

Computational Investigation of Energy Generation by Vertical Axis Wind Turbine using Highway Wind Turbulence

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Abstract With increase in world's population and economic development, there has been larger energy demand in recent times, experts predict that by 2050 the global energy increase nearly 50% compared with 2020. According to the same source, there will be energy demand increase by 1.3% per year, this increase in energy demand has also resulted to increase in global warming with CO₂ emission because a substantial of the energy generated is from the fossil fuel. One promising avenue in this quest for sustainability is the deployment of Vertical Axis Wind Turbines (VAWTs) for energy generation along highways but the operational performance and efficiency of VAWT's represent critical challenges in the field of renewable energy, their efficiency and operational reliability have remained subjects of concern, they often face challenges related to self-starting in region with inconsistent or lower wind speed conditions. The main objective of this work is to analyze the performance of VAWT and come up with optimum parameter for our design. Parametric studies were carried out using Computation Fluid Dynamics with ANSYS fluent and structural analysis with Fusion 360. We found out that symmetrical airfoils (have a moment coefficient (C_m) close to zero or with a small variation with angle of attack. In contrast, asymmetrical airfoil (S1223 in this case) has variable moment coefficient values with changes in angle of attack making it less stable and potentially requiring additional control mechanisms to manage the turbine's orientation.

Keywords: Vertical Axis Wind Turbines (VAWT), Horizontal Axis Wind Turbines (HAWT), Aspect Ratio (AR), Computational Fluid Dynamics (CFD), Shear Stress Transport (SST).

I. Introduction

In recent years, the problems of fossil resources and worldwide climate change are becoming increasingly serious because of the rapid development of the industrial economy and the fast growth of the world population. As such, the demand for clean and sustainable energy solutions globally has intensified rapidly [1]. Researchers and engineers are continuously exploring innovative renewable energy technologies that can be integrated into existing

infrastructures to harness clean power efficiently. One promising avenue in this quest for sustainability is the deployment of Vertical Axis Wind Turbines (VAWT) for energy generation along highways.

Wind is one of the most abundant sources of renewable energy and as such, harnessing this source will help to reach a sustainable energy dependent society. The term "wind turbine" no longer only refers to a rotary propeller but a machine known as an aerofoil powered generator [2]. A wind turbine is a machine used to convert the kinetic energy of wind into mechanical energy, which is then converted into electrical energy. The blades of the wind turbine capture the wind's kinetic energy, causing the

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rotor to turn. This movement is transferred to a generator, which converts the mechanical energy into electrical energy that can be used to power homes, businesses, and communities. Wind turbines come in different designs and capacities, and can be installed on land or offshore, depending on the wind conditions and energy demand in a particular area. Wind turbine can be classified based on several factors of which are; blade design (HAWT & VAWT), generator type (Direct type or gear-driven), Rotor orientation (upwind or downwind), Capacity (small-scale, mid-scale or large-scale), location of installation (onshore or offshore), power supply mode (grid-tied or standalone). Based on the orientation of the rotating axis, there are two types of wind turbines namely Horizontal Axis Wind Turbines (HAWT) and Vertical Axis Wind Turbines (VAWT) [3].

Conventional Horizontal Axis Wind Turbines (HAWT) have been widely utilized for large-scale wind energy projects; however, they come with limitations in terms of space requirements, noise, and visual impact. But recently, there is a renewed interest in different types of VAWTs because of environmental issues and energy security concerns in an urban environment [4]. Vertical Axis Wind Turbines offer distinct advantages that make them potentially suitable for deployment along highways. They are designed to rotate around a vertical axis, allowing them to capture wind from any direction and eliminate the need for complicated yaw mechanisms, making them more efficient in areas with variable or turbulent wind patterns. Additionally, their compact and low-profile design enables integration into existing infrastructure with minimal disruptions.

The Persians were the first to develop vertical axis windmills in the 19th century AD, which

were used for grinding grain and irrigation [5] as shown in Figure 1.0(a). The windmills were simple in construction and used drag forces, with a vertical axle connected to either six or twelve radially-mounted vertical wooden sails. The millstone was connected to redirect the axis of rotation. In the 20th century, steady advancement was experienced due to improvements in scientific understanding of aerodynamics, mainly from the aircraft industry. In 1931, Georges Jean Marie Darrieus, a French aeronautical and military engineer, patented the lift-driven VAWT, which consisted of vertically oriented airfoil-shaped blades rotating around an axis orthogonal to the flow direction. The patent describes a multi-bladed rotor with either fixed curved or straight blades, as depicted in the Figure 1.0 (b). The curved-bladed Darrieus configuration was designed to form the blades into a Troposkein shape, which would theoretically be free of bending stresses induced by centrifugal loads. [6].

Fluctuation in the source of wind is a major concern with the wind energy technology. However, it is still possible to make use of it for applications where less energy is required such as lighting the highways. Highways need lights for operating traffic signals, normal lighting and guiding signs. The amount of energy needed is low and as such the use of regular fuel for this purpose makes it less economical in the long run. Thus the application of wind turbines to produce this amount of energy from the moving vehicles seems promising [7].

