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Fatigue Analysis of H-Rotor Blade and Savonius Blade for a Micro Hybrid Vertical Axis Wind Turbine

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Abstract

Hybrid Vertical Axis Wind Turbines (VAWTs) integrate the ability to self-start from a Savonius rotor with the aerodynamic efficiency of Darrieus H-Rotor to become well-suited for decentralized energy production when there are relatively low wind speeds. Nevertheless, the structural integrity of hybrid turbine blades under cyclic loads has not been thoroughly addressed. This research work provides a structural and fatigue analysis of micro-scale hybrid VAWT, which comprises of a Savonius rotor along with an H-Rotor with NACA 0015 airfoil, using finite element modeling. A 3D model was created and analyzed using ANSYS Workbench with wind speeds at 5–8 m/s. Structural analysis resulted in von Mises stress values ranging between 15 and 95 MPa, remains within the range of yield strength of Aluminium Alloy 6061-T6, confirming structural efficiency of the proposed design. Fatigue analysis based on Stress-Life (S-N) analysis technique showed a fatigue life of 10–10 cycles. Thus, the results obtained show that the design is structurally reliable and fatigue resistant.

Keywords: Hybrid Vertical Axis Wind Turbine, Fatigue Analysis, Savonius Rotor, Darrieus H-Rotor, Finite Element Analysis, Renewable Energy.

1. Introduction

The increasing need for clean and sustainable energy sources have led to the advancement of renewable energy technologies that have the capability to reduce the reliance on fossil fuels

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and minimize greenhouse gases of all the renewable sources of energy, wind energy is considered as the most potential source due to its abundance, compatibility with the environment, and technical efficiency. HAWTs (Horizontal Axis Wind Turbines) are mostly used in large-scale power generation systems, although the operation of these devices is restricted in urban and areas where there are low wind speeds and has challenges in terms ofinstallation, wind directionality, and maintenance.

Out of all VAWT designs, the operating performance of the Savonius rotor and the Darrieus H-Rotor complement each other. Savonius rotor is a drag-based turbine design, which offers good self-starting performance as well as good performance under low wind speeds; however, it has a low aerodynamic efficiency. On the other hand, the Darrieus H-Rotor is a lift-based turbine design and offers good aerodynamic efficiency. However, it has poor self-starting performance under low wind speeds. By using the combination of both rotors in a single VAWT, one can make an efficient design where the high starting torque of the Savonius rotor is combined with the high aerodynamic efficiency of the H-Rotor.

Although remarkable progress has been made in terms of the aerodynamic design of hybrid vertical-axis wind turbines, relatively little work has been done on the structural design and fatigue behavior of such structures when cyclic loads are applied repeatedly. The blades of wind turbines are always under the action of varying aerodynamic and centrifugal loads, which could cause fatigue cracks and thus limit operational reliability.

In this research, a micro-hybrid VAWT that consists of a Savonius turbine with an H-Rotor equipped with NACA 0015 airfoil blades is analyzed through finite element method. Both static and fatigue analyses are conducted in ANSYS Workbench to analyze the stress distribution, deformations, fatigue life, fatigue damage accumulation, and factor of safety. The results obtained will shed light on the structural performance of the hybrid VAWTs and facilitate the design of feasible wind energy systems.

2. Literature Review

The use of Vertical Axis Wind Turbines (VAWTs) for decentralized power generation using renewable sources has gained much interest due to their capability of performing efficiently in conditions where wind direction and velocity are multidirectional and low, respectively.

When compared to HAWTs, VAWTs possess various benefits such as lower installation height, easier maintenance, low noise pollution, and insensitivity to wind direction. Several literature reviews on different types of VAWT configurations have shown that there is great potential for Savonius, Darrieus, and hybrid rotors for small-scale renewable energy generation but aerodynamic efficiency and durability remain as key issues [1], [2].

The aerodynamics of the lift-based Darrieus turbines have been widely studied using analytical, numerical, and experimental methods. The aerodynamic modeling has revealed that the blade shape, the airfoil shape, and the tip-speed ratio play an important role in determining the performance of the turbine in different wind regimes [3]. It has been observed that the optimized airfoil shape improves the aerodynamics of H-Rotor turbines operating in low wind regimes [4].

