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Multi-directional Wind Turbine System Optimisation and Mathematical Modelling for India's Sustainable Wind Energy Development

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Abstract

The global trend towards green energy usage is expanding. Wind power is clean and sustainable and may compete with fossil fuels in the electricity market. This project's manufacturing cost must match fossil fuels or other energy sources to be competitive. The main investment in wind generation is in machinery and infrastructure. Wind power becomes competitive by lowering energy costs through turbine design, building, and operation. Understanding wind turbine activity over its operational range requires an accurate mathematical model. This model allows complex control algorithms to optimize wind turbine operation. Modelling controls wind turbine performance. This study investigates the power coefficient parameter to meet wind turbine model goals. Next-generation turbine designers and researchers will benefit from model results. This information can optimize turbine design and lower generation costs, lowering wind energy expenses. This will make wind energy a profitable choice.

Keywords: Wind speed, turbine output, efficiency, blade speed ratio, electrical generator, power grid.

INTRODUCTION

Due to fossil fuel scarcity, wind power has increased worldwide since the 1990s. Wind turbines (WTSs) generate power. A gearbox reduces torque, an aeroturbine turns wind energy into mechanical energy, and a generator provides electricity [1]. A wind turbine has a nacelle, tower, and rotor with two or more blades coupled to an electric generator. The mechanical assembly's gearbox converts the wind turbine's lower rotational speeds into greater electric generator speeds. To sustain electricity output, a control system regulates generator shaft rotation. Two wind turbine designs exist. By rotating axis, wind turbines are horizontal or vertical. VAWTs are also named Darrieus rotors after their inventors [6]. Horizontal axis wind turbines (HAWTs) efficiently use wind energy year-round. In high-wind storms, HAWT blades can be modified to prevent damage.

Constant or variable-speed wind turbines exist. A constant speed turbine's rotor angular velocity is unaffected by wind. It avoids costly power electronics like inverters and converters. This limits rotor speed, reducing turbine efficiency at all wind speeds. In low winds, a constant wind speed turbine creates less energy than a variable wind speed turbine. The latter runs at rotor speed proportionate to wind speed below its rated wind speed [1].

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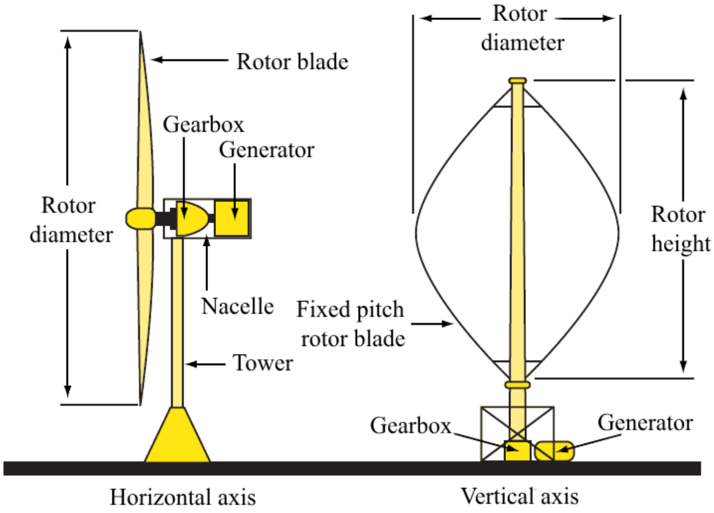

Figure 1. Wind turbine configuration.

Wind turbine power and torque depend on many things. Speed, tilt, pitch angle, size, shape, area, rotor geometry (horizontal or vertical), and wind speed affect wind turbine performance. The wind turbine mathematical model ties factors to produce power. Understanding wind turbine operation requires a mathematical model. Additionally, modelling regulates wind turbine performance. This work addresses wind turbine modelling goals. Wind turbines generate electricity from wind energy. The most common wind turbines are vertical axis and horizontal axis (Figure 1).

LITERATURE REVIEW

A literature review, often called a narrative review, analyses and summarizes relevant literature on a topic. A literature review is an academic document that summarizes major discoveries, theoretical, and methodological advances on a topic. Literature reviews are secondary sources without original or experimental discoveries. These reviews are common in academic publications and differ from book reviews. Literature reviews are essential to most academic research. A thorough literature review was undertaken to investigate the problem and gather information on earlier and current research. Organizational and institute publications and project papers have been thoroughly evaluated. These major literary works have been extensively analyzed (Table 1).