The highway infrastructure presents a unique opportunity for the integration of renewable energy solutions. Highways traverse through vast open spaces where wind resources are often

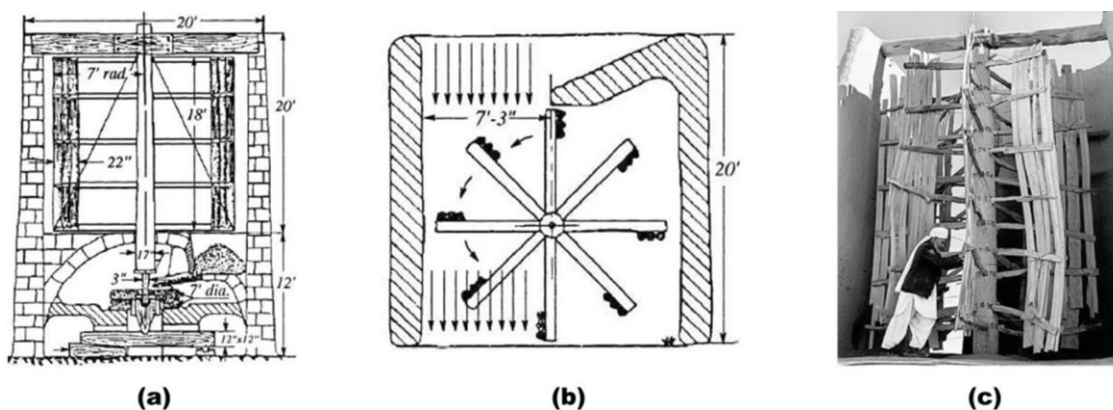


Figure 1.0: (a) Persian Vertical Windmill View (b) Elevation (c) Actual Images from Darrieus's Patent Showing the Turbine

abundant. By installing VAWTs along the highways, it is possible to tap into this clean energy source and contribute to the overall energy mix. Furthermore, the generated energy can be utilized to power various highway components, such as lighting, signage, and other auxiliary systems, reducing dependency on the grid and promoting sustainable in transportation infrastructure. Wind and solar become the two main sources of generation by 2040, and supply half of global electricity generation by 2050[8].

A VAWT is a type of wind turbine where the main rotor shaft is set vertically, as opposed to a horizontal axis wind turbine (HAWT) where the rotor shaft is set horizontally. Due to their compact size, low noise levels, and ability to generate power from any direction, VAWTs have attracted significant interest in recent years. There have been several bibliographies published that summarize the research and development of VAWTs.

There are several types of vertical axis wind turbines (VAWTs), each with its own unique design and advantages. The most common types are Savonius turbines and Darrieus turbines. Savonius Turbines was named after tis inventor,

Finnish engineer Sigurd Johannes Savonius. It consists of two or three vertical curved blades that are bent in a U-shape. The Savonius turbine is ideal for low speeds and is often used for small-scale applications. Darrieus turbines which was developed in 1931 when the French aeronautical and military engineer Georges Jean Marie Darrieus patented the lift-driven VAWT, which consisted of vertically orientated airfoil shaped blades which rotate around an axis orthogonal to the flow direction[5]. The patent describes a multi-bladed rotor with either fixed curved or straight blades as depicted in Figure 2.0. The design philosophy behind the configuration was to form the blades into a Troposkien shape which would theoretically be free of bending stresses induced by centrifugal loads. Darrieus also foresaw a number of embodiments of his fundamental idea that would be trialed at large scale many decades later. These included use of both curved-blade shown in Figure 2.0 and straight blade versions of his rotor. Active control of the pitch of the blades relative to the rotor as a whole, so as to optimize the angle of attack of the wind on each blade throughout its travel around the rotor circumference was as well proposed.

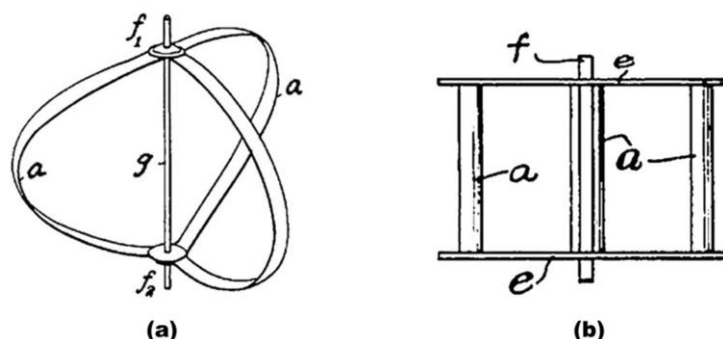


Figure 2.0. Images from Darrieus's Patent Showing the Turbine with (a) Curved Blades (b) Straight Blades. Annotations refer to (a) Blades (e) Support structure (f) Hub (g) Shaft

One of the early challenges faced by VAWT designers was the limited strength and durability of materials available at the time, which made it difficult to build reliable and efficient turbines. This led to the development of new materials and manufacturing techniques, which helped to improve the performance of VAWTs. In the decades that followed, advances in materials science and engineering led to the development of more efficient and cost-effective VAWTs, which saw increasing use in a variety of applications, including small-scale residential installations and large-scale commercial wind farms.

