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Design and Analysis of Vertical Axis Windmill Blades

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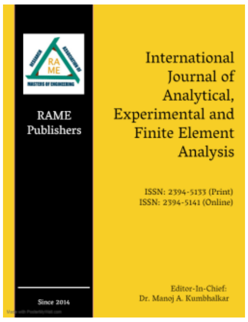

Abstract: As an alternative to traditional horizontal axis windmill turbines vertical axis windmill turbines ($VAWT_s$) have gained attention due to their unique design and advantages in certain applications. One of the very important components of $VAWT_s$ is blade design which significantly influences the turbine's efficiency, reliability and performance. This abstract focuses on the advancements and considerations in designing vertical axis windmill blades. These abstract reviews the fundamental principles of aerodynamics governing VAWT blade design and highlights key design parameters such as chord length, twist angle and blade shape. In conclusion, the designs of vertical axis windmill blades in a complex and multidisciplinary field that requires a holistic integrating aerodynamics, material science and mechanical engineering.

Keywords: VAWT, Renewable Energy, Analysis, Improved Efficiency, Vertical Axis Windmill Blades

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1. Introduction

The wind is a free energy resource, until governments put a tax on it, but the wind is also a very unpredictable and an unreliable source of energy as it is constantly changing in both strength and direction [5-6]. So, to ensure we get the most out of the available wind energy, it is important that the wind turbine blade design is of an optimal performance [7-8]. To produce useful amounts of power, wind turbines generally need to be large and tall, but to work efficiently they also need to be well designed and engineered which makes them expensive too [9-10]. Most wind turbines designed for the production of electricity have consisted of a two or three bladed propeller rotating around a horizontal axis [11-12]. It's obvious to say that these propeller-like wind turbine blade designs convert the energy of the wind into usable shaft power called torque. This is achieved by extracting the energy from the wind by slowing it down or decelerating the wind as it passes over the blades [13]. A study by Rohit Lakshmanan (2022) which is about Environmental impact of additive manufacturing on the renewable energy industry in which author talks about additive manufacturing play important role in reducing waste by efficient resource consumption and reduce manufacturing waste [1]. The renewable energy industry has challenges such as energy security, environmental impacts, and reliability of system. A paper by Nikhil Karwa, and Shivprakash B. Barve (2021) says that savonius wind turbine is a good alternative which can be used to power household as it functions in varying wind speed and is omnidirectional [2]. Wind turbine modeled in solid works and analyzed in ansys and solid works. Rahul Vaidhye, Prof Ritesh Banapurkar, Pravin Vasram Jadhav (2013) the paper summarised about design and analysis of jet wind turbine with help of catia for design and analysis purpose [3]. The article is motivated by key role of blades in performance of jet wind turbine. Sumedha Singh Rathore, Rushabh Dalmia, Karan Tamakuwala, Sreekanth Manavalla (2016) says that low cost material and easily available material confirming to standards were used to keep the overall cost minimal [4]. The purpose of wind mill is to meet power requirements during natural disaster like earthquake, cyclone, and flood when power supply from grid is interrupted.

The depletion of fossil fuels and their significant contribution to pollution emphasize the need to shift toward cleaner, renewable energy sources. Wind energy, being a renewable resource, offers a more efficient means of power generation compared to other renewables, yet it still falls short in efficiency when compared to non-renewable sources. This project focuses on improving the efficiency of vertical axis windmills by exploring different blade designs, particularly examining various angles and materials to enhance performance. The primary aim is to increase the efficiency of the windmill to generate more power. The objective is to maximize the Annual Energy Production (AEP) of the turbine by optimizing its design to operate effectively under the specific wind speed probability distribution of its location.

2. Design of windmill blade

The table below outlines the key dimensions of the windmill's shaft and blades. The shaft includes both hollow and solid sections, with varying heights and diameters to suit the structural design requirements. The blades, designed for optimal aerodynamic performance, have specific height, outer diameter, and curve radius measurements to enhance efficiency in capturing wind energy.

Table 1. Critical dimensions for the components of the windmill design.

Component	**Specification**	**Dimension**
Shaft	Hollow Shaft Height	900 mm
	Hollow Shaft Outer Diameter	54 mm
	Hollow Shaft Inner Diameter	47 mm
	Solid Shaft Height	350 mm
	Solid Shaft Outer Diameter	47 mm
	Solid Shaft Inner Diameter	25 mm
Blades	Blade Height	800 mm
	Blade Outer Diameter	400 mm
	Blade Curve Radius	130 mm