Conclusions of the Literature Survey

- There is a significant potential in creating a Multi-directional Wind Turbine that harnesses renewable energy and is environmentally sustainable.
- Additionally, making a few tweaks to the wind turbine can greatly improve its performance, which can be done with relative ease.
- Vertical axis wind turbines provide advantages over horizontal axis for urban and rural applications.
- Due to their installation at a low altitude, VAWTs are easily maintainable.
- VAWTs demonstrate high efficiency at low wind speeds.
- Further investigation can be conducted from an economic perspective about the materials used for turbine blades.

Motivation

- The Savonius vertical axis wind turbine has a larger swept area than comparable types.
- The wind turbine blades experience resistance from the surrounding wind. In order to mitigate power losses caused by this issue, the model includes a deflector.
- The efficiency of this turbine can be enhanced by decreasing the blade count. The optimal number of blades for maximum efficiency is two.

Table 1. Literature review.

S.N.	Author	Topic name	Major findings
1.	Sevvel P., *et al.* [1]	Revolutionary Multi-Directional Wind Turbine	The redesigned design results in a significant 74% gain in power, as it disregards the wind resistances that oppose it.
2.	Kumara E.A.D, *et al.* [2]	Vertical Axis Wind Turbine design, manufacturing, and testing with wind deflectors.	In order to maximise efficiency, many factors were considered, including the number of rotor blades and the shape of the deflector.
3.	Kok Hoe Wong, *et al.* [3]	In three dimensions, a VAWT flat plate deflector is simulated and parametrically examined.	Simulations indicated enhanced wake flow that the deflector accelerated and diverted before striking the turbine.
4.	Craig Stout, *et al.* [4]	Installing a deflector front of Vertical Axis Wind Turbines (VAWTs) improves their efficiency.	Deflectors redirected fluid flow from turbine blades, minimising negative torque. Deflectors with 36° and 45° angles increase turbine performance 1.266%.
5.	Rakesh Kumar, *et al.* [5]	Wind turbines with a vertical axis (VAWTs) in urban areas: a review.	Features that improve efficiency, reduce noise, and ensure the safety of Vertical Axis Wind Turbines (VAWTs) are recommended for widespread use in light and variable winds.
6.	Sahishnu R. Shah, *et al.* [6]	Modelling, design, and cost analysis of vertical-axis wind turbines.	Authors compared Savonius rotor blades to straight and curved blades for rotation. The turbine may generate 7838 KWh and save $846.51 annually.
7.	Jaydeep Patel, *et al.* [7]	Optimisation of wind farm layout using geometric pattern-based approach.	The upgraded passing vehicle search algorithm for rectangular wind farm considers multi-directional variable wind velocity. The results reveal 4.29 % power production growth.
8.	W.T. Chong, *et al.* [8]	Urban high-rise vertical-axis wind turbine with Omni-directional guide vane	A guide vane was found to improve the inflow wind's velocity by directing it to a more favourable flow angle before it reached the rotor blades. This boosts turbine efficiency and has urban applications.
9.	H.L. Bai, *et al.* [9]	Limited long channel savonius vertical axis wind turbine performance numerical analysis.	Results show that channel VAWT power generation is 200% higher than open space.
10.	E. Antar, *et al.* [10]	Savonius vertical axis wind turbine casing parametric sizing optimisation	At lower Tip Speed Ratios, the optimised casing turbine outperformed the caseless one. There is no uniform ideal case dimension for peak turbine performance at all TSRs.

Objectives

- To create a Savonius multi-directional wind turbine in the SOLIDWORKS software, in accordance with the practicality of our project.
- To enhance the efficacy of the chosen wind turbine model through minimal alterations.
- To perform Computational Fluid Dynamics (CFD) analysis using the redesigned model within the ANSYS software environment.
- To perform structural analysis of wind turbine blades using the ANSYS software.