Despite these advances, VAWTs are yet to see widespread adoption compared to HAWTs, which are the more commonly used type of wind turbine. This is partly due to the lower energy output and technical challenges associated with VAWTs, as well as the lower reliability of some early VAWT designs. However, ongoing research and development efforts aim to improve the performance of VAWTs, making them a more viable alternative to HAWTs in the future. In recent years, there has been growing interest in the use of VAWTs in urban areas, where space is limited and noise levels are a concern. The compact design and quiet operation of VAWTs make them well-

suited for use in densely populated areas, and research is ongoing to improve their performance and reliability in these applications.

II. Materials and Methods

Two distinct scopes were pursued to craft our turbine to attain optimal design aligned with our research goals which are:

Computational Fluid Dynamics (CFD) Analysis: In this phase, we utilized CFD simulations to study the fluid dynamics and aerodynamic properties affecting our turbine's performance.

Performance Analysis: This involved an in-depth examination of the factors influencing the turbine's performance. We conducted parametric studies employing various techniques to determine the turbine's overall dimensions and various performance characteristics.

The wind turbine parameters considered in the design process are:

1. Turbine swept area which is the total surface area encompassed by the rotating blades of the turbine as it interacts with the wind. A larger swept area allows the VAWT to intercept more wind, thus capturing a greater amount of kinetic energy leading to increased power generation potential. The formula for calculating

the Turbine Swept Area (A) of a VAWT is as follows:

$$A = \pi \times R^2 \quad (1)$$

Where A represents the Turbine Swept Area (in square meters, m²), π is the mathematical constant Pi, approximately equal to 3.14159, R denotes the radius of the circle described by the rotating blades (in meters, m). The Turbine Swept Area formula calculates the effective area through which the wind interacts with the VAWT's blades for energy conversion. In this study, we kept the swept area to 3m².

2. Tip Speed Ratio (TSR) which holds significant importance in wind turbine design. It is defined as the ratio of the tangential speed at the blade tip to the actual wind speed, expressed as

$$TSR = \frac{\omega R}{U_{\infty}} \quad (2)$$

where R denotes the hub radius, and ω represents the angular speed of the blades. Maintaining an appropriate TSR is critical. If the blade angular speed (ω) is too low, a substantial portion of the wind may pass through the blade swept area without performing useful work. Conversely, if ω is excessively high, fast-rotating blades can obstruct the wind flow, diminishing power extraction. Each rotor design possesses an optimal TSR, where maximum power extraction is achieved. We vary the TSR values to get optimum value for our design.

3. Number of Blades refers to the quantity of blade components affixed to the rotor and holds substantial sway over the wind turbine's ability to harness wind energy effectively. A smaller blade count can diminish aerodynamic resistance, potentially compromising energy capture, whereas a greater blade count can

enhance energy capture but may introduce higher drag forces. Moreover, the quantity of blades influences the turbine's start-up speed, rotor behavior, noise emissions, and visual appeal, rendering it a pivotal factor in the quest to optimize wind turbine performance.

4. An airfoil, also known as an aerofoil, is a streamlined shape with a curved upper surface and a flatter lower surface, typically designed for use in air or other gases. It is used to generate lift when it moves through the air or gas. The specific shape and contour of an airfoil are designed to efficiently control airflow and generate the desired aerodynamic forces for its intended purpose [9].

5. Aspect Ratio, in aerodynamics and engineering, is a numerical measure that describes the ratio of an airfoil's or wing's span (the distance from one wingtip to the other) to its average chord (the width of the wing from the leading edge to the trailing edge) as is typically denoted by the symbol "AR." It is an important parameter because it significantly influences the aerodynamic performance of an airfoil or wing. Higher AR generally result in lower induced drag and higher lift-to-drag ratios. This makes high AR wings more efficient for activities like gliding or long-endurance flight.

6. Turbine Solidity refers to the measure of how closely the blades of a turbine are spaced or how much blade material occupies the space through which the wind flows. The Turbine Solidity ratio is calculated by dividing the total area of the wind turbine blades (including their cross-sectional area) by the area of the circular disc swept by the rotating blades as they pass through the wind.

$$\text{Turbine Solidity} = \frac{\text{(Total Blade Area)}}{\text{Swept Area by Blade}} \quad (3)$$

It stands as a crucial dimensionless parameter that influences a VAWT's capacity for self-starting. In the case of straight-bladed VAWTs, this parameter is determined using the formula:

$$\sigma = \frac{B \times c}{R} \quad (4)$$

Where 'B' represents the number of blades, 'c' signifies the blade chord, and it's assumed that each blade sweeps the area twice. It's worth noting that this formula does not apply to HAWTs due to their different swept area shape. Solidity serves as a critical factor in determining the conditions under which momentum models hold true. Specifically, for self-starting VAWTs, a high solidity, typically $\sigma \geq 0.4$, is required to meet this criterion.

