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Research Paper

Structural Optimization-Based Enhancement of the Dynamic Performance for Horizontal Axis Wind Turbine Blade

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Abstract. Wind energy is simple and environmentally friendly, it takes the energy of the wind to produce electricity. Wind turbines that have rotor blades connected to generators can efficiently harvest this energy from the wind's motion. The optimization of wind turbine blades is crucial to the success of wind energy technology, beyond the simple mechanical advantage, the pursuit of structural enhancements that have a significant impact on dynamic performance is also involved. This research aims to improve the efficiency and power of wind turbine blades in order to enhance the efficiency and power of the devices. It employs a complex optimization framework that combines aerodynamics and structural analysis via MATLAB and a genetic algorithm. The investigation maximizes the length of the chord, the angle of twist, and the selection of airfoils while maintaining constraints. This work investigates various geometric variables and employs numerical calculations on top of high-performance computing with ANSYS Fluent and ANSYS Structural. The results show significant enhancements in blade performance near the root, which supports the framework's legitimacy. The investigation also focuses on the necessity of estimating torque and the frequency of blade modes in order to reduce the cost of maintenance and ensure operational reliability. This research demonstrates the transformative power of wind turbine blade optimization, it promotes innovation and sustainability in the field of clean energy by achieving 50% improvement in aerodynamic performance and 14% improvement in the modal frequency of the blade while maintaining the weight of the blade.

Keywords: Aerodynamic Performance, CFD, Genetic Algorithm, Blade Element Momentum (BEM), Modal Frequency.

1. Introduction

Renewable energy, which is derived from naturally replenishing reservoirs, has a significant role in mitigating the effects of climate change while also providing a dependable energy source. Among environmentally friendly technologies, wind power is a simple solution that utilizes the energy of motion in the air to produce electricity [1-4]. Wind turbines that have rotor blades connected to generators take advantage of the wind's energy by rotating with the wind's force, these turbines utilize the wind's flow over the blades to generate lift and begin to rotate. The spinning blades, in turn, produce electricity via the generator, this is accomplished through the use of a magnetic field. Wind power has become a significant component of the global power production industry, with wind farms having a significant role in the production of clean energy [5]. China, the U.S., Germany, and India are leading nations in terms of wind power capacity, their renewable energy goals are accomplished successfully [6]. Wind generators come in a variety of types, each designed to perform a specific function. Among two primary types, the Horizontal-Axis Wind Turbine (HAWT) is the most popular of them all, it is used in a variety of different settings, including large-scale utility wind farms, decentralized energy generation, and residential applications. Notably effective, HAWTs have the ability to produce power in response to varying wind speeds [7].

Conversely, Vertical Axis Wind Turbines (VAWT) have a distinct profile. VAWTs have benefits like having an omni directional wind signature and being appropriate for urban areas [8]. However, it is crucial to recognize the diverse landscape of wind turbine designs, this has led to a complex endeavor that is multidisciplinary in nature. The process of optimization extends past the mere efficiency of aerodynamics, it also encompasses structural enhancements that have a significant impact on dynamic performance. Within this context, structural optimization is of paramount importance. Increasing the structural design of wind turbine blades involves a multi-faceted approach towards improving their dynamic capabilities. This is of special importance in the long-term stability and reliability of wind power plants in different operating environments.

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Profile	NACA 4412	Diameter	3000mm
r/R	Twist [deg]	r/R	Chord [mm]
0.067	24.5	0.067	255
0.133	22	0.133	236
0.2	15	0.2	196
0.267	10	0.267	156
0.333	6.5	0.333	130
0.4	4	0.4	110
0.467	3	0.467	95
0.533	2	0.533	84
0.6	1.1	0.6	76
0.67	0.5	0.67	67.74
0.733	0	0.733	62
0.8	-0.5	0.8	57
0.867	-0.9	0.867	53
0.933	-1.3	0.933	49
1	-1.8	1	48

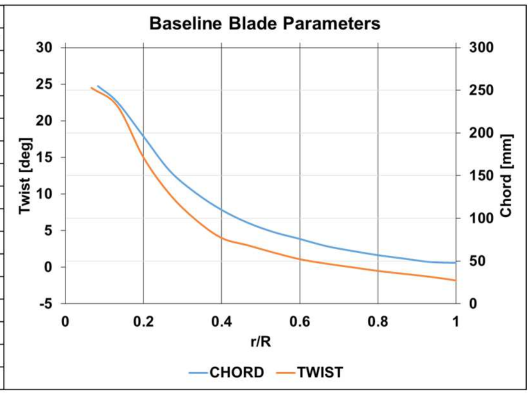


Fig. 1. Baseline blade properties [17].

Over time, the fields of science, technology, and wind power plant utilization have gained a lot of knowledge regarding the effects of factors on the efficiency and cost of wind power plants. Recent research in the field of wind turbine blade design and optimization has been noteworthy. Song [9] utilized MATLAB to optimize a 2 MW turbine that employed the Wilson method and space-based transformation theory for the location of the blade's elements. Dynamic performance analysis was accomplished by combining SolidWorks with ANSYS. Wang [10] employed a theory of blade elements that had 11 degrees of freedom, a more refined model for tip loss correction, and a more extensive database. The goal was to minimize energy expended by adjusting the variables associated with the blade's shape parameters. The experimental tests on wind turbine blades yielded data that were of great value in the finite element numerical analysis of structural behavior, the purpose was to predict the fatigue life of the structure. Hu Park's research [11] on structural optimization of a 2 MW turbine blade for a minimum weight and cost, while adhering to various requirements. Barnes [12] evaluated the effects of different structural geometries in turbine blade designs, while Neto [13] developed a method for optimizing the rotor blade's structural geometry. Yang [14] described a discrete optimization method that was specifically designed to operate at low wind speeds, this method increased the annual production of energy by approximately 7.96% through blade changes. Malawi [15] introduced an optimization model for designing horizontal-axis wind turbine blades. This model primarily focuses on optimizing the main spar, which is depicted as a thin-walled tubular beam composed of uniform segments with distinct cross-sectional properties and lengths, aiming to achieve the maximum frequency design criterion. The crucial element in the aerodynamic contour design of wind turbine blades is the air-inducible factor. Calculating the axial and circumferential inducible factors for wind turbine blades poses challenges due to the blade's complex spatial configuration. Moreover, modern high-performance wind turbine blades are constructed using composite layer structures, making precise modeling, especially capturing the layer structure accurately, a formidable task. This complexity necessitates an iterative optimization process to achieve a viable wind turbine blade design. Pourrajabian [16] introduced an aero-structural design method with a focus on the initial phase of small wind turbine blades. The study emphasized rapid startup by considering startup time and output power in the objective function while adhering to stress constraints. They used blade-element momentum theory to compute output power and startup time. Vahid [17] employed the blade element momentum technique and the differential evolution algorithm for optimization. The research emphasized the impact of airfoil type on turbine startup performance, with the SG6043 airfoil excelling in power coefficient and the BW-3 airfoil in startup time. Amer [18] focused on multi-cross-section HAWT blade designs with and without fences, showcasing a remarkable 16% increase in the total power coefficient and improved flutter stability with strategically placed fences. Battaso [19] presented a comprehensive multidisciplinary design optimization approach for wind turbines, emphasizing merit function maximization and constraint adherence through high-fidelity simulations. Recent developments in multi-objective optimization techniques will be discussed, highlighting their role in balancing multiple design criteria such as efficiency, cost, and reliability. These techniques are essential for achieving optimal performance while meeting various conflicting objectives in turbine design. In the similar context, the use of surrogate models, which provide computationally efficient approximations of complex systems, will be explored. These models are crucial for reducing computational costs and accelerating the optimization process, allowing for more rapid and effective exploration of design options. The integration of design of experiment (DOE) with optimization methods will be examined, emphasizing how structured experimentation can enhance the design process. DOE helps in systematically exploring design variables and understanding their effects, which, when combined with optimization techniques, leads to more informed and robust turbine designs. These studies collectively advance wind turbine blade optimization, addressing factors like startup time, airfoil type, and multidisciplinary design while enhancing efficiency and performance.

This research, however, focuses on optimizing small wind turbine blades, maximizing their aerodynamic efficiency and structural integrity by increasing modal frequency while keeping the weight constant or reducing it. Multidisciplinary optimization is the key, using MATLAB for a robust framework that integrates aerodynamics and structural analysis. High-fidelity Computational Fluid Dynamics (CFD) simulations will assess aerodynamic performance, while structural analysis with ANSYS Workbench ensures reliability. Fluid-structure interaction (FSI) analysis will capture the dynamic interaction between aerodynamics and structure, fine-tuning the blade design for optimal performance and safety. The ultimate phase of this research encompasses the empirical validation of the optimized wind turbine blade. Incorporating multidisciplinary optimization, high-fidelity CFD analysis, structural assessments through ANSYS, Fluid-Structure Interaction analysis, and empirical testing, this research is fundamentally focused on delivering a wind turbine blade design distinguished by its superior efficiency and structural soundness. It is geared radically towards advancing the field of clean and sustainable energy.