MATHEMATICAL FORMULATION OF TURBINE MODEL

The amount of work (W) needed to accelerate a mass (m) and a velocity (v) from rest to a distance (s) under a force (F) is equal to the amount of kinetic energy (E) that the item possesses. Thus, $E = W = Fs$. According to Newton's second law of motion, an object's force (F) is proportional to its mass (m) multiplied by its acceleration (a). Thus, the formula $E = m * a$ describes the relationship between mass and velocity.

In solid motion kinematics, $v^2 = u^2 + 2as$ describes the relationship between final velocity (v), initial velocity (u), acceleration (a), and displacement (s). Hence, $(v^2 u^2) / 2s$ is the final value of an. The acceleration is calculated as the square root of the product of the final velocity and the displacement squared, since the initial velocity was zero. According to equation (2), E is equal to $1/2m * v^2$, where m and v represent mass and velocity, respectively.

Constant material mass is the foundation of kinetic energy. Since wind is a fluid, its density and speed can vary, making its mass variable.

We shall assume that air density remains relatively constant regardless of altitude or temperature in this investigation. We shall use equation (3) of the kinetic energy law. A mass m travelling with a velocity *vw* (wind) in the air has kinetic energy (measured in joules) that may be calculated using equation (3). The derivative of kinetic energy with respect to time determines wind power *P*:

$$P = \frac{dE}{dt} = \frac{1}{2}\frac{dm}{dt}v_w^2$$

However, mass flow rate (*dm/dt*) equals *ρAvw*. Here, A represents the wind flow area and *ρ* represents air density. With this expression, equation (4) becomes:

$$P = \frac{1}{2}\rho A v_w^3$$

The difference between upstream and downstream wind powers is measured in watts and written as *Pw* [1].

$$P_w = \frac{1}{2}\rho A v_w\left(v_u^2 - v_d^2\right)$$

Where v_u is the wind speed upstream of the rotor blades in metres per second and v_d is the wind speed downwind of the rotor blades in metres per second. The ratio of these two speeds is what determines the tip speed of the blades, as we shall see. From the rate of mass flow:

$$\rho A v_w = \frac{\rho A(v_u + v_d)}{2}$$

Vw is the average of turbine rotor blade entry and exit velocities. Using this expression, equation (6) simplifies to $Pw = 1/2\rho A(v_u^2 - v_d^2)\,(v_u + v_d)/2$:

$$\begin{aligned} P_w &= \frac{1}{2}\left[\rho A\left\{\frac{v_u}{2}\left(v_u^2 - v_d^2\right) + \frac{v_d}{2}\left(v_u^2 - v_d^2\right)\right\}\right] \\ &= \frac{1}{2}\left[\rho A\left\{\frac{v_u^3}{2} - \frac{v_u v_d^2}{2} + \frac{v_d v_u^2}{2} - \frac{v_d^3}{2}\right\}\right] \\ &= \frac{1}{2}\left[\rho A v_u^3\left\{\frac{1-\left(\frac{v_d}{v_u}\right)^2+\left(\frac{v_d}{v_u}\right)-\left(\frac{v_d}{v_u}\right)^3}{2}\right\}\right] \end{aligned}$$

Or

$$P_w = \frac{1}{2}\rho A V_u^3 C_p$$

Where,

$$C_p = \frac{1-\left(\frac{v_d}{v_u}\right)^2+\left(\frac{v_d}{v_u}\right)-\left(\frac{v_d}{v_u}\right)^3}{2}$$

Or

$$C_p = \frac{\left(1+\frac{v_d}{v_u}\right)\left(1-\left(\frac{v_d}{v_u}\right)^2\right)}{2}$$

In equation (9), *Cp* is the proportion of upstream wind power the rotor blades harness. *Cp* is called the Betz limit after German scientist Albert Betz derived it in 1919. Also termed rotor power coefficient or efficiency. Dynamic power coefficient. Relationship depends on wind turbine tip speed ratio. The turbine's *λ* is the ratio of downstream wind speed *vd* to upstream wind speed *vu*.

$$\lambda = \frac{v_d}{v_u}$$

$$\lambda = \frac{Blade\ tip\ speed}{Wind\ speed}$$

Here, λ represents wind turbine tip speed ratio. The turbine's spinning speed and blade length define the blade tip speed in m/s.