A comprehensive examination of key analysis parameters is conducted in this study, with consideration given to ensure a holistic evaluation of the aerodynamic performance of the NACA 0018, S1223, DU-06-w-200, and NACA 0021 airfoils within VAWT systems. Central to the assessment are the lift and drag coefficients, which are derived from simulations and provide insights into the airfoil's ability to generate lift for turbine rotation while managing drag resistance.

A. Computational Fluid Dynamics (CFS)

Modern engineering practices involve a combination of experimental and Computational Fluid Dynamics (CFD) analyses, as they complement each other. For instance, engineers may experimentally determine global properties like lift, drag, pressure drop, or power, while utilizing CFD to obtain detailed information about the flow field, such as shear stresses, velocity and pressure profiles, and flow streamlines. Moreover, experimental data often serve to validate CFD solutions by comparing

the computed and experimentally determined global quantities. CFD is then employed to expedite the design cycle through controlled parametric studies, effectively reducing the need for extensive experimental testing.

Solution Procedures:

1. Define the computational domain (geometry) and generate a grid or mesh, dividing the domain into numerous small elements known as cells.
2. Specify boundary conditions along each edge (for 2-D flows) or each face (for 3-D flows) of the computational domain.
3. Define the fluid type (water, air, gasoline, etc.) and fluid properties (temperature, density, viscosity, etc.) in this case, air is selected.
4. Select numerical parameters and solution algorithms for the CFD simulation.
5. Assign initial values to flow field variables for each cell.
6. Initiate an iterative process to solve the flow equations, starting from the initial guesses (typically at the center of each cell).
7. Upon convergence of the solution, visualize and analyze flow field variables like velocity and pressure graphically.
8. Calculate global properties such as pressure drop and integral properties such as forces (lift and drag) and moments acting on a body, using the converged solution.

B. Governing Equations

The Shear Stress Transport (SST) model is a popular turbulence model used in Computational Fluid Dynamics (CFD) simulations to predict flow characteristics. This model combines element of both k- ω (k-omega)

and $k-\epsilon$ (k-epsilon) turbulence models, aiming to provide accurate predictions for a wide range of flow conditions, making it suitable for simulating the flow around Vertical Axis Wind Turbines (VAWTs). The governing equations for the SST turbulence model VAWT simulation typically include the following

1. Reynolds – Averaged Navier-Stokes (RANS) Equations: These equations describe the conservation of mass and momentum for the mean flow which include the continuity equation in both the x (streamwise) and y (crossflow) directions
2. Transport Equations for Turbulence Quantities:
K Equation: Governs the turbulent Kinetic energy (K), which represents the energy associated with turbulent fluctuations in velocity.
W Equation: Governs the specific rate of turbulence dissipation (ω) which represents the rate at which turbulent kinetic energy is dissipated into heat due to viscous effects.
3. Transport Equation for the Specific Turbulence Production (P): this equation calculates the production of turbulent kinetic energy which is typically a function of mean velocity gradients.
4. Turbulent Viscosity Equation:

Determines the eddy viscosity (μ_t), a key parameter in modelling the turbulent stresses.

The SST model also includes additional terms and coefficients to account for the switch between the k-w and k-e models in different flow regions. It does this by employing a blending function that transitions between the two models depending on the local conditions.

$$\rho(\mathbf{u} \cdot \nabla) \mathbf{u} = \nabla \cdot [-p\mathbf{I} + \mathbf{k}] + \mathbf{F} \quad (5)$$

$$\rho \nabla \cdot \mathbf{u} = 0 \quad (6)$$

$$\mathbf{k} = (\mu + \mu_T)(\nabla \mathbf{u} + (\nabla \mathbf{u})^T) \quad (7)$$

$$\rho(\mathbf{u} \cdot \nabla) \mathbf{k} = \nabla \cdot [(\mu + \mu_T \sigma_k^*) \nabla \mathbf{k}] + p_k - \beta_0^* \rho \omega \mathbf{k} \quad (8)$$

$$\rho(\mathbf{u} \cdot \nabla) \omega = \nabla \cdot [(\mu + \mu_T \sigma_\omega) \nabla \omega] + \alpha \frac{\omega}{k} p_k - \rho \beta_0 \omega^2, \quad \omega = \text{om} \quad (9)$$

$$\mu_T = \rho \frac{k}{\omega} \quad (10)$$

$$p_k = \mu_T [\nabla \mathbf{u} : (\nabla \mathbf{u} + (\nabla \mathbf{u})^T)] \quad (11)$$

In VAWT simulation, these equations, along with appropriate boundary conditions and a grid that captures the geometry of the VAWT are solved numerically using CFD software. The SST model's advantage is its ability to handle various flow regimes, from attached boundary layers to separated and transitional flows, making it a good choice for VAWT simulations, where flow conditions can vary widely depending on the turbine's design and operating condition as shown in Figure 3.