The paper is organized according to the following plan. The first section discusses the baseline wind turbine blade selected for the study, including its properties and optimization results from previous research. The second section describes the multidisciplinary design optimization framework used in the study, which involves using MATLAB for a robust framework that integrates aerodynamics and structural analysis. The third section focuses on wind turbine blade design and optimization in the multi-disciplinary optimization (MDO) framework, including the design criteria utilized during the optimization process and the methodology used to compute the forces and power generated by the wind turbine. The section also discusses the MATLAB framework developed to design a small wind turbine for desired output power and the optimization process used to reach an optimum design. Finally, the paper concludes with a discussion of the empirical validation of the optimized wind turbine blade and its potential for advancing the field of clean and sustainable energy solutions.

Table 1. Optimized blade properties from [17].

Profile	SG6043	Diameter	2420 mm
r/R	Twist (degree)	r/R	Chord (mm)
0.132	16.218	0.132	244.42
0.193	24.132	0.193	211.75
0.253	19.922	0.253	208.12
0.312	13.523	0.312	142.78
0.37	11.503	0.37	130.68
0.43	9.145	0.43	121
0.492	7.293	0.492	104.06
0.551	5.946	0.551	91.96
0.611	5.104	0.611	84.7
0.673	4.43	0.673	82.28
0.73	4.093	0.73	78.65
0.792	2.241	0.792	70.18
0.852	2.409	0.852	72.6
0.912	1.736	0.912	71.39
1	0.22	1	62.92

2. Wind Turbine Blade Baseline

The selected baseline wind turbine blade belongs to Anderson et al. [20]. The same blade was recently validated by Vahid [17] by using a framework for multidisciplinary design optimization of small application horizontal axis wind turbines. Figure 1 shows the properties of the baseline blade.

Vahid [17], later optimized wind turbines for multiple airfoil sections. He presented that for a production of 1 kW power, a 3-blade horizontal axis wind turbine with blade section of SG6043 produces maximum power and takes second best least time to startup.

In this research, we will use the blade optimized by Vahid [17] and optimize it further through a novel method for wind turbine blade optimization. Additionally, in order to add to the work done by Vahid [17], we will also perform structural design and optimization of the same blade. Table 1 lists the properties of the optimized blade.

3. Multidisciplinary Design Optimization Framework

Multi-disciplinary optimization (MDO) is an engineering and design approach that involves simultaneously optimizing multiple interacting disciplines or subsystems within a complex system. Figure 2 shows the flow chart for Multidisciplinary Design Optimization (MDO). The framework is coded in MATLAB to form a tool. All the necessary computations and analyses are performed in MATLAB environment except the final computational fluid dynamic (CFD) simulations and computational structural analysis performed in high fidelity analysis tools. The optimization process is automatic and needs no user input apart from the input required to state the user requirements and specifications to start the optimization process. The user requirements include 4 parameters, namely desired power output, wind speed for which the blade should be optimized, number of blades required in a single wind turbine, and wind turbine radius. The blade is designed using blade element and momentum theory, keeping the Betz limit in mind which is derived from the axial momentum theory of rotors with a theoretical maximum value of power coefficient not exceeding 0.593. The profiles of the blade are arranged along the length of the blade at the maximum lift-to-drag ratio angle of attack. This angle of attack for each blade profile is calculated using 2D aero analysis in XFOIL. The framework utilizes the evolutionary optimization algorithm of genetic algorithm to manipulate the chord, twist, and skin thickness of the blade to reach an optimum design equally suitable in the context of aerodynamic and structural requirements desired and input by the user. The flow chart for activities performed for validation of results acquired through optimization framework, aerodynamic analysis through CFD, and structural analysis through static /one-way FSI. To achieve optimal aerodynamic performance of the blade, it is essential to determine the lift and drag coefficient of the airfoil used in each part of the blade. Access to experimental polar for airfoils is infrequent. In addition, due to the large number of airfoils generated by the design technique doing wind tunnel studies for each airfoil appears to be unfeasible. The Xfoil code [21] has been utilized to create numerous specialized airfoils [22, 23] due to its efficient and reliable viscous/inviscid interaction method. This schematic is crucial in illustrating the practical engineering application of the problem, highlighting how the proposed approach can be implemented in real-world scenarios. By incorporating this figure, it is aimed to bridge the theoretical aspects of our research with its practical utility, thereby enhancing the overall understanding of the problem's significance from an engineering perspective.

3.1. Wind Turbine Blade Design and Optimization in MDO Framework

When embarking on the conceptual design of a wind turbine blade, specific user requirements and design criteria come into play. These design considerations encompass factors such as blade configuration, rotor diameter, structural integrity, material selection, aerodynamic efficiency, and the blade's potential for energy capture. Table 2 outlines the essential design criteria utilized during the optimization, serving as the benchmark against which the feasibility of a particular blade design is evaluated and refined. The objective function of optimization is to increase the power efficiency and structural integrity. The optimized blade is further optimized using the genetic algorithm (GA) evolution-inspired optimized function in MATLAB to achieve a more refined and optimized blade shape. During optimization, the hub part of the blade is not optimized and kept constant. The hub radius for this research is kept at 15% of the total blade radius. Table 3 shows the design variable, population size, and number of generations used in GA optimization.

The objective function is to improve the aerodynamic performance and structural integrity by increasing the power coefficient and calculating the minimum thickness required for the blade to operate on the design requirement such that the maximum flapwise deflection does not exceed 1% of the total blade radius. Equation (1) shows the objective function.

Objective function:

$$F_{obj} = \propto \times (C_{pd} - C_i) \times \beta \times (t_d - t_i) \tag{1}$$

Table 2. Design criteria.

Parameters	Values/range
Configuration	3 blade HAWT
Diameter	3 m
Material	Epoxy Carbon Woven
Coefficient of Power (C_p)	> 0.4
Wind Speed	8 to 12 m/s

Table 3. Design variable, population size, and Generations for Genetic Algorithm implementation.

Blade section = 15	Population size = 2 x 31 = 62 Generation 100 to start with
Design variable	Values
chord	15
twist	15
thickness	1 (uniform thickness at all sections)
total	31