$$Blade\ tip\ speed = \frac{Angular\ speed\ of\ turbine\ (\omega) \times R}{Wind\ speed}$$

R is the turbine radius, while ω is measured in radians per second. Inputting equation (10) into (9), yields:

$$C_p = \frac{(1+\lambda)(1-\lambda^2)}{2}$$

Calculate the greatest value of *Cp* by differentiating it as a function of and setting it equal to zero.

$$\frac{dC_p}{d\lambda} = \frac{(1+\lambda).(-2\lambda)+(1-\lambda^2).1}{2} = 0$$

$\lambda = -1$ or $\lambda = 1/3$. At $\lambda = 1/3$, *Cp* peaks. Maximum is 16/27. According to the Betz limit, wind turbines can convert 16/27 (59.3%) of wind kinetic energy into mechanical energy, *Cpmax= 0.59*. Wind turbines cannot function above this limit. Even the best-designed wind turbines often fall below the Betz limit, often 0.35 to 0.45. Wind passes through low-rotor-speed wind turbine blade gaps, limiting power extraction. The rotating blades produce an impenetrable barrier that prevents wind flow, lowering power output if the rotor turns too rapidly. For optimal wind power extraction, turbines should run at their ideal wind tip speed ratio (λ). A larger λ value potentially improves generator efficiency. There are drawbacks. High λ exacerbates the erosion of blade leading edges due to airborne dust and sand particles. Energy prices may rise with erosion-resistant coatings. Increased λ results in noise, vibration, reduced rotor efficiency, and potential turbine failure at high speeds due to drag and tip losses.

Turbine energy conversion is limited by gearboxes, bearings, blade number and arrangement, etc. Very little wind power is transformed into electricity.

Air density (ρ) affects rotor system flow. Air pressure and temperature determine *P*. Increased air pressure raises density (ρ). Lower air temperature increases air density (ρ). According to state equation: The equation $P = \rho RT$ links pressure (*P*), density (ρ), temperature (*T*), and gas constant *(®)*. High altitude lowers pressure and temperature. Due to air density changes, height influences power output, hence site choice matters. Average atmospheric pressure is 14.7 psi, temperature is 600°F, and density is 1.225 kg/m^3. Elevation alters pressure and temperature. As illustrated [6], this component impacts air density:

$$\rho = \rho_0 e^{-\frac{0.297}{3048}H_m}$$

Here, site elevation is *Hm* in metres. Air density corrections matter at high heights.

DESIGN

Six steps comprise the project process. Steps include information collecting, concept generation, model generation, model analysis and refinement, concept selection, and verification. These phases are shown in Figure 2.

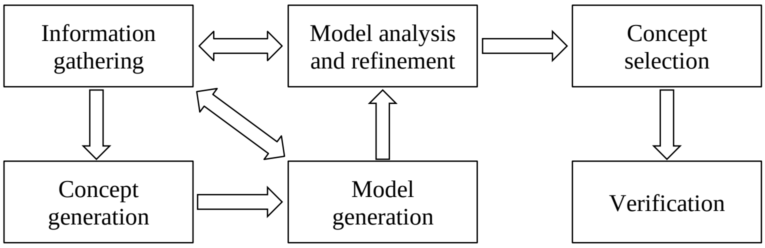

Figure 2. Different 6 phases of project methodology.

There are numerous wind turbine proportions:

- Turbine height is 410mm.
- Turbine blades are 10mm wide.
- Shaft diameter is 30 mm.
- Rotor diameter (D) is 400 mm.
- Two blades make up the Savonius wind turbine.
- These blades are semi-circular.

The aforementioned design data is derived from a comprehensive review of existing literature.

DATA COLLECTIONS

Finding out the wind velocity of Tripura throughout the year was very much important for the CFD analysis, so a graphical representation of data was collected which is given Figure 3.