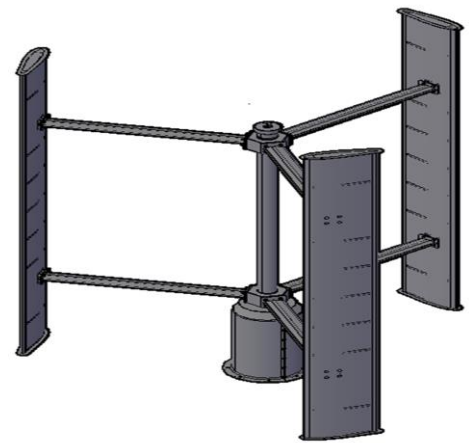


Figure 3 Vertical Axis Wind Turbine 3D Model

C. Results Analysis

i. 2-D airfoil analysis

In this section, the analysis is detailed on four distinct airfoils: NACA 0018, S1223, DU-06-w-200, and NACA 0021, with the aim of enhancing our understanding of their performance in Vertical Axis Wind Turbines (VAWTs). These airfoils represent a diverse

range of profiles, and our analysis seeks to uncover their specific aerodynamic characteristics and performance characteristics, including lift and drag coefficients, pressure distributions, and flow behavior within the VAWT context. This research contributes valuable insights into optimizing VAWT design for sustainable energy generation. Figures 4 shows mode Geometry of (a) NACA 0018 (b) S1223 (c) DU-06-W-200 (d) NACA 0021

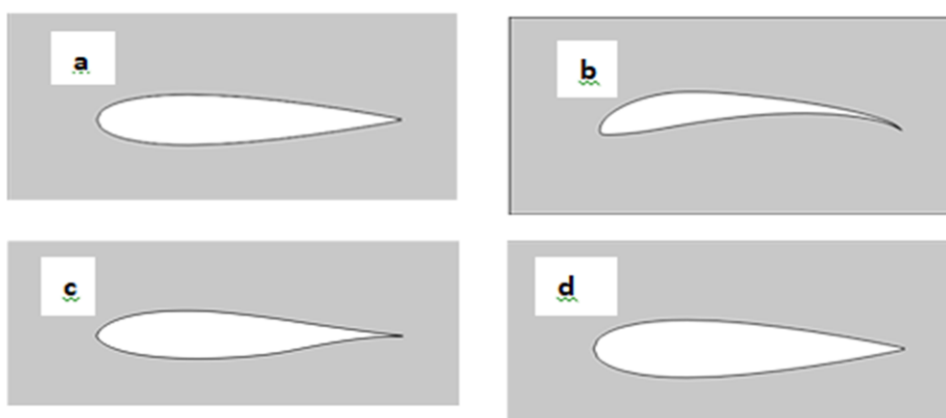


Figure 4 Mode Geometry of (a) NACA 0018 (b) S1223 (c) DU-06-W-200 (d) NACA 0021

ii. Aerofoil selection

The selection of airfoils is regarded as a pivotal step in the methodology, serving as the foundation for a comprehensive analysis of VAWT performance. The chosen airfoils, namely NACA 0018, S1223, DU-06-w-200, and NACA 0021 were scrutinized based on multiple criteria to ensure the relevance and reliability of our investigation such as airfoil profiles characterized by distinct geometric shapes and aerodynamic characteristics. To ensure the robustness of our analysis, considerations were given to the availability of comprehensive experimental and computational data for these

airfoils. This guarantees a well-founded basis for the evaluation of their performance metrics within the VAWT context. While these airfoils have been addressed in prior research, a step further was taken by our study, which concentrated on their performance exclusively in VAWT setups. Through the addressing of this research gap, novel insights are contributed to the body of knowledge concerning VAWT design. The methodological rigor and relevance of our study are underscored by this judiciously curated selection process, positioning it to provide a holistic understanding of the aerodynamic behaviors of NACA 0018, S1223,

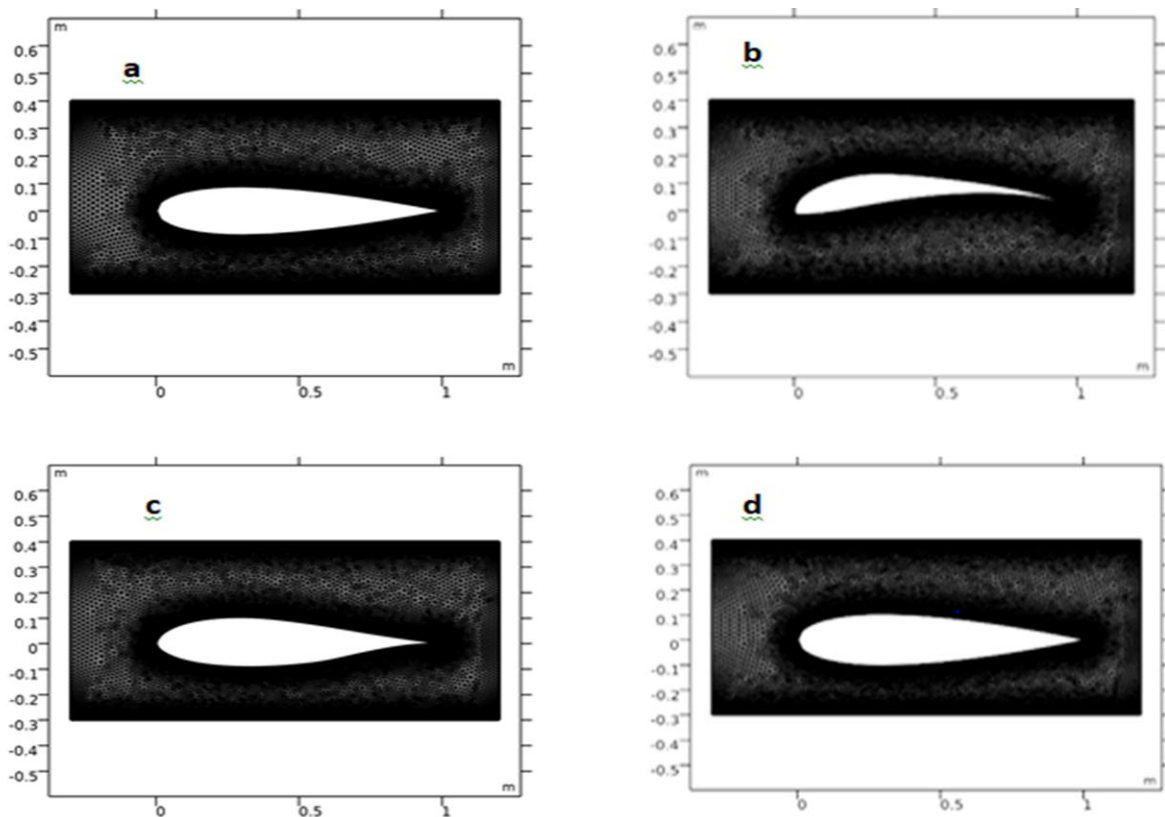
DU-06-w-200, and NACA 0021 airfoils within VAWT system