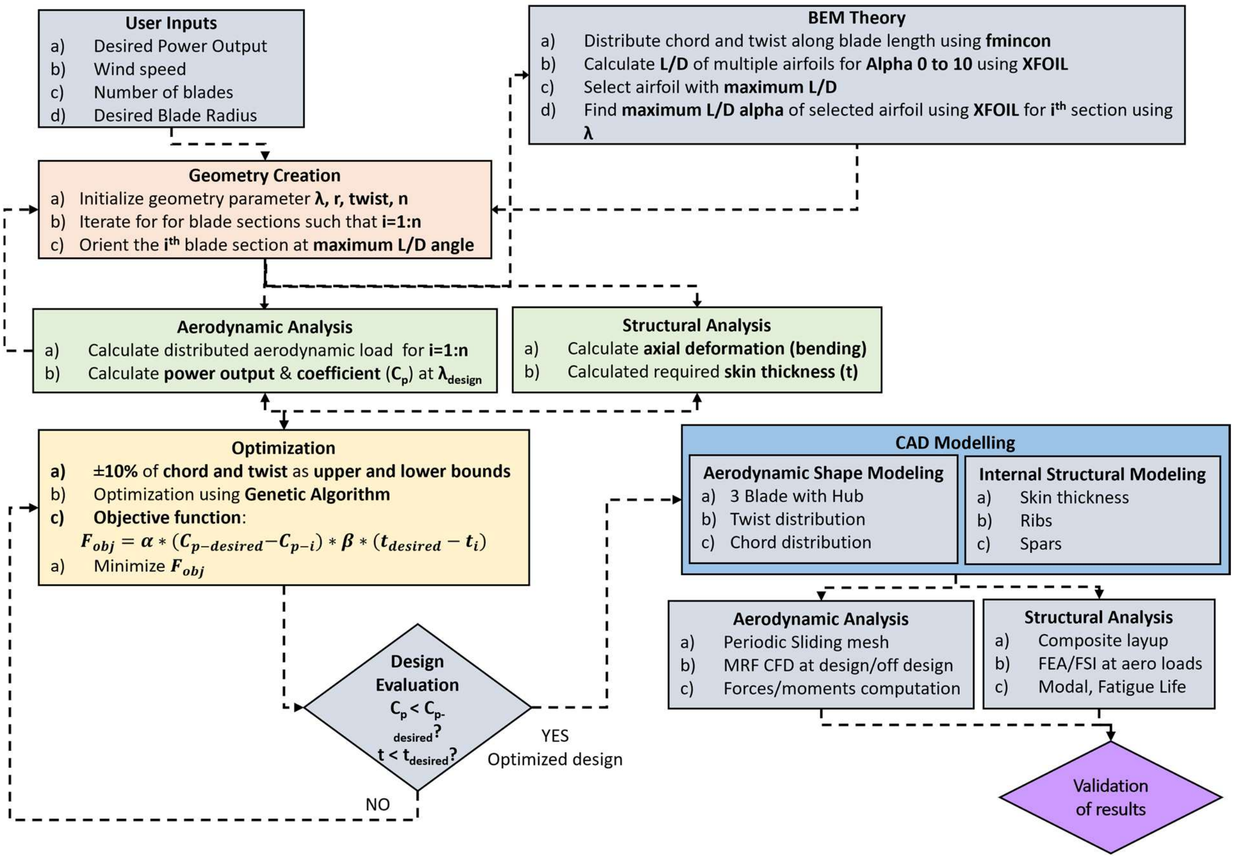


Fig. 2. Flow chart for multi-disciplinary optimization (MDO) framework and validation.

where: t: skin thickness, $\propto$, β: the weightages.

Based on these design criteria, a group of suitable airfoils is selected for the expected aero loads and thickness of the airfoil required. Geometric twist and chord distribution along blade length are then computed using Blade Element Momentum (BEM) theory. The BEM method, sometimes referred to as the strip theory or Glauert/Wilson method, stands as a cornerstone in classical wind turbine rotor aerodynamics [24]. This method ingeniously merges two fundamental theories: momentum theory and blade element theory. Its elegant approach takes advantage of the rotor's geometry by dividing the wind turbine blade into numerous sections. Each of these sections sweeps through an annular area as the rotor elegantly rotates. Importantly, these annuli exist in relative isolation, devoid of any mutual interaction. In essence, this methodology decomposes the stream tube along various radial positions, creating distinct annuli, each equipped with its bespoke momentum balance. By partitioning the wind turbine blades into these annular blade elements and meticulously applying one-dimensional linear momentum conservation principles to each annular element, the BEM method adeptly computes the forces and power generated by the wind turbine. This intricate calculation process is anchored in the fundamental parameters of the sectional airfoil lift and drag coefficients, chord lengths, and twist angles that define the blade's geometry. The essential aerodynamic data for these airfoils, namely the lift, drag, and moment coefficients, are typically derived from meticulous wind tunnel measurements, providing the foundation for the BEM analysis. Wood et al. [25] identified the need to incorporate the wake vorticity term into the axial momentum equation. While this modification might not encompass all necessary changes for precise calculations in the high-thrust region, it is anticipated to be a crucial factor. Additional experimental data in the vicinity of the runaway condition is essential for finalizing the BEMT revision. Similarly, Martínez et al. [26], introduces a modified BEM model that successfully matches experimental power curves from diverse wind turbine tests without free fit parameters, demonstrating its effectiveness across various conditions and blade configurations.

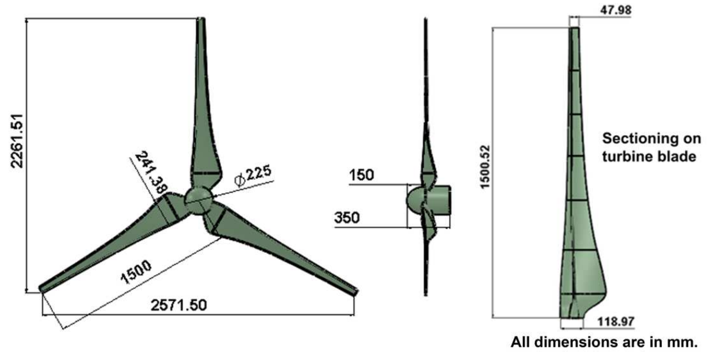


Fig. 3. Blade solid CAD model.

To illustrate the concept further, the figure of blade is presented in Fig. 3, which vividly portrays the division of the wind turbine blade into distinct sections, each representing an annular element as it interacts with the oncoming wind. The BEM method allows for a granular examination of these elements' performance, leading to a comprehensive understanding of the wind turbine's behavior.

This ideal power output is used as a reference to get an optimized blade in such a way that the output power of the resulting blade is as close to this as possible. The code then calls the Xfoil software to generate the airfoil data required for fitness function evaluation. Xfoil is MATLAB's internal software used to analyze 2D sections for aerodynamic loads and moments. The aero data generated by Xfoil is then used in the power co-efficient calculation of the blade using the formula below as shown in Eq. (2) and Eq. (3):

$$P = \frac{1}{2} \times \rho \ \times A \times C_P \times V^3 \tag{2}$$

where P: The ideal power (in Watts); ρ: Air density (in kg/m^3); A: Swept area of the rotor (in m^2); C_P: Power coefficient (dimensionless); V: Wind speed (in m/s).

$$C_P = \frac{8}{\lambda^2} \times \int_{\lambda_r}^{\lambda} {\lambda_r}^3 \, a'(1-a) \left(1 - \frac{C_D}{C_L} \cos\phi\right) d\lambda_r \tag{3}$$

where λ is the tip speed ratio, λ_r is the local speed ratio, a and a' are the axial and rotational induction factors, C_L, C_D are the lift and drag coefficient, ϕ is the flow angle.

The chords and twists of blade sections are iteratively changed using BEM theory guidelines in such a way the final output power is as close as possible to the ideal output power.

Chord length (C) and twist angle (θ_r) can be calculated as follows in Eq. (4) and Eq. (5) [24]:

$$C = \frac{8\pi r}{NC_L} \left(\frac{\sin\phi}{3\lambda_r} \right) \tag{4}$$

$$\theta_r = \phi - \alpha \tag{5}$$

where ϕ is flow angle and α is the angle of attack.

The axial (dF_x) and tangential (dF_y) forces on a blade element can be obtained as follows in Eq. (6) and Eq. (7) [16]:

$$dF_x = \frac{1}{2} \rho V^2 c dr (C_L \cos\emptyset + C_D \sin\emptyset) \tag{6}$$

$$dF_y = \frac{1}{2} \rho V^2 c dr (C_L \sin\emptyset - C_D \cos\emptyset) \tag{7}$$

Aerodynamic torque can be calculated as follows in Eq. (8):

$$dQ = r dF_y = \frac{1}{2} \rho V^2 c r dr (C_L \sin\emptyset - C_D \cos\emptyset) \tag{8}$$

The optimized angle of attack and chord length for each blade section along blade length is computed using 2D aero analysis in XFOIL. This is an iterative process in which each blade section is analyzed at multiple angles of attack to find the angle of attack corresponding to the maximum lift-to-drag ratio. Similarly, the chord length is also varied to reach an optimum L/D and required airfoil thickness chord length. Figure 4 shows the convergence history of chord length for each blade section. The whole process is automatic and incorporated using MATLAB scripting using a constraint minimization algorithm where the objective function, i.e., L/D and thickness of airfoil, is calculated using XFOIL.

It is desirable to keep angle of attack constant along blade length so that the blade can operate at maximum L/D. However, if the blade section profile is changed along the blade length, then the angle of attack will vary but in our case the blade section profile is kept the same along blade length. It is between 5.5 and 6 degrees. The exact angle of attack prediction for maximum L/D is actually tricky and with low fidelity tools it will always be an approximate number.

3.2. Geometry Parametrization and Internal Layout

Geometry is generated through parametrized blade planform, blade section twist, number of blades, blade radius, airfoil and skin thickness using user inputs as constraints wherever applicable. Blade planform is parametrized using eight geometric parameters. These parameters are interdependent and the efficiency of the optimization framework is highly dependent on these parameters. For this research, the 15-blade sections were used for 3-blade HAWT with a 3m diameter. Table 4 explains these parameters.

Table 4. Geometric parameters and design variables.