Further studies using numerical simulations to examine the blade pitch angle have also found that suitable optimization of blade pitch will increase the power coefficient along with reduced aerodynamics losses [5]. Likewise, variable pitch VAWT studies through both experiments and computation have shown improvement in their aerodynamic performance when compared to fixed-pitch systems [6]. Active pitch control is an effective method of increasing the performance of small H type Darrieus turbines [7].

Drag-type Savonius wind turbines have also been extensively studied owing to their outstanding self-starting ability and robust performance at low wind speeds. Experimental research has revealed that any changes in the design of the blades and the rotor can lead to increased torque production and better rotor performance [8]. In addition, literature review on optimization of Savonius rotor has established that variables such as overlap ratio, aspect ratio, end plates, and bucket shape play an important role in influencing aerodynamic efficiency [9]. Nevertheless, Savonius wind turbines still possess relatively low power coefficients compared to lift-type Darrieus turbines.

In order to address the limitations associated with the design of single rotor turbines, many researchers have suggested the idea of using a combination of Savonius and Darrieus rotors to form a hybrid VAWT. Comparatively speaking, studies have revealed that such designs are more efficient in terms of self-starting properties as well as aerodynamics than the regular Savonius wind turbines [10]. Recent studies have found that the hybrid Darrieus-Savonius wind turbines work by utilizing the starting torque generated by drag force and generating power using lift force, making them more efficient [11].

The accurate prediction of the aerodynamics continues to be an important part of wind turbine design. Researches, which are based on the Blade Element Momentum Theory (BEM), have shown that the aerodynamic modeling is important in order to predict the performance and optimize the turbine blade design in practical operation [12].

Though considerable advances have been made in the area of enhancing the aerodynamic and energy conversion efficiency properties of Savonius, Darrieus, and VAWTs hybrids, most of the research works carried out till date have mainly concentrated on the aerodynamic performance of the VAWTs. On the other hand, comparatively less research works has been carried out with respect to the structural behaviour of the hybrid turbine blades under repeated cyclic loading conditions, considering the fact that fatigue is one of the major modes of failure for wind turbines.

3. Methodology

This research study proposes a numerical approach to analyze the structural strength and fatigue behavior of a hybrid Vertical Axis Wind Turbine (VAWT) with a combination of Lift-driven H-Rotor and Drag-driven Savonius rotor. The numerical approach employed comprises steps such as aerodynamic design, geometrical modeling, Finite Element Analysis, and fatigue analysis due to wind loading.

The entire workflow followed during the investigation is illustrated in Figiure 1, the analysis starts with the selection of the hybrid rotor configuration and concludes with fatigue life assessment and interpretation of structural performance.

The hybrid arrangement was chosen to ensure that the rotor has the self-starting feature of the Savonius rotor along with the aerodynamic efficiency of the Darrieus H-Rotor. The profile of the H-Rotor blades was designed using the symmetrical NACA 0015 airfoil due to its effective lift and stable behavior at low Reynolds numbers.