iii. Geometry and meshing

The geometry and meshing phase assumes a critical role in establishing the groundwork for our analysis. During this phase, the geometries of the four selected airfoils, specifically NACA 0018, S1223, DU-06-w-200, and NACA 0021, were meticulously prepared, with careful consideration of their unique contours and dimensions to ensure precise geometric representations. Subsequently, a structured grid approach was employed to generate meshes for the computational domain, encompassing the VAWT setup and airfoil placements. This meshing process aimed to achieve a grid with sufficient resolution, facilitating accurate

simulations while adhering to grid quality standards by minimizing skewness and distortion

In tandem, pressure distributions across airfoil surfaces are scrutinized, revealing insights into airflow behavior and pressure gradients influenced by variations in airfoil shape. Furthermore, the variation of the angle of attack is introduced to facilitate an understanding of performance under diverse wind conditions. To deepen the analysis, Reynolds number and pitch angle are incorporated, allowing for exploration of the impact of flow characteristics at varying scales and the effect of airfoil orientation on aerodynamic efficiency. The inclusion of these parameters underscores the commitment to a comprehensive evaluation of airfoil performance, contributing crucial insights to the field of VAWT design



Figures 5 Model Mesh of (a) NACA 0018 (b) S1223 (c) DU-06-W-200 (d) NACA 0021

iv. Structural analysis

Structural analysis is carried out on the model using Autodesk Fusion 360 software, to determine the maximum stress the structure can withstand and the resulting strain. This is divided into two main sections; namely

1. Stress and strain analysis
2. Fatigue analysis

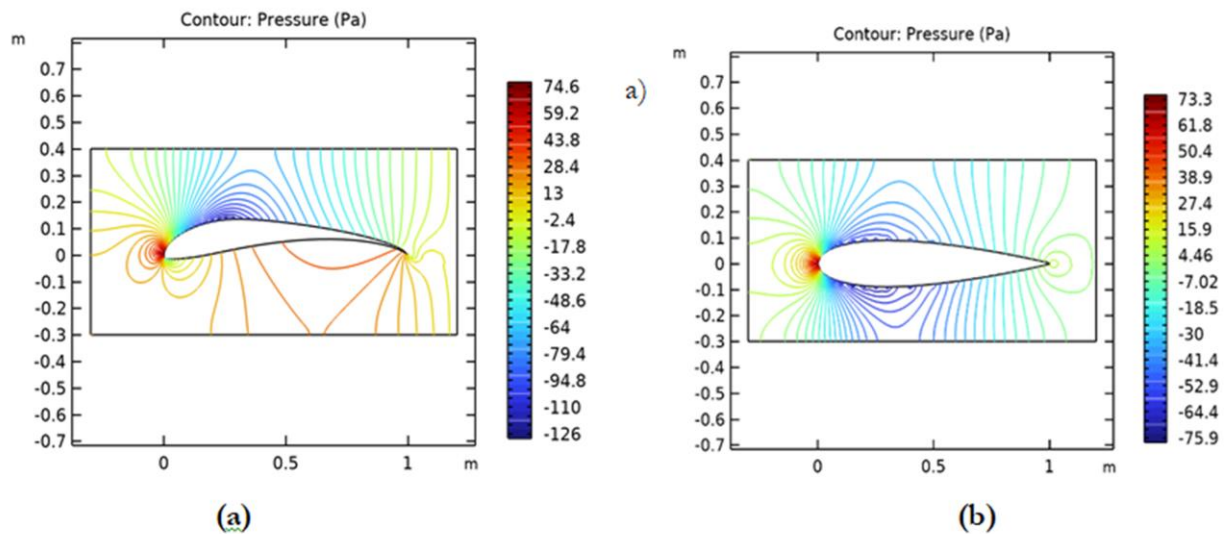
Stress Analysis was used to predict the equivalent stress at which yielding occurs in the materials using Von-mises criterion. Total Deformation was used to determine the Alteration in the shape or dimensions of the VAWT as a result of the application of stress to it, in other words it is the transformation of the VAWT from a reference configuration to a new configuration as a result of applied stress. Modal analysis was carried out to identify how an object deforms based on its stiffness and