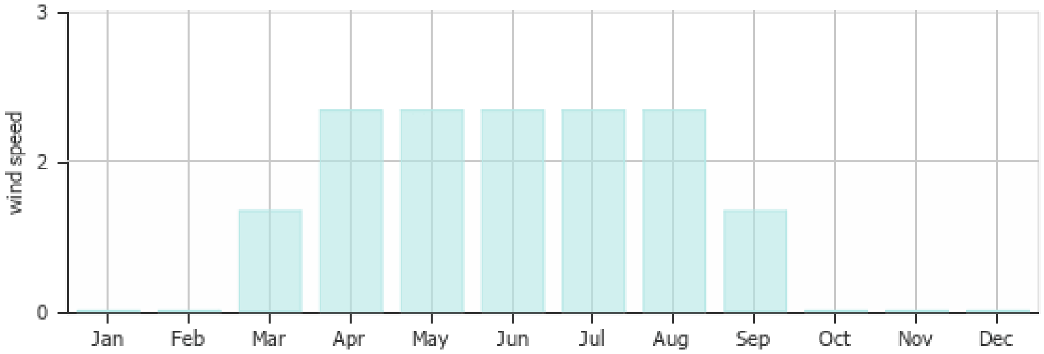

Figure 3. Variation of speed in Tripura throughout the year.

From the above data, we have taken average wind velocity of 2 m/s for our analysis.

Computational Modeling and CFD Analysis

We utilized computer aided design (CAD) Software, specifically Solidworks 2017, to construct the model of our wind turbine.

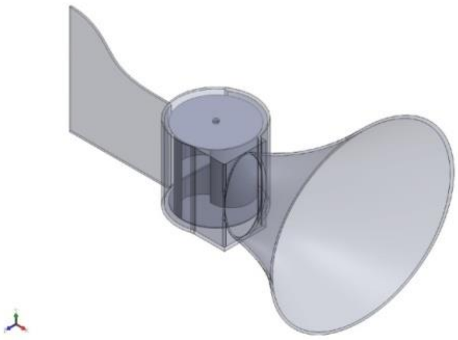

Figure 4. Isometric view (assembly).

ANALYSIS

Various analyses have been conducted to assess the structural integrity of the turbine blades, power output, and the flow of streamlines across the model. These analyses also include the examination of pressure and velocity distribution. We utilized computer aided design (CAD) software, specifically ANSYS 18, for this purpose (Figure 4).

CFD Analysis given in Figures 5–9.

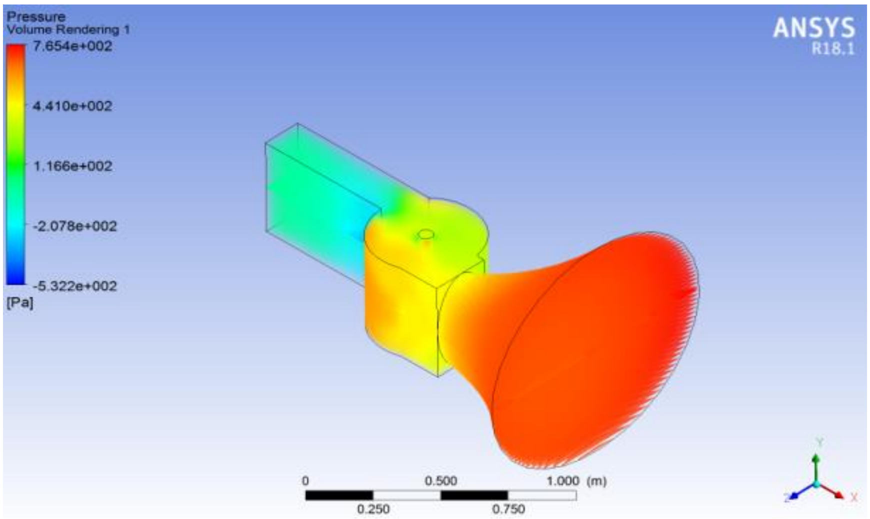

Figure 5. Pressure distribution.