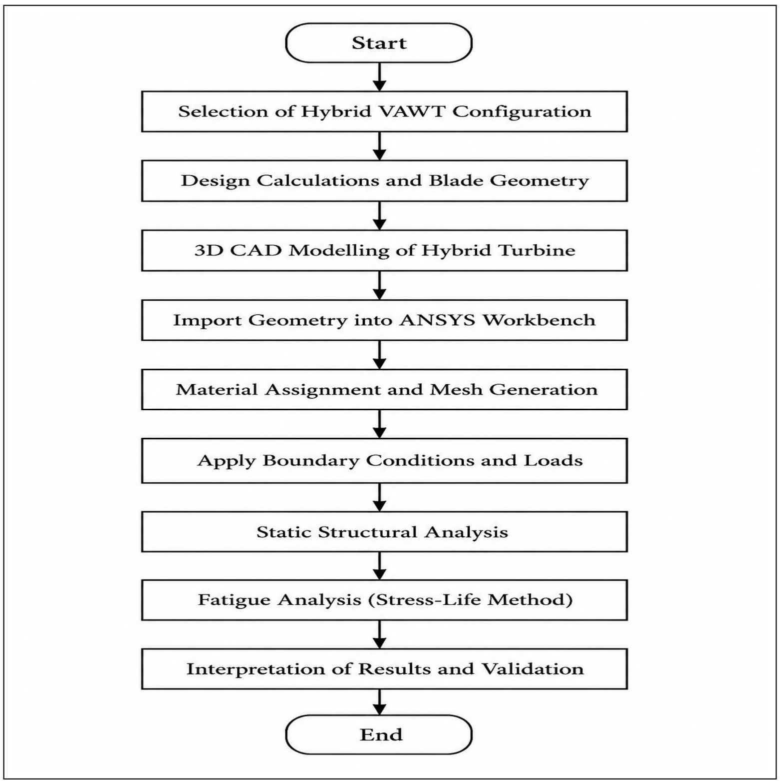

Figure 1. Workflow of the proposed methodology

The geometrical considerations such as blade height, chord, rotor diameter, shaft dimensions, and swept area were chosen according to the design guidelines for micro-scale VAWTs with wind speeds of 5 to 8 m/s. The mechanical power available from the turbine was estimated using

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

where, ρ is the air density, A is the swept area, V is the free-stream wind velocity, and C_p is the coefficient of performance of the hybrid turbine. These preliminary calculations established the operating conditions used in the numerical simulations.

The turbine assembly, which comprises of the Savonius rotor, H-Rotor blades, shaft, support arms, and hub assembly, was modeled using SolidWorks software and imported into the ANSYS Workbench for structural analysis. Certain minor geometry features that will have no bearing on the distribution of stress were removed from the model in order to make the analysis process efficient and quick.

Aluminium alloy 6061-T6 was chosen as the blade material owing to its good strength-to-weight ratio, high corrosion resistance, and appropriate fatigue properties. It

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was considered to be uniform, isotropic, and linearly elastic during the numerical simulation. Properties of the material used in the simulation are listed in Table 1.

Table 1. Mechanical properties of aluminium Alloy 6061-T6

Property	Symbol	Value	Unit
Density	ρ	2700	kg/m³
Young's Modulus	E	68.9	GPa
Poisson's Ratio	ν	0.33	—
Yield Strength	y	276	MPa
Ultimate Tensile Strength	u	310	MPa
Shear Modulus	G	26	GPa
Fatigue Strength (10 cycles)	f	96	MPa

Higher order solid tetrahedral elements were used to perform the mesh discretization of the imported geometry, including localized mesh refinement in the regions of the blade root, shaft junction, support arm joints, and welds where high stress concentrations are expected. The mesh generated from the imported geometry of the hybrid turbine is illustrated in Figure 2, showing proper discretization of the structural model to predict the regions of stress concentration.

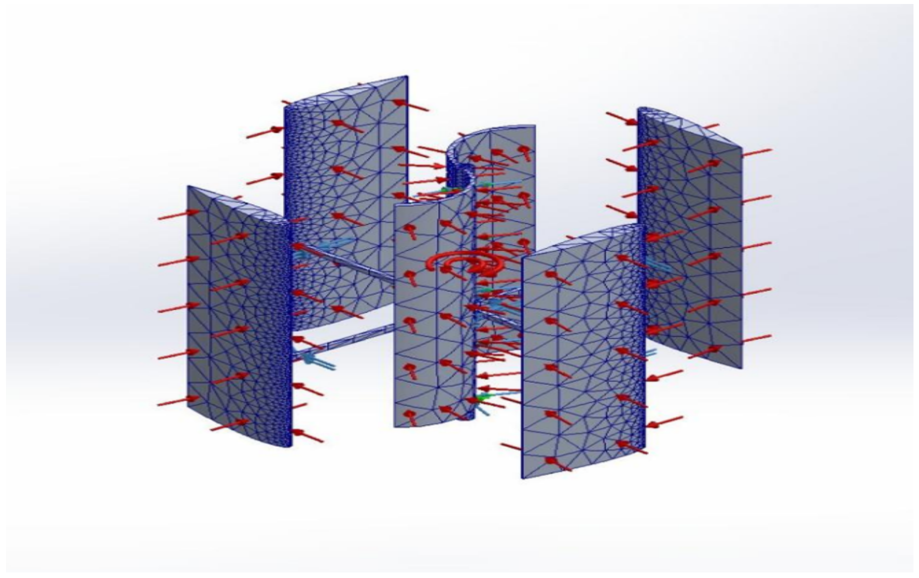


Figure 2. Meshed model of hybrid savonius–darrieus vertical axis wind turbine for structural analysis

The shaft was restrained through the application of a fixed support in order to simulate the real-life constraint condition, while loads of pressure based on wind speeds ranging from 5-8 m/s were applied perpendicular to the surfaces of the blades. At the same time, the loading due to centrifugal forces resulting from rotation at speeds ranging from 150-300 rpm was modeled into the structure to simulate the inertial effect felt by the turbine. The loading conditions and constraints are shown in Figure 3 below.