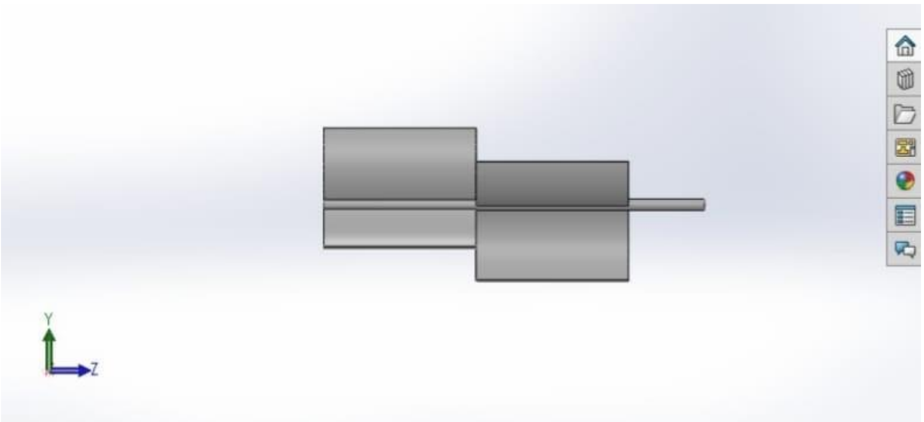

Figure 1. 3D Model

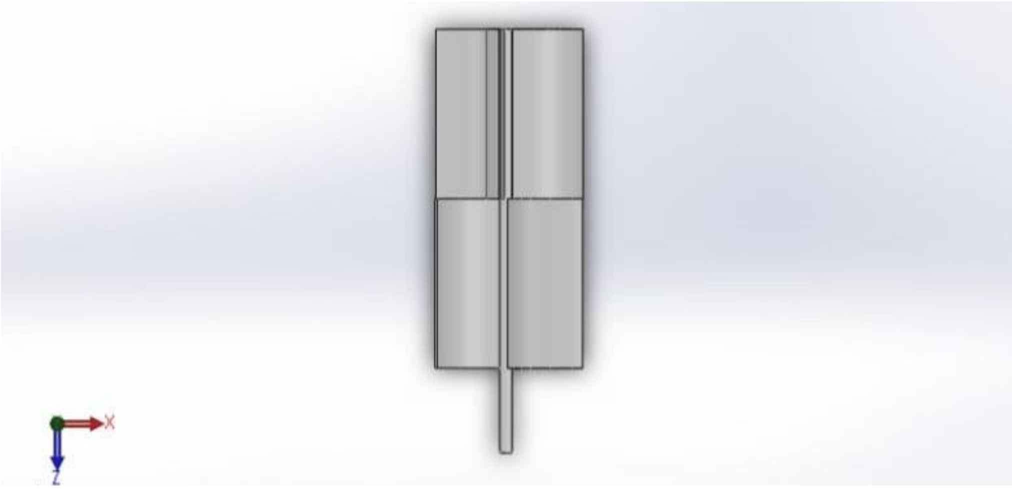

Figure 2. 3D Model of Windmill Blades

Figure 3. Blade Design

3. Mass properties of materials

The table below summarizes the mass properties of the aluminum material used in the windmill design. These properties include the density, mass, volume, surface area, and the moments of inertia, both at the center of mass and aligned with the output coordinate system. The principal axes of inertia and moments of inertia are also provided to describe how the material resists rotational forces. This table highlights the aluminum's significant mass properties, which play a crucial role in optimizing the structural and rotational performance of the windmill.

Table 2. Material properties of Aluminium of the manufacturing of windmill

Property	**Value**
Material	Aluminium
Density	0.000 grams/mm³
Mass	7606.37 grams
Volume	2,817,173.12 mm³
Surface Area	152,078.86 mm²
Center of Mass (mm)	X = 0.00, Y = 0.00, Z = -384.41
Principal Axes of Inertia	
Ix = (0.00, 0.00, 1.00)	Px = 10,097,194.35 g·mm²
Iy = (0.00, -1.00, 0.00)	Py = 496,720,281.98 g·mm²
Iz = (1.00, 0.00, 0.00)	Pz = 496,720,281.98 g·mm²
Moments of Inertia at Center of Mass	
Lxx = 496,720,281.98 g·mm²	Lxy = 0.00 g·mm²
Lyx = 0.00 g·mm²	Lyy = 496,720,281.98 g·mm²
Lzx = 0.00 g·mm²	Lzz = 10,097,194.35 g·mm²
Moments of Inertia at Output Coordinate System	
Ixx = 1,620,695,726.62 g·mm²	Ixy = 0.00 g·mm²
Iyx = 0.00 g·mm²	Iyy = 1,620,695,726.62 g·mm²
Izx = 0.00 g·mm²	Izz = 100,971,194.35 g·mm²

4. CFD Analysis

CFD analysis at different wind velocities provides critical insights into the aerodynamic performance of wind turbines. At 2.5 m/s, the analysis focuses on how lower wind speeds affect pressure distribution, velocity profiles, and turbulence around the blades, revealing the drag and lift forces in play. As wind speed increases to 6 m/s, the CFD analysis highlights improved aerodynamic efficiency, with better pressure differentials and more significant turbulence effects that inform optimal blade design and positioning. At 12 m/s, the analysis captures the impact of higher wind speeds on aerodynamic forces and flow dynamics, including stronger lift and complex turbulence patterns, which are essential for addressing potential issues such as stall or excessive drag and refining turbine design for high-speed conditions.