mass, it is carried out using Autodesk inventor software. Based on safety margin, SAFETY FACTOR was used to describe the structural capacity of the VAWT beyond the expected or actual load.

III. Result and Discussions

A. Pressure Distribution

The analysis of pressure distribution over the surfaces of the four airfoils, NACA 0018, S1223, DU-06-W-200, and NACA 0021, has unveiled insights into their aerodynamic behavior. As shown in Figures 6 & 7, each airfoil exhibits distinct pressure patterns. Notable observations include NACA 0021's ability to maintain favorable pressure distributions even at higher angles of attack, contributing to its lift efficiency. In contrast, DU-06-W-200 exhibits pressure patterns indicative of its stability under varying conditions



Figures 6.0: Pressure Contour of (a) NACA 0018 (b) S1223

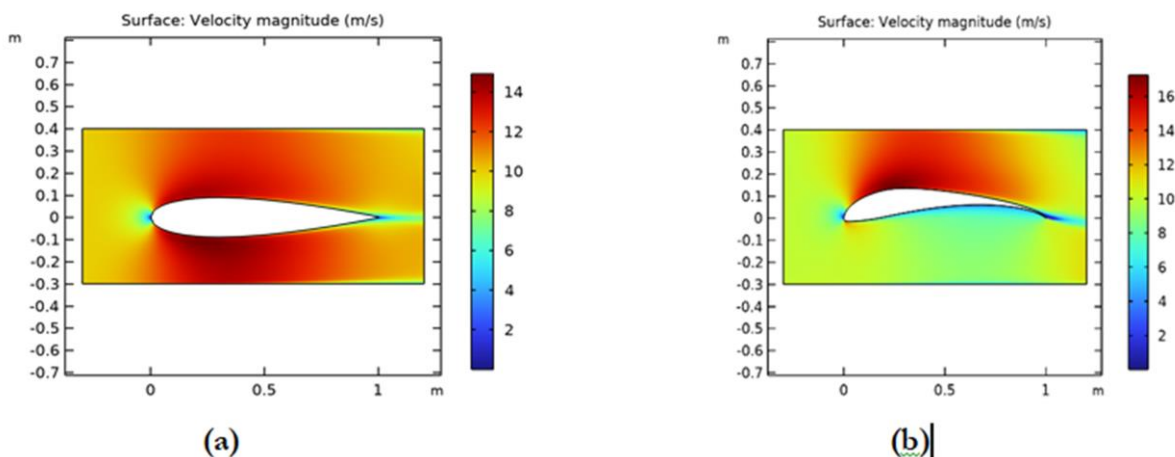


Figure 7.0: Velocity Distribution of (a) NACA 0018 (b) S1223

B. Velocity Distribution

The analysis of velocity distributions is vital in assessing how airflows interact with the airfoil surfaces. These distributions highlight regions of acceleration, deceleration, and potential flow separations. S1223 emerges as an airfoil with exceptional velocity management as shown in

Figure 7.0b, demonstrating smooth and consistent airflow patterns across varying angle of attack. Conversely, NACA 0018 exhibits velocity characteristics that are sensitive to angle of attack changes, necessitating careful consideration in turbine design as shown in Figures 8.0.

