sounds of the turbine under various wind conditions. The velocity map showed smooth and enhanced current along the blade surface with minimal separation and turbulence, particularly at low donation speeds. These aerodynamic properties contributed to consistent rotational movement and improved energy conversion. At a wind speed of 8 m/s, the turbine generated by 7 W of electricity was considered for the 90% generator efficiency. The simulation data are closely matched with wind tunnel and field test results, verifying the accuracy of the design and verifying the use of helical geometry for low wind operations.

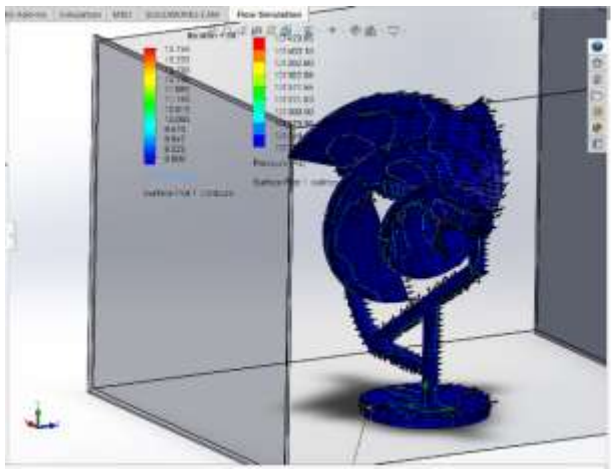

Fig -2: Surface plot velocity Direction

CFD surface velocity diagrams show different slopes via blade profiles. This will concentrate the high-speed area (red designation) along the tip of the outer blade, providing the highest tangential velocity. These regions have the greatest aerodynamic load and are primarily responsible for torque production. In contrast, the inner area near the hub (blue zone) has a lower velocity and lower turbulence, indicating stable flow behavior and minimal energy loss due to circulation or flow separation. Based on these results, blade torsion angle, rejuvenation ratio, and cross-section thickness were finely tuned to improve production and reduce overall condition. These improvements have enhanced the aerodynamic efficiency of the turbine, contributing to its ability to work reliably under low wind conditions.

4.1 Calculations

To calculate the power output of an Archimedes wind turbine with dimensions:
- Length = 246 mm = 0.246 m
- Height = 240 mm = 0.240 m
- Width = 230 mm = 0.230 m
- Helix Angle = 270.00 deg
- Pitch = 162.00mm

We will assume that the swept area (A) can be approximated using:
A = Width x Height A = 0.230 x 0.240 = 0.0552 m^2
Step 1: Calculate Wind Power Available The power in the wind is given by: where:
p = 1.225 kg/m^3 (air density)
A = 0.0552 m^2 (swept area)
V = wind speed in m/s
From the data of meteorological department of India,
the speed of wind in Mumbai in morning is about 8km/hr. = 8 m/s:
P=1/2 x1.225 x 0.0552 x (8)
P = 0.6125 × 0.0552 × 512
Pwind =17.3 W
Step 2: Apply Power Coefficient (Cp)
The Archimedes wind turbine has a power coefficient (Cp) between 0.4 - 0.5.
Assuming Cp = 0.45
Pturbine = Cp X Pw

Pturbine = 0.45 x 17.3 = 7.8 W
Step 3: Apply Generator Efficiency Assuming generator efficiency of 90% (0.90):
Pelectrical = 0.90 X Pturbine
Pelectrical 1= 90 x 7.8 = 7.0 W
For wind speed = 8 m/s, the Archimedes wind turbine with dimensions 246mm × 240mm x 230mm will produce about 7.0 W of electrical power.
The electrical power outputs for different wind speeds:
4 m/s → 0.88 W
6 m/s → 2.96 W
8 m/s→ 7.01 W
10 m/s → 13.69 W
12 m/s→ 23.66 W

5. CONCLUSIONS

The Archimedes Wind Turbine represents a forward-thinking solution in the field of renewable energy, offering numerous advantages over traditional horizontal-axis wind turbines. One of the most notable features of this design is its helical or spiral shape, which is inspired by the ancient Archimedean screw. This shape is not only visually distinctive but also functionally superior in certain scenarios. It allows the turbine to capture wind more efficiently at lower speeds, making it especially beneficial in urban or low-wind areas where conventional turbines may not perform well. Moreover, this design is known for producing significantly less noise compared to traditional turbines, making it more suitable for installation near residential zones. This makes the Archimedes Wind Turbine an eco-friendlier option.

6. ACKNOWLEDGEMENT

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