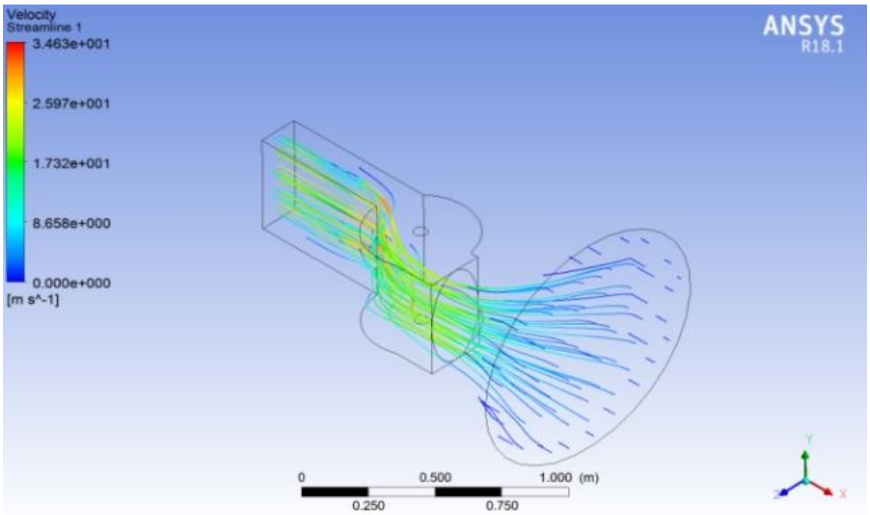

Figure 6. Velocity streamlines.

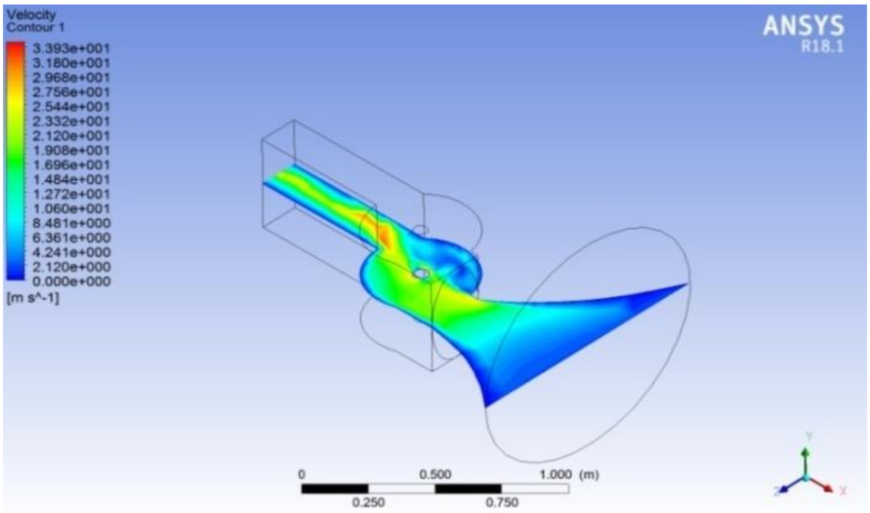

Figure 7. Velocity distribution.

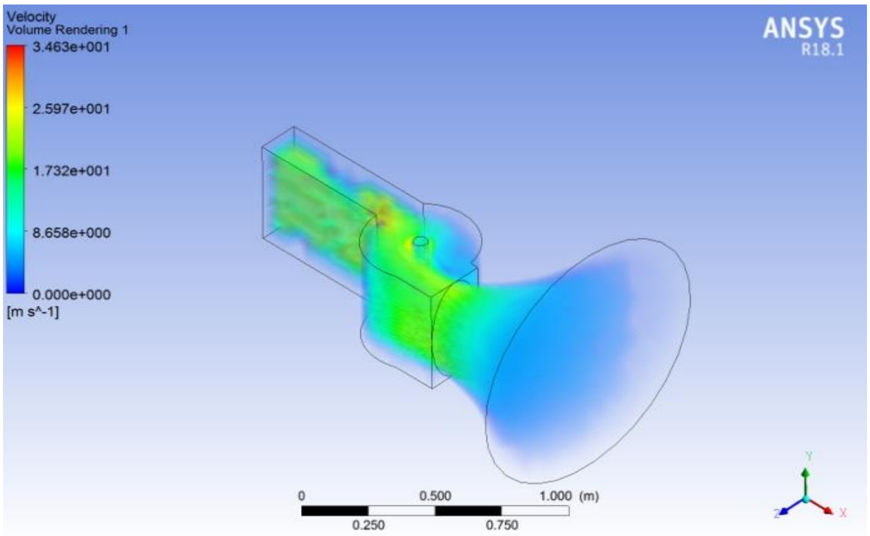

Figure 8. Velocity volume rendering.