Variable	Values
Radius of blade [m]	r
Number of blades	N
The number of sections the blade is divided into	n
Twist angle of each section [deg]	[1 x n]
The chord length of each section [m]	[1 x n]
Radial location of blade section	[1 x n]
The composite layer thickness along the blade radius	[n x n]
Airfoil	SG6043

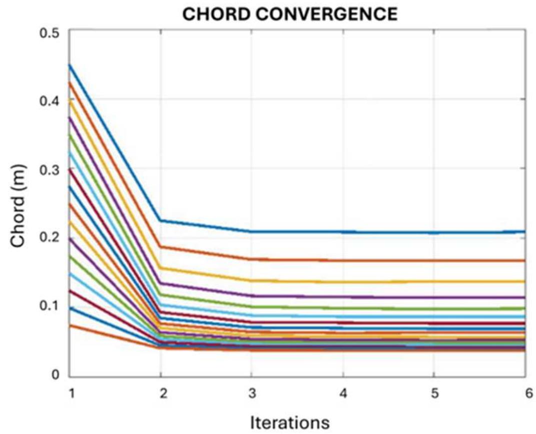


Fig. 4. Chord and convergence history along the blade length.

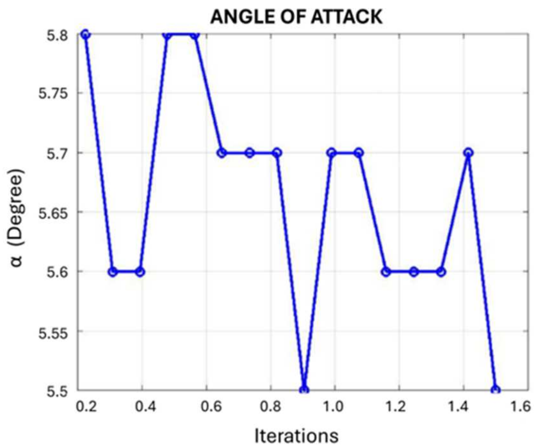


Fig. 5. Angle of attack and convergence history along the blade length.

3.3. Aerodynamic Analysis of Wind Turbine Blade

The optimized blade is then opened in ANSYS SpaceClaim to prepare the CAD model for meshing and subsequent aerodynamic analysis. The process of setting up and running a CFD simulation for wind turbine blade analysis can be computationally intensive. Careful attention to model preparation, mesh generation, boundary conditions, and turbulence modeling is essential for obtaining accurate and meaningful results. The aerodynamic analysis aims to numerically simulate the wind turbines to validate the power output promised by the optimization framework, find the wind power output at off-design conditions, and find out the aerodynamic/structural load required to qualify the blade for successful operation in the field.

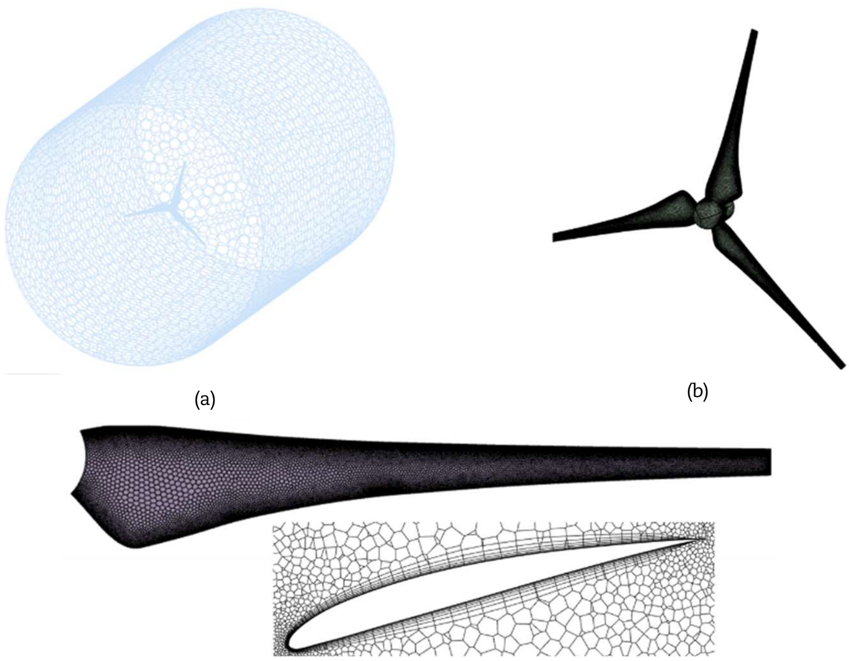
While meshing, careful attention, and required refinement are needed on the leading edge, trailing edge, and other high curvature areas of the geometry to capture the actual flow physics at these areas. A coarse mesh or large surface mesh cells can result in divergence or unrealistic results of pressure and velocity distribution in these areas. Figure 6 shows the mesh generated for the analysis of the optimized blade. It can be seen that very small mesh cells with high refinement are generated in regions of high curvature around the hub, leading edge, and trailing edge of the blade. To ensure uniformity in mesh, a mesh refinement density was applied through the length of the blade. Other mesh-related important parameters are listed in Table 5. The parameter *D* represents the diameter of the wind turbine.

3.4. Structural Design and Optimization

The structural design of wind turbine blades directly affects their aerodynamic performance. Appropriate design weight and material selection ensure that the blades efficiently convert wind energy into rotational motion and maximize the power output. The design weight of the wind turbine blade directly affects the start time and starting wind energy requirements for power generation. In this regard, special considerations should be made to keep the net weight of a single blade below the thrust or lift produced by the single blade at the design tip speed ratio. Considering a 10-degree rotation of a static turbine, an equation for the approximate net weight of a wind turbine single blade can be derived using force and moment equilibrium, as shown in Fig. 7(a). Figure 7(b) demonstrates the cross section as well as the interior reinforcing structure of the blade.

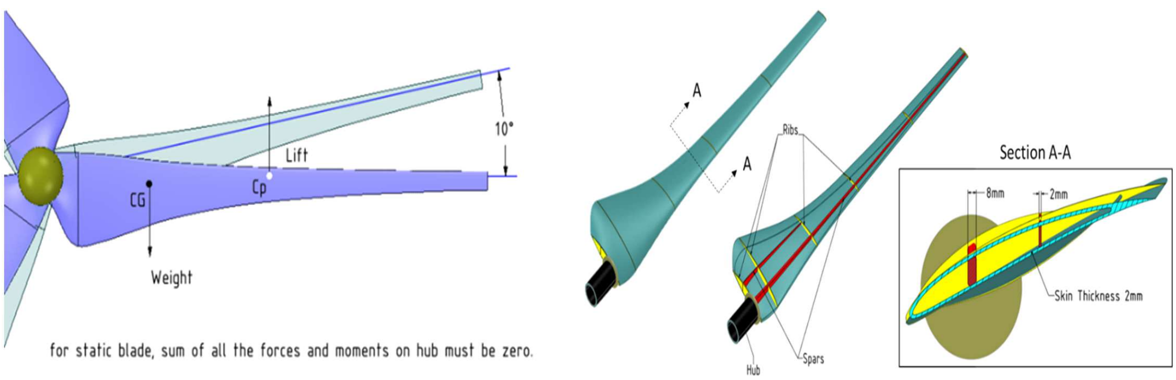
Table 5. Parameters of aerodynamic mesh on the optimized blade.

Variable	Values
Domain shape	Cylinder with 3D diameter
Domain length upwind	3D
Domain length downwind	7D
Cell size in density box	< 12 mm
Minimum edge size on the surface	0.5 mm
Maximum cell size in far-field	300 mm
Near wall cell layers	7 layers to capture viscous boundary layer with 0.25 mm first cell height
Mesh size	2 million



(a) (b) (c)

Fig. 6. (a) View of mesh on the domain, (b) optimized blade, (c) airfoil section of the optimized blade.



(a) (b)

Fig. 7. (a) Equilibrium state for initial weight estimation of wind turbine blade, (b) initial internal structural layout of the blade.

Equation (9) caters to the effect of 3 blades and can be used to get an initial guess of the maximum weight of the blade that can be designed for:

$$Weight < \frac{Lt}{3} \times \left(\cos(10^o) + \cos(20^o) + cos(40^o)\right) \tag{9}$$

The derivation begins by considering the lift force acting on each blade in the system. The lift force for each blade is influenced by its angular orientation, which can be represented as $L_b \times \cos(\theta)$ is the lift force and θ is the angle of orientation. For a system with 3 blades, the total contribution of all blades is the sum of these angular contributions.

Given that L_t represents the total lift force of all blades combined, each blade effectively contributes a lift force of ($L_t/3$). Substituting this into the formula for the total lift contribution yields Eq. (10):

$$\frac{L_t}{3} \times (\cos(10^\circ) + \cos(20^\circ) + \cos(40^\circ)) \tag{10}$$

Table 6. Lift force produced by a single blade at various wind speeds.

Blade pitch	TSR	Wind speed	Tangential force (N)	Single blade weight (N)	Mass single blade (Kg)
4	7	8	13.58	12.187	1.24
4	7	10	20.77	18.63	1.899
4	7	12	31.19	27.97	2.85

Table 7. Material Properties used in structural optimization.