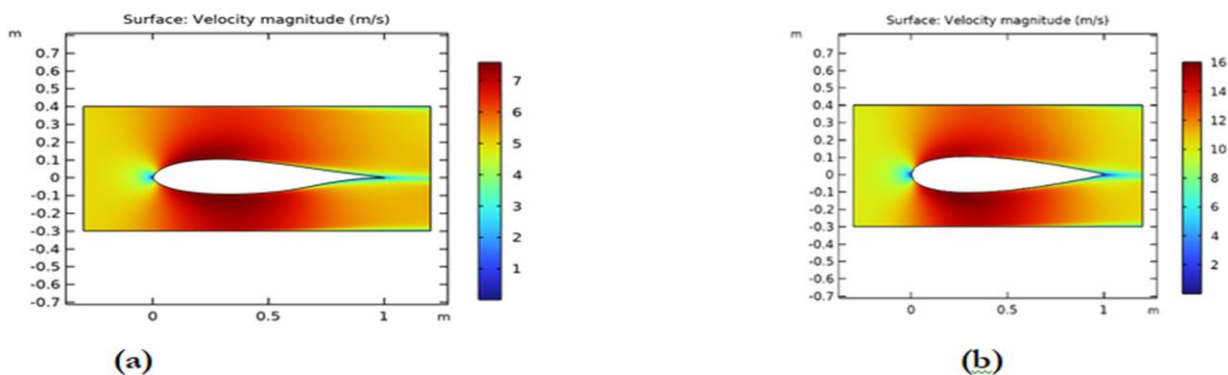


Figure 8.0: Velocity Distribution of (a) DU-06-W-200 (b) NACA 0018

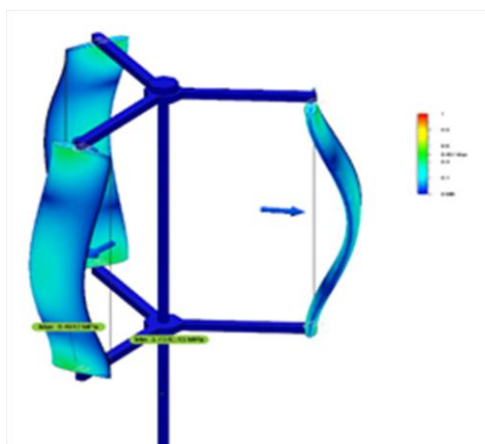
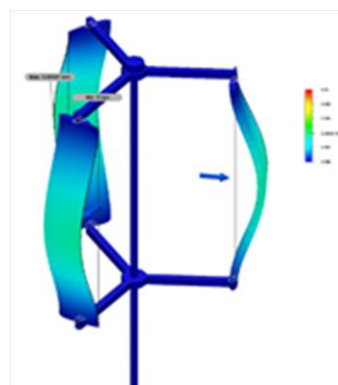
C. Structural Analysis results

With appropriate material selection and necessary loads specified, Stress analysis as specified in chapter three was carried out on the model using Autodesk Fusion 360.

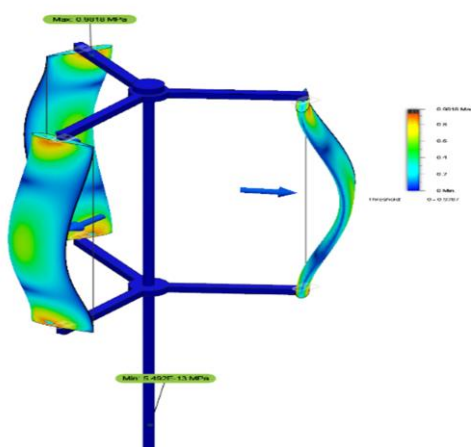
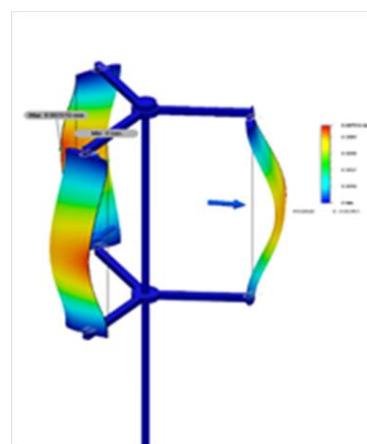
Steel was specified as the material for the components of the turbine, subjected to static stress analysis, it displayed the following responses: Table 1 and 2 shows the loading responses of typical steel turbine under invariable load of 50N and 100N respectively.

Table 1: Turbine Properties Under a force of 50N

Force	50 N
Yield Strength	207 Mpa
Ultimate Tensile Strength	345 Mpa
Equivalent Strain	2.337×10^6
Total Displacement	0.00391 mm

**Figure 9: Von Mises Stress under Force of 50N.****Figure 10: Total Displacement under Force of 50N****Table 2 Properties of Turbine for a Force of 100N**

Force	100 N
Yield Strength	207 Mpa
Ultimate Tensile Strength	345 Mpa
Equivalent Strain	4.735×10^6
Total Displacement	0.007513 mm

**Figure 11: Von mises stress under Force of 100 N****Figure 12: Total Deformation under Force of 100 N**

Results showed that the material (Steel) assigned is safe for the operating condition of the Vertical Axis Wind Turbine with Factor of Safety of 8. Also, Since the yield strength of the material used is 207 Mpa and the maximum stresses generated in the member are 0.491 and 0.981 Mpa for a force of 50N and 100N respectively, the model will not fail during loading due to stresses. However, wind momentum and vortex effects are other major factors that could affect values of permissible stresses and also choice of materials. Furthermore, out of alignment of the turbine during rotation due to wind impact will adversely affect the output of the process, stability of the input and durability of the set up.

IV. Conclusion

The results of this research collectively provide a comprehensive understanding of the aerodynamic performance of the four airfoils under investigation at Reynolds numbers of 100,000. The data obtained from these analyses serve as a valuable resource for engineers and designers, guiding them in the selection and optimization of airfoils based on specific lift, drag, and stability requirements for diverse aircraft application.

Based on outcome of this article, it is recommended that experimental studies be conducted to validate the computational results obtained towards providing essential data for real-world performance assessment and offer a bridge between simulation and practical application. Also, to ensure the sustainable and responsible development of wind energy, it is imperative to investigate the environmental impact of VAWTs. This includes assessing noise levels, wildlife interactions, and visual aesthetics, thus addressing the broader ecological context

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