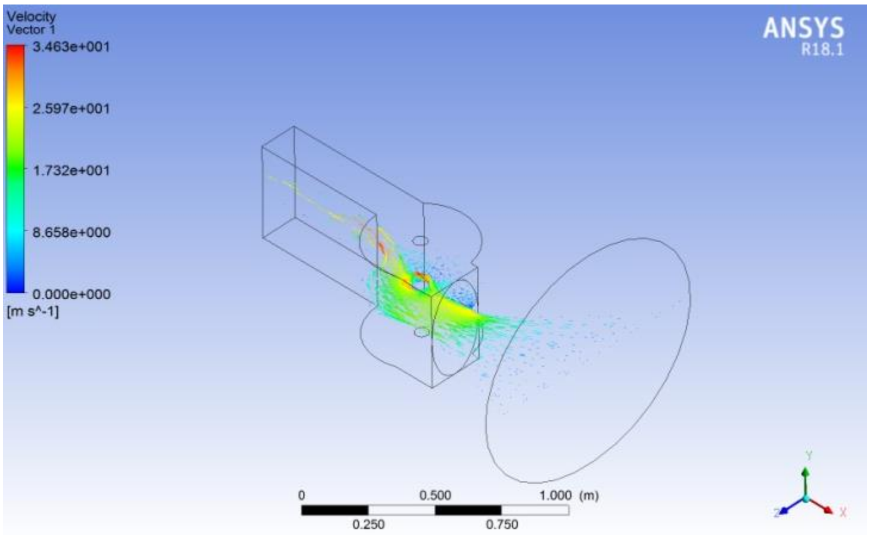

Figure 9. Velocity vector.

STRUCTURAL ANALYSIS (Figures 10–12)

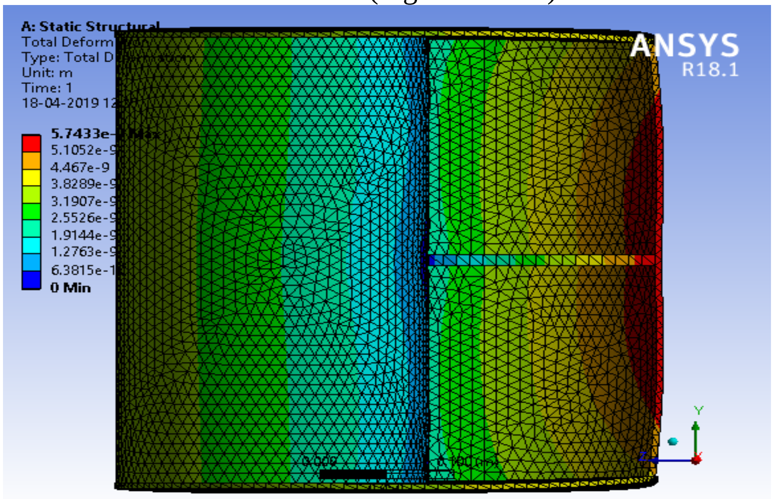

Figure 10. Complete deformation.

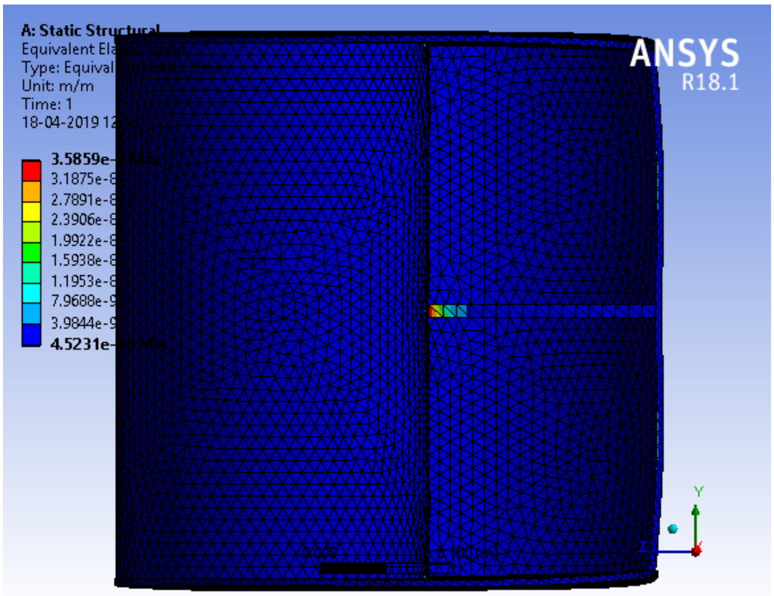

Figure 11. Stress in elasticity equivalent.