Property	Direction	CBD-1	CBD-2	Units
Elastic Modulus	X	61340	91820	MPa
	Y	61340	91820	
	Z	6900	9000	
Poisson ratio	XY	0.04	0.05	
	YZ	0.3	0.3	
	XZ	0.3	0.3	
Shear Modulus	XY	19500	19500	MPa
	YZ	2700	3000	
	XZ	700	3000	
	Y	509	439	
	Z	170	140	
Shear	XY	125	120	MPa
	YZ	65	50	
	XZ	65	50	
Density		1.42E-06	1.48E-06	Kg/mm^3

This equation estimates the maximum weight the blade system can support by accounting for both the lift force and angular effects of the blades.

Table 6 shows the tangential force produced by wind turbine blades at various wind speeds. The blade weight estimation for design conditions is calculated for all wind speeds. However, the design conditions for the current blade design are a tip speed ratio of 7 and a wind speed of 10 m/s. Corresponding to these conditions the initial estimate of blade mass is approximately 2 kg.

The initial structural design of the blade is done based on the optimized thickness of the skin from the optimization framework and initial weight estimation. The skeleton is designed in such a way that the internal structure can be changed and optimized with a few steps in later stages of the analysis process if required. Figure 7(b) shows the internal structural layout or skeleton of the blade. The small spar in the blade is kept to reduce the torsional deformations under high aerodynamic loads. The thickness of ribs, spars, and skin, along with several composite layers in the skin, were taken as design variables. A design of experiments (DoE) study was carried out with various cases to find the optimum structural layout and thickness distribution along the blade length. The objective of DoE was to increase the modal frequency and reduce the weight of the blade while maintaining or reducing the total deformation produced in the blade at the highest aerodynamic load conditions. Two different materials are used in the DoE to limit the scope of work and draw logical conclusions independent of material selection (CBD-1: Epoxy Carbon Woven (230 Gpa), CBD-2: Epoxy Carbon Woven (365 Gpa)). The properties of these materials are shown in Table 7.

In addition to material properties, it is essential to exactly model the composite material on mesh in any software package to get accurate results. ANSYS ACP (Advanced Composite Products) tool is a specialized software package developed and designed to facilitate the simulation, analysis, and optimization of advanced composite materials and structures. The composite layup scheme used in ACP for CBD-2 material is shown in Fig. 8. It can be seen that sub-laminates are prepared using proper composite material thickness applied with exact definitions for rosettes and orientations of the fiber. In addition, the composite layup is modeled to optimize the weight in the initial design as well. The total and component weight of the initial blades composite model is shown in Table 8. It can be seen that the total weight of a single blade is reduced from the values calculated in Table 6.

One of the main features and the reason for using ANSYS ACP in this research is that this software integrates with optimization tools, allowing users to perform structural optimization studies to find the most efficient composite designs based on specific performance criteria. In addition, this process can be seamlessly integrated with other ANSYS software products, such as ANSYS Mechanical and ANSYS Fluent, to provide a comprehensive simulation environment for composite material applications.

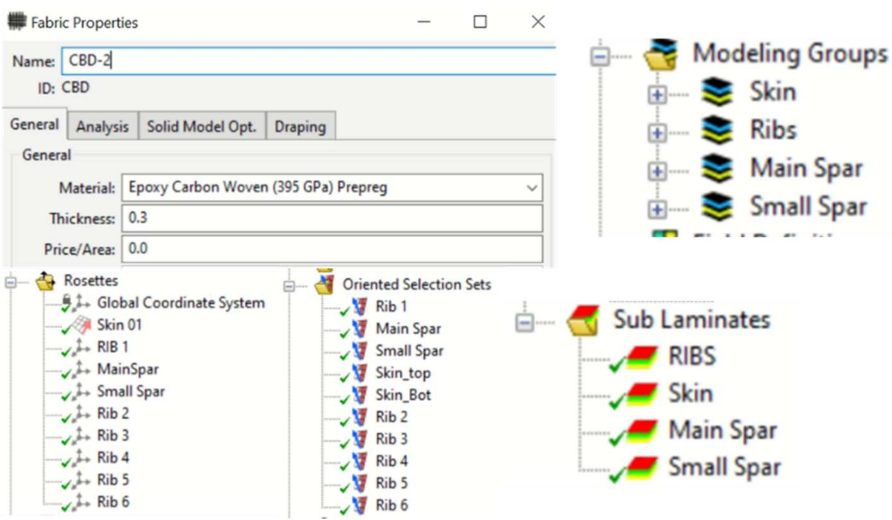


Fig. 8. Composite layup scheme in ACP.

Table 8. Composite material weight in the initial composite structural model of ACP.

Section	Component	Weight (grams)	% of total
1.1	Skin	872.55	79.87
2.1	Rib 1	13.78	1.26
2.2	Rib 2	10.20	0.93
2.3	Rib 3	3.95	0.36
2.4	Rib 4	1.77	0.16
2.5	Rib 5	0.86	0.08
2.6	Rib 6	0.50	0.05
3.1	Main Spar	168.82	15.45
3.2	Small Spar	19.99	1.83
Total Weight		1092.414	grams

Table 9. Load cases for structural analysis.

Load case	Pitch (degree)	Wind speed (m/s)	F_x (N)	F_z (N)
LC1	4	8	109.46	-13.58
LC2		10	171.37	-20.78
LC3		12	249.57	-31.19
LC4	6	8	100.81	-8.76
LC5		10	164.59	-14.52
LC6		12	230.14	-20.06

3.4.1. *Boundary Conditions*

Figure 9 shows the boundary conditions applied to the blade model for static structural analysis. Essential boundary conditions are applied to simulate real-world scenarios. This includes fixing the root of the blade to the hub, applying aerodynamic loads, and accounting for gravitational effects.

3.4.2. *Load Application*

Wind turbine blades experience dynamic loads due to wind forces and their rotation. These forces are applied as distributed loads along the blade's surface, varying along its length. For optimization, the complexity is reduced by converting the aerodynamic loads into concentrated loads with point applications. These loads are grouped into load cases, which correspond to ultimate limit and design limit loads. These load cases are presented in Table 9.

4. Results and Discussion

By harnessing cutting-edge parameterization and optimization techniques, a remarkable enhancement in turbine performance was achieved. To showcase the credibility of this research findings, a comparison of the optimized blade parameters with the baseline blade parameters was established, as illustrated in Fig. 10(a). This study reveals that the optimization framework developed in this research has led to an augmentation in the chord and twist distribution, particularly in sections closer to the blade's root. This transformation translates into a tangible enhancement in the overall performance of the blade, thereby promising a substantial boost in the output power of the turbine blade.

Thorough aerodynamic analyses were conducted using ANSYS Fluent software, focusing on power output assessments. The results from these analyses were compared with the expected power output based on our optimization framework. Figure 10(b) provides a visual representation of this comparison. The study found a consistent alignment between the power coefficients calculated within the optimization framework and CFD analysis at a tip speed ratio. This emphasizes the optimization framework's accuracy and robustness in various operational scenarios, supporting its practical applicability in wind turbine operations. On the other hand, accurately estimating torque is a critical aspect of the optimization framework, as it simplifies the process and helps identify necessary geometric adjustments for maximizing wind energy extraction. Figure 11 provides an analysis of torque distribution along the blade's length, comparing ANSYS simulations with the optimization framework. The results indicate a substantial alignment in the inboard 70% of the blade length, showcasing the framework's ability to replicate ANSYS simulations accurately. However, disparities become evident in the outboard 30% of the blade length due to complex interactions involving Reynolds number effects and nonlinearities from viscous flow phenomena, particularly at high tip speed ratios. This underscores the need for a nuanced understanding of fluid dynamics and fine-tuning, especially at the blade tip, to further enhance wind energy extraction precision. This evaluation emphasizes the importance of holistic modeling and simulation techniques in optimizing wind turbine blade designs and operations.