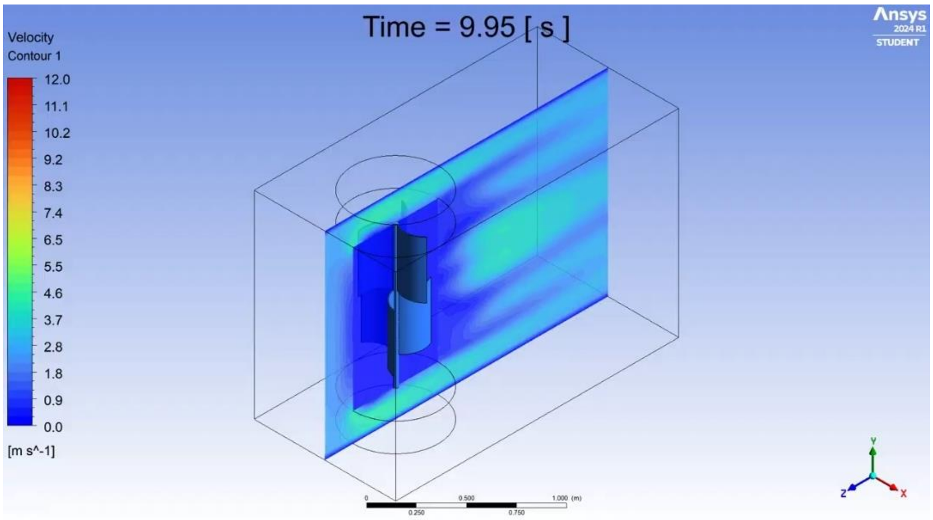

Figure 3. CFD Analysis at 2.5 m/s Wind Velocity

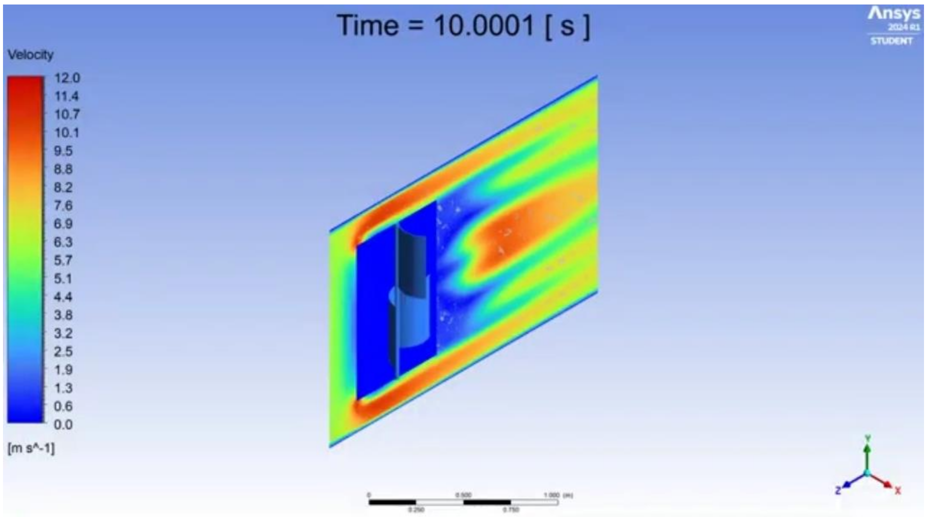

Figure 4. CFD Analysis at 6 m/s Wind Velocity

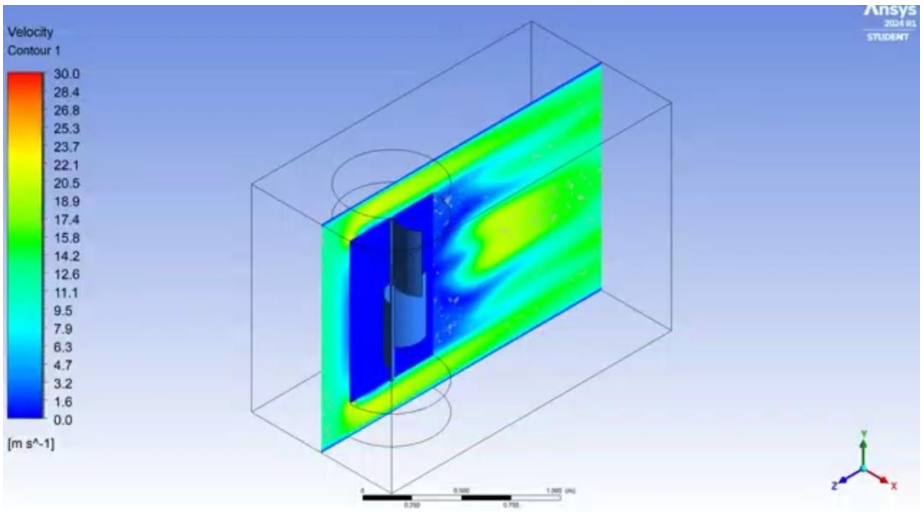

Figure 5. CFD Analysis at 12 m/s Wind Velocity

5. Optimization of windmill blades

In order to evaluate wind energy production, we compute certain characteristics specifically for different wind speeds. In accordance with the ideal gas law, the air density remains constant. The overall power in the wind stream is directly proportional to the cube of the velocity, thereby increasing with wind speed. Based on Betz's Law, the maximum achievable power is the theoretical upper limit of power extraction and increases in proportion to wind speed. From a practical standpoint, the appropriate available power is determined by applying a realistic coefficient of performance, which is typically less than the maximum value. The maximal torque and axial thrust are contingent upon the power output and rotational speed, and they exhibit a positive correlation with wind velocity. The thorough methodology presented herein illustrates that increased wind speeds yield much higher power outputs and mechanical forces, which are essential for the optimization of wind turbine performance.

1. **Air Density (ρ)**
   The air density is calculated using the Ideal Gas Law:
$$\rho = \frac{P}{RT}$$
2. **Total Power in Wind Stream (P_T)**
   The total power in the wind stream is given by:
$$P_T = \frac{1}{2}\rho A_1 U_0^3$$
3. **Total Power Density**
$$P_{\text{density}} = \frac{1}{2}\rho U_0^3$$
4. **Maximum Obtainable Power (P_max)**
   Using Betz's Law (with a coefficient Cp_{max}=16/27):
$$P_{max}=Cp_{max}\times P_T$$
   Power density:
$$P_{\text{max density}} = \frac{16}{27} \times \frac{1}{2}\rho U_0^3$$
5. **Reasonable Available Power (P_R)**
   For practical purposes, assuming C_p=0.4:
$$P_R=C_p\times P_T$$
   Available power density:
$$P_{\text{R density}} = 0.4 \times \frac{1}{2}\rho U_0^3$$
6. **Maximum Torque (T_max)**