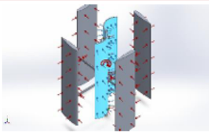
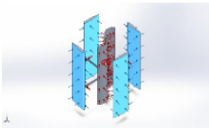
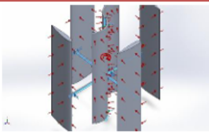
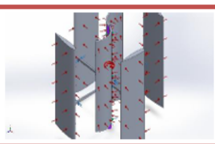
Load name	Load Image	Load Details
Pressure-1		Entities: 4 face(s) Type: Normal to selected face Value: 60 Units: N/m^2 Phase Angle: 0 Units: deg
Pressure-2		Entities: 4 face(s) Type: Normal to selected face Value: 65 Units: N/m^2 Phase Angle: 0 Units: deg
Pressure-3		Entities: 9 face(s) Type: Normal to selected face Value: 30 Units: N/m^2 Phase Angle: 0 Units: deg
Centrifugal-1		Centrifugal, Ref: Face< 1 > Angular Velocity: 100rpm Angular Acceleration: 100rpm^2

Figure 3. Boundary conditions and load application on hybrid savonius–darrieus rotor blades

Static Structural Solver from ANSYS Workbench was used to determine the equivalent von Mises stress, total deformation, and equivalent elastic strain of the turbine structure. The stress obtained was later used to perform fatigue analysis based on Stress-Life (S-N) method that is found in ANSYS Fatigue Module. Fatigue damage accumulation was estimated using Miner's linear cumulative damage theory,

$$D = \sum_{i=1}^{n} \frac{n_i}{N_i}$$

where n_i represents the applied loading cycles and N_i denotes the corresponding cycles to failure obtained from the S–N curve of Aluminium Alloy 6061-T6. In fatigue analysis, the predictions of fatigue life, cumulative damage, and factor of safety were obtained, which makes it possible to detect those regions that can develop cracks and eventually lead to degradation of the structure. Thus, the approach allows for a complete analysis of not only the instantaneous

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response of the structure but also its lifetime.

4. Results and Discussion

Structural performance analysis of the hybrid Vertical Axis Wind Turbine (VAWT) rotor under the mentioned loading conditions was carried out with the help of a finite element model of the rotor which was created in ANSYS Workbench. The numerical analysis involved an examination of structural behavior due to aerodynamic loading and centrifugal forces.

The principal results obtained from the static structural and fatigue analyses are summarized in Table 2.

Table 2. Summary of static structural and fatigue analysis results for the hybrid VAWT

Parameter	Numerical Result	Engineering Interpretation
Operating wind speed	5–8 m/s	Low wind speed operating condition
Rotor speed	150–300 rpm	Typical operating range
Equivalent von Mises stress	15–95 MPa	Below the yield strength of Al 6061-T6
Maximum equivalent strain	0.0004–0.0014	Elastic deformation region
Maximum blade-tip deformation	0.5–2.0 mm	Adequate structural stiffness
Estimated annual loading cycles	7×10^7 cycles	High-cycle fatigue regime
Estimated design life cycles	4×10^8 cycles	Six-year operating life
Predicted fatigue life	$10^8 - 10^9$cycles	Satisfactory fatigue resistance
Fatigue factor of safety	1.8–2.5	Structurally safe under cyclic loading
Critical stress locations	Blade root, shaft interface, welded and bolted joints	Regions requiring design attention

As shown in Table 2, the computed equivalent stress is far less than the yield strength of Aluminium Alloy 6061-T6, demonstrating that the blades will always deform elastically in the tested operating range. Likewise, the calculated values for deformation and strain are low enough to maintain the aerodynamic shape of the blades in the process of the turbine working. The obtained results are presented in Figure 4 to 7, prove that the chosen geometry of the blades ensures sufficient stiffness with minimum deformation, which can negatively impact the aerodynamic performance and durability.