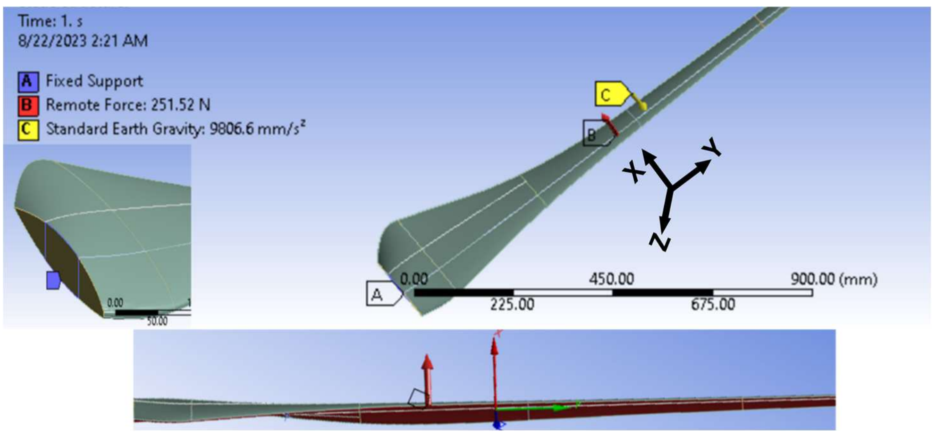
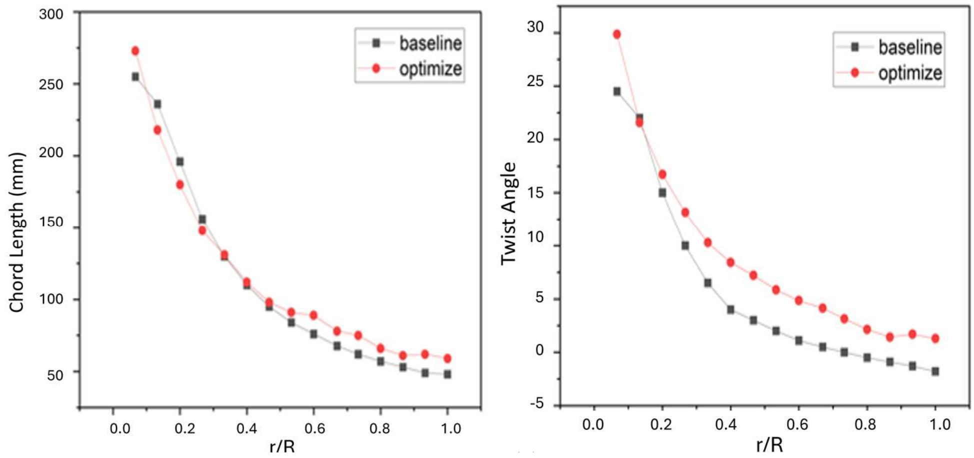
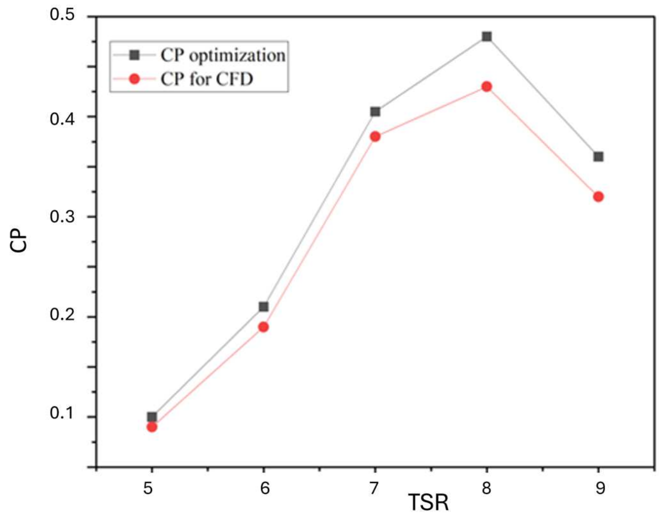


Fig. 9. Boundary conditions and supports.



(a)



(b)

Fig. 10. (a) Geometric and aerodynamic comparison of baseline and optimized blade, (b) coefficient of power comparison between optimization framework results and CFD results.

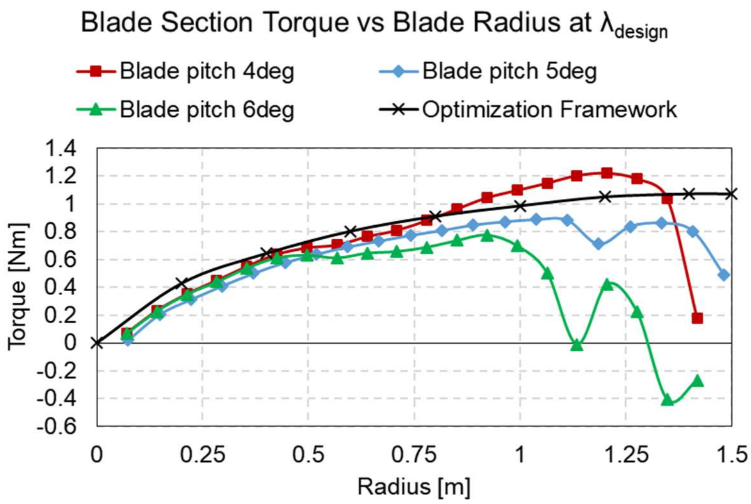


Fig. 11. Comparison of torque distribution along blade length in ANSYS and optimization framework results.

4.1. Validation of the Optimized Framework

To have confidence in the results of the optimization framework, it is always desired to validate the results from the MDO framework with a high-fidelity tool like ANSYS. The design conditions used in the MDO framework, output power, and blade pitch angle of the optimized blade are presented in Table 10 along with the results obtained from CFD.

From Table 10, it can be seen that the CFD results are in good agreement with the results of the MDO framework with less than 5% error. This error is almost expected in all low-fidelity analysis tools. Therefore, it is concluded that even though an error exists in calculations, the health, validity, and utility of the MDO framework developed in this research remain useful.

Table 10. Validation of results of MDO framework through CFD.

Output parameters	Design condition	MDO framework	CFD
Output power (kw)	Wind speed = 10 m/s, Tip speed ratio = 7	1.7	1.633
CP	Wind speed = 10 m/s, Tip speed ratio =7	0.4	0.38

Another interesting observation in the results of CFD is that the power coefficient of the blade is low at low tip speed ratios and increases linearly with the increase in tip ratio until a very high tip speed ratio is encountered where the blade stalls and the power coefficient drop significantly. This observation further dictates that the power coefficient can be maintained by reducing the blade pitch to keep the tip speed ratio as close to the design tip speed ratio as possible. This property was further investigated in CFD by using two two-blade pitch settings that is 4o and 6o. Figure 12 shows the comparison of the power coefficient produced with the tip speed ratio at multiple blade pitch settings.

It can be seen from Fig. 12 that the power coefficient decreases with an increase in blade pitch setting at all tip speed ratios. It, therefore, suggested that wind turbine blades must be kept at low pitch angles to extract maximum power from wind energy, or the blades must be optimized for high pitch angles, which can be accomplished through blade airfoil section optimization. However, such optimizations would result in highly cambered airfoil sections, which are not structurally feasible for wind turbine application and they often stall quickly in variable wind condition environments. For further aerodynamic analysis through CFD, blade pitch angles of 4° and 6° were explored at various wind conditions. Figure 13 shows the comparison of pressure distribution on wind turbine blades at different blade pitch settings, tip speed ratio of 7, and wind speed of 10 m/s. It can be seen that the 6-degree pitch blade tips stall at a tip speed ratio.

4.1.1. *Off-Design CFD Analysis*

Wind turbines do not necessarily inhibit design conditions. The mother nature often changes its moods and the wind conditions may vary depending upon the climate and weather of the local area. Therefore, it is always desired to quantify the off-design performance of the wind turbines. For current research, it was assumed that the wind gust may vary wind conditions so much so that the wind velocity may vary up to 20 percent. Keeping in mind these requirements, the off-design CFD analysis was conducted at tip speed ratios of 5 to 9 and wind speeds of 8, 10, and 12 m/s. Figure 14 shows the comparison of the power coefficient with the tip speed ratio at various wind speeds and various blade pitch settings. An interesting observation is that the power coefficient for a particular blade pitch setting does not vary much with ±20% variation in wind speed. This observation suggests that blade pitch setting has a major impact on the power output of a wind turbine; therefore, the blade pitch should be selected with careful consideration since the wind turbine does not incorporate many pitch angle variations. Secondly, for higher blade pitch settings, the design point of the wind shifts to higher tip speed ratios. This would result in higher structural loads and higher maintenance costs.