$$T_{\text{max}} = \frac{60 P_{\text{max}}}{2\pi N}$$
7. **Axial Thrust at Maximum Efficiency (F_x_max)**
$$F_{x_{\text{max}}} = \frac{\pi \rho D^2 U_0^2}{9}$$

Table 3: Rotational speed of windmill blades

Sr. No.	Air Velocity (m/s)	RPM
1.	2.5	90
2.	6	330
3.	12	450

Table 4. Parameters for Wind Velocities 2.5 m/s, 6 m/s, and 12 m/s

Parameter	**2.5 m/s**	**6 m/s**	**12 m/s**
Air Density (ρ)	1.169 kg/m³	1.169 kg/m³	1.169 kg/m³
Total Power in Wind (P_T)	1147 W	15,865 W	126,922 W
Total Power Density	9.13 W/m²	126.25 W/m²	1010.02 W/m²
Maximum Obtainable Power (P_max)	679 W	9401 W	75,211 W
Max Power Density (P_max Density)	5.31 W/m²	74.82 W/m²	598.53 W/m²
Reasonable Available Power (P_R)	485 W	6346 W	50,768 W
Available Power Density (P_R Density)	3.65 W/m²	50.50 W/m²	404.00 W/m²
Max Torque (T_max)	0.0739 kNm	0.272 kNm	1.596 kNm
Axial Thrust (F_x_max)	408 N	2350 N	9401 N

6. Conclusion

The comprehensive analysis of wind energy generation across different wind velocities—2.5 m/s, 6 m/s, and 12 m/s—demonstrates the significant impact of wind speed on turbine performance. At lower wind speeds, such as 2.5 m/s, the power output and efficiency are relatively modest, with lower maximum obtainable power and torque. As wind speed increases to 6 m/s, both the total power in the wind stream and the maximum obtainable power rise considerably, leading to enhanced aerodynamic performance and efficiency. Further increasing the wind speed to 12 m/s results in even greater power outputs and more complex aerodynamic interactions, including stronger lift forces and pronounced turbulence effects. CFD analysis at these velocities provides critical insights into pressure distribution, velocity profiles, and turbulence, which are crucial for optimizing blade design and turbine performance. Overall, higher wind velocities lead to substantially increased energy generation and mechanical forces, emphasizing the importance of accounting for wind speed in the design and operation of wind turbines to maximize their efficiency and reliability.

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