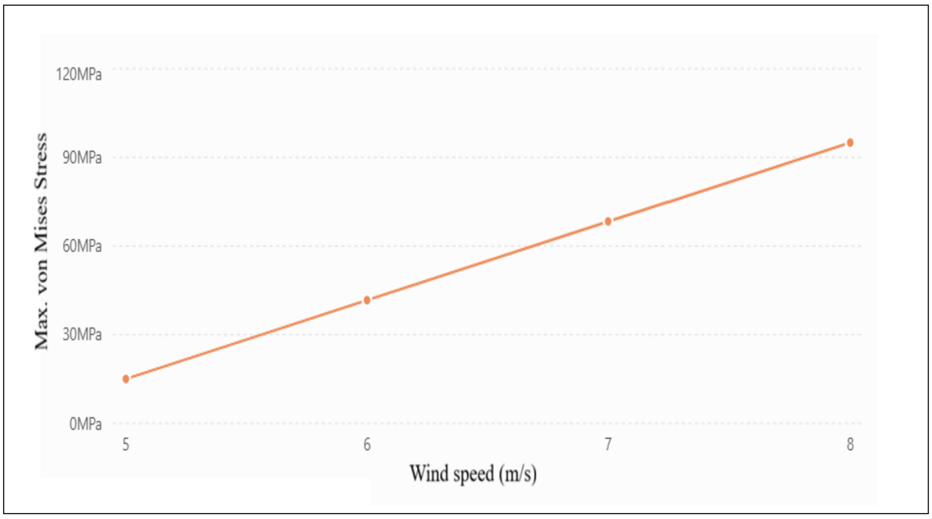

Figure 4. Variation of maximum von mises stress with wind speed

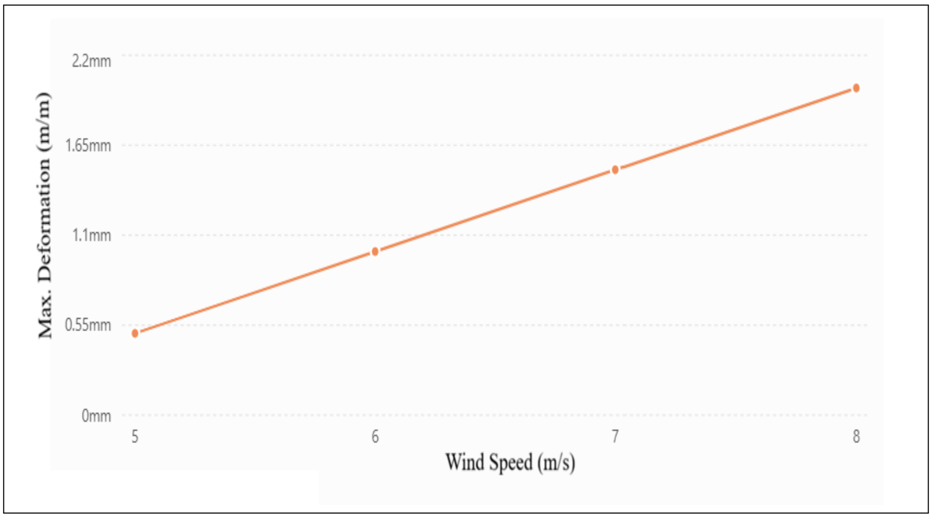

Figure 5. Variation of maximum blade-tip deformation with wind speed

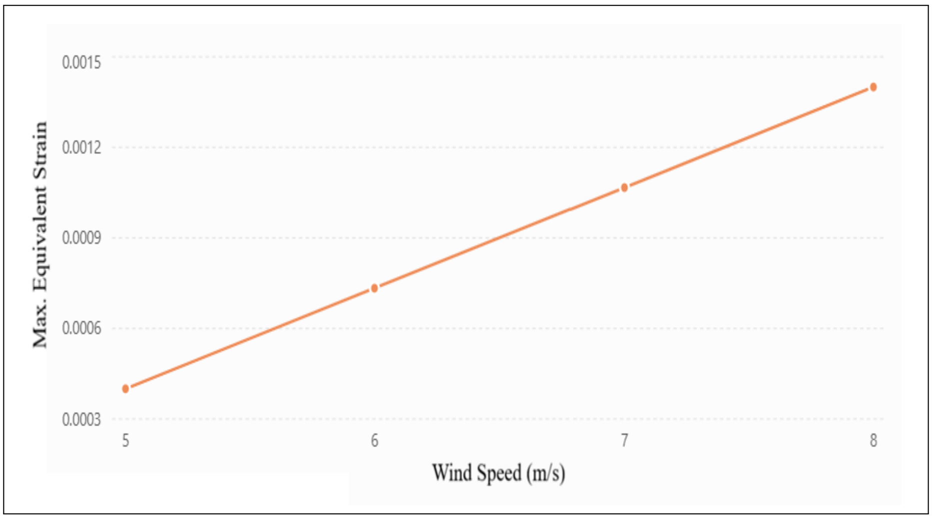

Figure 6. Variation of maximum equivalent elastic strain with wind speed

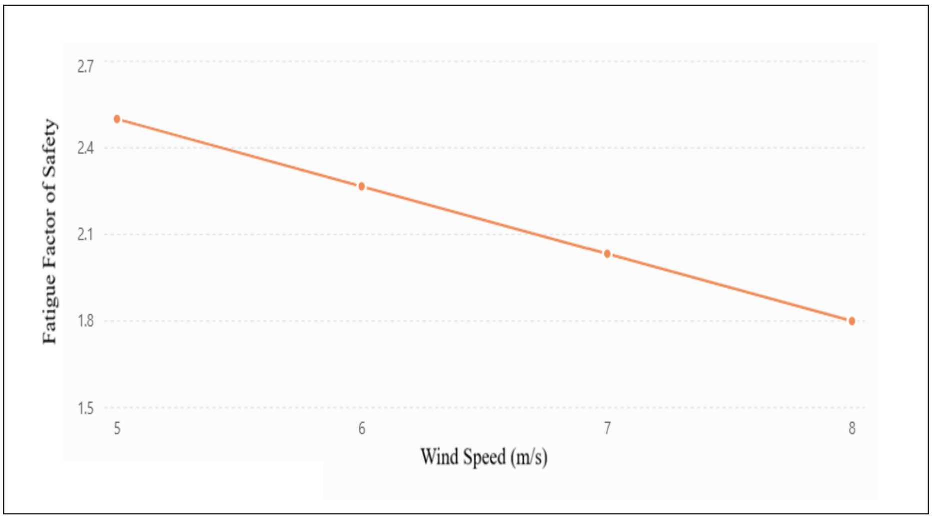

Figure 7. Variation of fatigue factor of safety with wind speed

The effect of wind speed on the structural and fatigue factors is shown in Figures 4-7. Maximum von Mises stress, deflection at the tip of the blade, and equivalent elastic strain increase with the increasing wind speed due to higher aerodynamic forces, whereas the fatigue safety factor decreases in proportion. The outcomes fall within the acceptable range of structural and fatigue values, demonstrating sufficient stiffness and elastic behavior of the blade. The maximum stress and fatigue susceptibility are observed at the root of the blade, shaft connections.

The fatigue analysis also supports the long-term structural reliability of the suggested hybrid design. The expected fatigue life is greater than the total number of cycles the structure is subjected to, whereas the calculated factor of safety is always greater than one. It means that the chosen materials and the blade geometry are able to resist cyclic loads for a long period without experiencing fatigue fractures. However, the distribution of fatigue damage shows that cracking is likely to start in the vicinity of the blade root, shaft connection, welded joints, and bolted joints due to stress concentration in these areas.