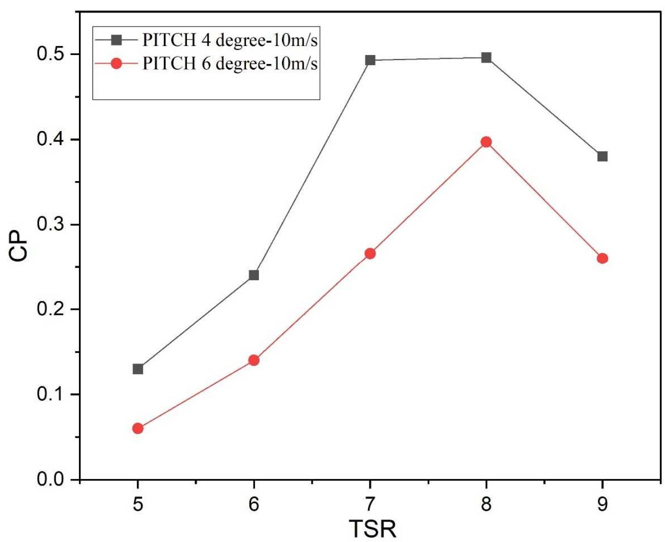


Fig. 12. Power coefficient for multiple blade pitch settings.

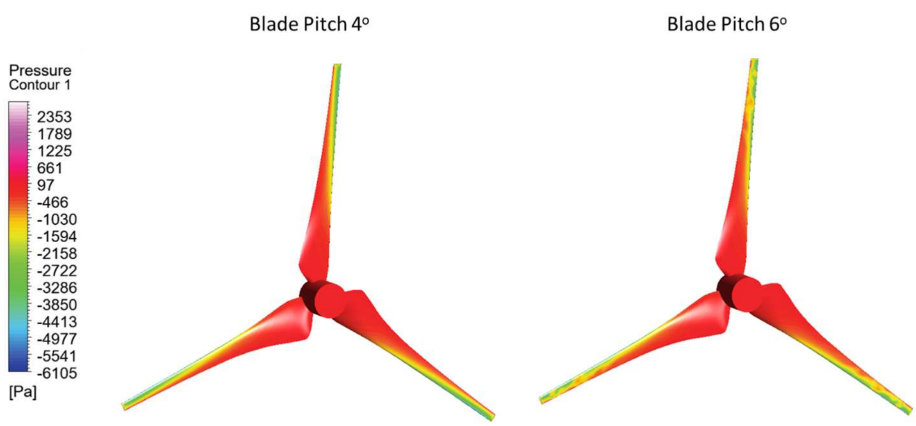


Fig. 13. Comparison of pressure distribution on the blade at various blade pitch.

Table 11. Structural qualification loads at various blade pitch settings.

Pitch angle	Wind speed (m/s)	Axial force (N)	Tangential force (N)	Bending (N)	Torsion (Nm)	Torque (Nm)
4	8	109	-13	-106	1	9.9
4	10	171	-20	-167	1.6	15.2
4	12	249	-31	-243	2.3	22.7
6	8	101	-8	-95	1.05	4.7
6	10	164	-14	-157	1.7	8.14
6	12	230	-20	-217	2.4	10.8

4.2. Aerodynamic Loads for Structural Qualifications

Structural qualification loads are the aerodynamic loads produced on wind turbine blades that are necessary for the wind turbine blade structure to withstand a successful and optimal operation with the desired power output. These loads are produced on wind turbine blades due to the pressure gradients caused by the moving air around the wind turbine blades. Table 11 shows the aerodynamic loads produced on wind turbine blades at various pitch settings and various wind speeds. It is pertinent to mention here that it is assumed that the wind turbine is rotating anticlockwise when viewed from the front. The highest loads be used as external loads on the wind turbine blade in structural analysis to test the structural integrity of the designed blade and to compute the total deformation encountered by the blade at these loads.

4.3. Results of the Optimized Structural Design

Validation and optimization of the structural design, including skin thickness, were performed through extensive high-fidelity structural analyses using ANSYS Structural software. The weight analysis, as shown in Fig. 15, revealed a critical insight: approximately 80% of the total blade weight is concentrated in the blade's skin. This emphasizes the pivotal importance of optimizing the blade's weight with a delicate balance between structural integrity and weight. The number of composite material layers in the skin is a key factor. More layers reduce deformation but increase overall weight, while fewer layers result in a lighter blade but higher deformation. Our analysis, which includes deflection, weight, and modal frequency plots, indicates that the optimal configuration for the current design is four composite skin layers. This configuration maintains structural stability while reducing weight, which directly enhances turbine performance by improving responsiveness to lower wind speeds and overall efficiency. This underscores the significance of the optimization framework in enhancing structural integrity and elevating wind turbine efficiency and sustainability. Achieving this balance contributes to the effective utilization of wind energy resources and a more environmentally friendly, energy-efficient future.

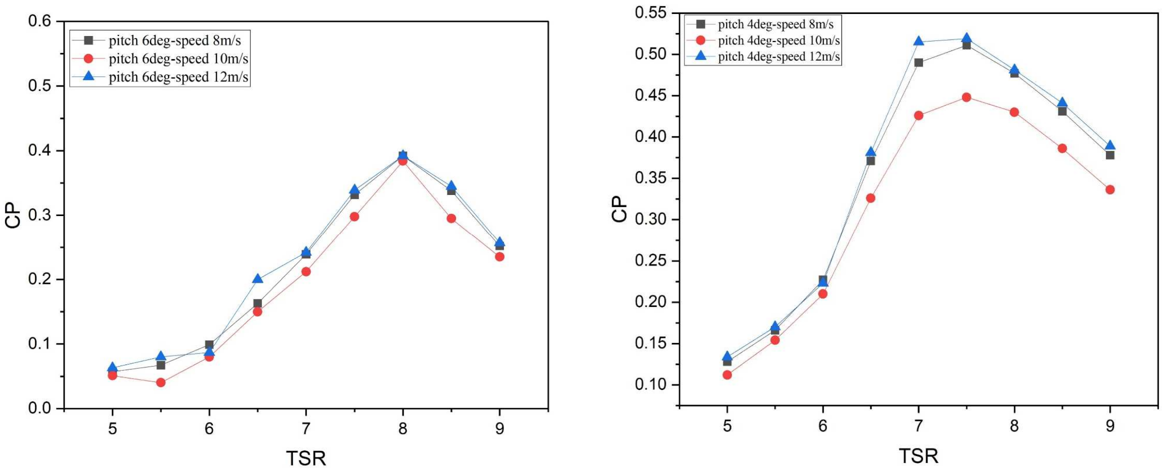


Fig. 14. Power coefficient vs. tip speed ratio at various wind speeds and various blade pitch setting.

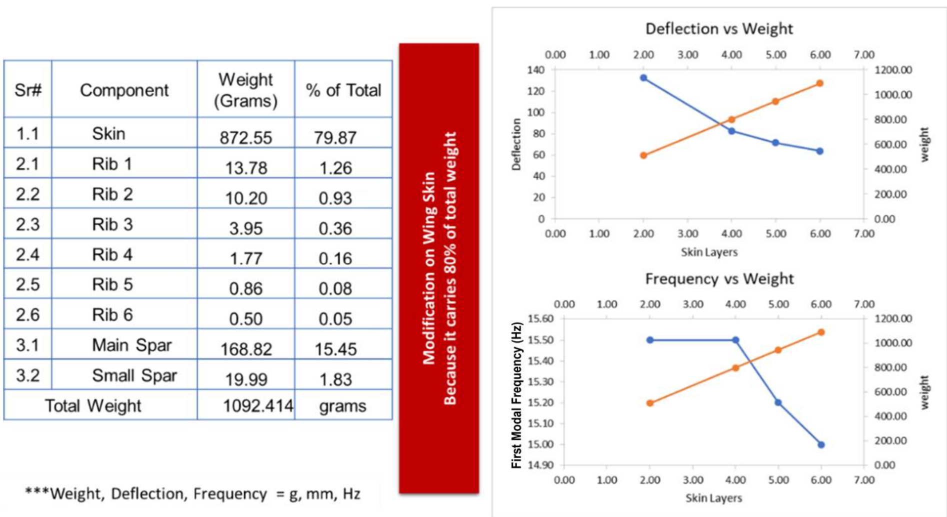


Fig. 15. Weight distribution in the blade and the optimum number of composite material skin layers required.

In the pursuit of weight reduction, it is crucial to concurrently enhance the blade's dynamic response or at least maintain its current performance. Striking this balance is a multifaceted task, with a key focus on increasing the blade's modal frequency. Raising the modal frequency acts as a strategic measure against undesirable occurrences like flutter and wind-induced vibrations that can affect the blade's structural integrity. A higher modal frequency reduces the blade's vulnerability to these forces, resulting in cost-efficient maintenance operations for wind turbines. Blades with higher modal frequencies are inherently more robust and less susceptible to wind-induced vibrations, which translates to reduced maintenance costs and extended operational reliability. Through a thorough optimization process, driven by high-fidelity structural analysis on ANSYS, we have successfully elevated the blade's modal frequency. This achievement not only enhances the blade's resistance to vibrational stresses but also minimizes the risk of structural fatigue and damage. The results, as shown in Fig. 16, indicate an increased modal frequency and acceptable levels of blade deformation. These findings represent progress in structural design and long-term performance of wind turbines, contributing to a more reliable, efficient, and cost-effective wind energy sector and promoting a greener and sustainable future.