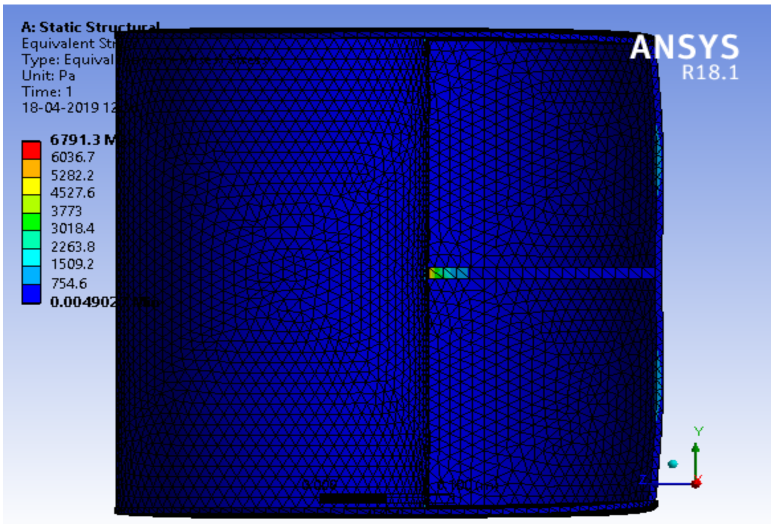

Figure 12. Von misses stress equivalent.

RESULT AND DISCUSSIONS

The following results have been found out which are as follows:

1. Total deformation (maximum) of the blade = 5.7433×10^{-9} m
2. Equivalent elastic strain (Maximum) on the blade = 3.5859×10^{-8} m/m
3. Equivalent (Von Mises) Stress = 6731.3 Pa
4. Maximum Pressure on the model = 765.4 Pa
5. Minimum pressure on the model = -532.2 Pa
6. Power
    - Without modification

      Kinetic Energy = $\frac{1}{2}.\rho.V.v^2 = \frac{1}{2}\times1.225\times1\times2^2 = 2.45$ kg m^2/s^2

      Power of wind = K.E.×Velocity of wind= $2.45\times2 = 4.9$ kg m^3/s^3
    - With modification

      Kinetic Energy = $\frac{1}{2}.\rho.V.v^2 = \frac{1}{2}\times1.225\times1\times3.4^2 = 7.08$ kg m^2/s^2

      Power of wind = K.E.×Velocity of wind= $7.08\times3.4 = 24.07$ kg m^3/s^3

Based on the provided data, it is evident that the power is significantly growing when the model is modified. In this variant, the blade is made of Aluminium Alloy.

CONCLUSIONS

The high-stability 2-bladed savonius vertical axis wind turbine (VAWT) was built and modelled in SolidWorks before being put through a CFD study in ANSYS 18.1. Pressure, velocity, and streamline flow distributions met predictions. Even at 2 m/s wind speed, a nozzle-deflector system increased wind turbine efficiency. The structural investigation revealed that the blades deformed only a few nanometers. This was done with aluminium alloy. Composite glass fibre, which resists corrosion, can replace the blade material. However, hardware and software limits affected the results.

Future Scope

- India has great potential for harvesting wind energy, especially with Vertical Axis Wind Turbines, which work well in low wind speeds.
- Improve the efficiency of the Savonius VAWT by incorporating new improvements to the design of the blades.
- Efforts can be made to lower blade material costs.
- Our goal is to implement this idea in Tripura's paddy fields and underutilised spaces. Therefore, we developed district-wise potential maps.

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Data Availability

The authors affirm that this research report contains the information necessary to understand the findings of the investigation.

Conflict of Interests

All of the authors contributed equally and have no conflict of interest in any way with this paper.

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