The overall results from the numerical analysis show that the combination of Savonius and H-Rotor designs offers both aerodynamical and structural advantages. The use of the Savonius rotor increases the turbine's self-starting ability in areas of low wind speeds, while the H-Rotor design helps to increase the aerodynamic efficiency of the turbine during its steady-state running. This combination of designs shows an ability to operate within good levels of stress, structural deflection, and fatigue endurance.

5. Conclusion and Future Scope

This study presented an investigation of the structural behaviour and fatigue performance of a hybrid Vertical Axis Wind Turbine comprising a Savonius rotor and a Darrieus H-Rotor with a NACA 0015 airfoil. A finite element model was developed in ANSYS Workbench to evaluate the effects of aerodynamic pressure and centrifugal loading on the structural response of the turbine. The analysis demonstrated that the maximum equivalent stress remained below the yield strength of Aluminium Alloy 6061-T6, confirming that the blades operate within the elastic deformation region. The predicted deformation was sufficiently small to maintain structural stability, while the fatigue assessment indicated a service life exceeding the estimated operating cycles with a satisfactory factor of safety. The critical regions susceptible to fatigue damage were identified at the blade root, shaft interface, and connection points, providing guidance for future structural refinement. Overall, the results confirm that the proposed hybrid VAWT exhibits adequate structural strength and fatigue durability for low wind speed applications, demonstrating its potential as a reliable solution for decentralized renewable energy generation.

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