The modal forms of wind turbine blades have a substantial impact on their dynamic response, offering valuable insights on the structural behavior of the blades under different operating conditions. The use of modal shapes enables the prediction of flutter responses and the identification of regions in the composite material skin where the blade is most prone to failure or crack initiation. Blades designed with unsuitable modal frequencies may encounter diminished energy capture efficiency and heightened structural fatigue, therefore resulting in a lower operational lifespan. The present work provides the modal frequencies and characteristics of the optimized blade, as depicted in Fig. 17. An important observation is that raising the modal frequency of the first mode leads to a decrease in stress concentrations in the middle section of the blade. The reallocation of stress over the whole blade leads to a more even distribution of load, thereby improving the blade's longevity and decreasing the need for frequent maintenance inspections and operational interruptions. The significance of this enhancement lies in its direct correlation with an extended lifespan for the wind turbine blades, thereby augmenting their general dependability and diminishing the long-term maintenance associated costs. It is crucial to acknowledge that although higher modal geometries may seem irregular or intricate, as depicted in Fig. 17, they are improbable to arise during the operating lifespan of wind turbines. A reason for this is that wind gusts generally have low-frequency properties, which do not stimulate these higher frequency patterns. Hence, the research targets the optimization of the first three modes, since they have the highest significance in determining the structural performance of the blade under normal wind loading circumstances. By focusing on these modes, the study intends to enhance the blade's dynamic response, guaranteeing its efficient operation and resilience against structural problems caused by wind-induced vibrations and other dynamic forces. This focused strategy for structural optimization emphasizes the need of precisely adjusting modal frequencies to improve the efficiency, dependability, and durability of wind turbine blades.

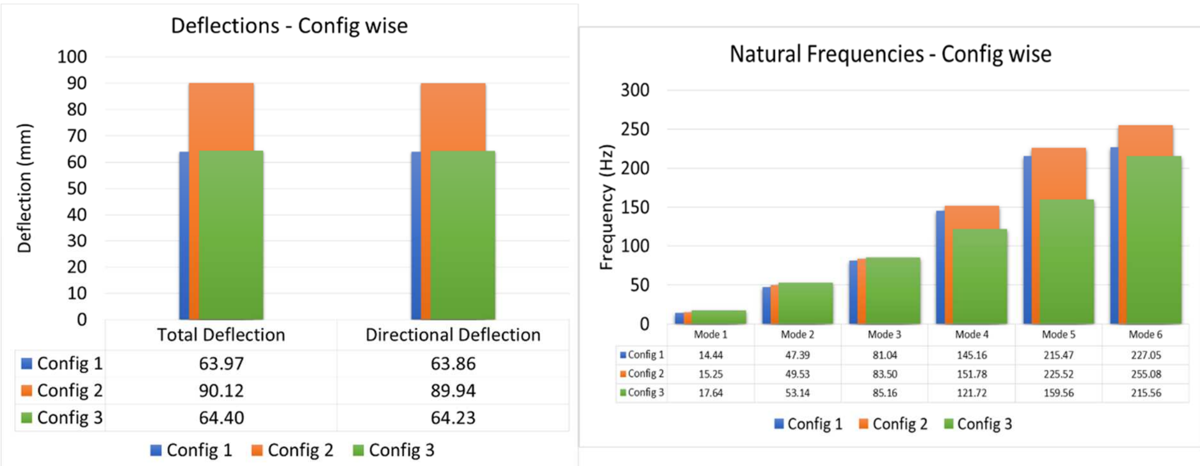


Fig. 16. Optimization results of axial deflection and modal frequency of blade.

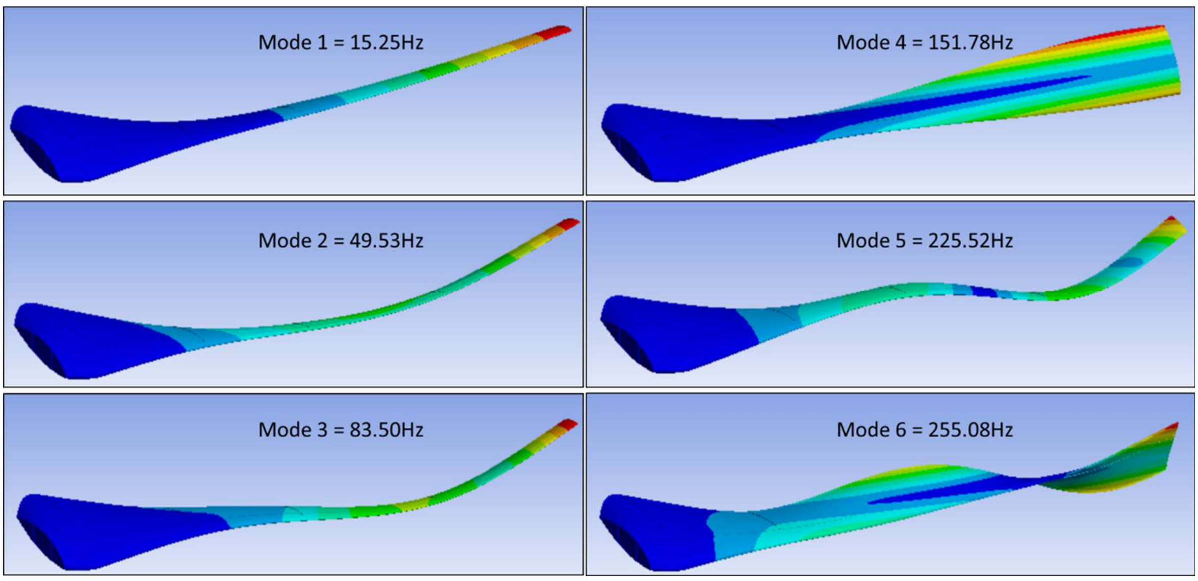


Fig. 17. Modal frequencies and shapes for the optimized blade.

5. Conclusions

In places with distinctive climatic circumstances such as southern Iraq, the optimization of wind turbine blades is of paramount importance in augmenting wind power generation. Through rigorous refinement of crucial blade parameters, such as chord and twist distributions, this study showcases the possibility of in-house blade design and manufacture, which greatly enhances turbine performance and power conversion. The reliability and precision of the existing optimization methodology have been confirmed through high-fidelity aerodynamic studies conducted under specific operational conditions. Within this paradigm, precise torque estimation has played a crucial role in maximizing the extraction of wind energy. Furthermore, the study highlights the need of weight distribution inside the blade, with a substantial proportion localized in the blade skin. The research effectively attains a desirable equilibrium between weight reduction and structural integrity by the optimization of the number of composite material layers. Furthermore, it is recommended to choose four composite skin layers, backed by thorough examinations of deflection, weight, and modal frequency, in order to improve the overall performance and efficiency of the turbine. Moreover, it has been demonstrated that raising the modal frequencies of blades can decrease vulnerability to problems such as flutter and vibrations caused by wind. This, in turn, results in cost-efficient maintenance and prolonged operational dependability for wind turbines. This study highlights the substantial beneficial influence of blade optimization on energy efficiency, sustainability, and the wider wind power sector. By utilizing cutting-edge technology and materials, it establishes the foundation for groundbreaking in-house designs and signifies the start of a new era in wind turbine performance. The results lead to a more environmentally friendly and financially viable energy future with consequences that go beyond the focus of this research. Further investigation of the incorporation of more sophisticated composite materials, improvement of aerodynamic models, and consideration of environmental variables such as severe weather conditions could significantly augment the efficiency and durability of wind turbine blades.

Author Contributions

The authors confirmed the contribution to this study as follows: A.K. Zarzoor: Methodology Development, Formal Analysis, Data Curation, Writing Original Manuscript; A. Abdulhady: Data Curation, Writing Original Manuscript; A. Adnan: Supervision, Writing Original Manuscript. The manuscript was written through the contribution of all authors. All authors discussed the results, reviewed, and approved the final version of the manuscript.

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Conflict of Interest

The authors declared no potential conflicts of interest concerning the research, authorship, and publication of this article.

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Data Availability Statements

The data that support the findings of this study are available on request from the corresponding author.

Nomenclature

a, a'	Axial and rotational induction factors	C_p	Power coefficient
c	Chord length	α	Angle of attack
θ	Twist angle	C_L, C_D	Lift and drag coefficients
ϕ	Flow angle	λ_r	Local speed ratio
λ	Tip speed ratio		

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