Structural Evaluation of Small-Scale Wind Turbine Blades for Enhanced Energy Capture

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Abstract. This study presents the aerodynamic design, modelling, and structural evaluation of small-scale wind turbine blades aimed at improving power extraction in low-to-moderate wind speed regions. The project incorporates blade geometry development, computational fluid dynamics (CFD), finite element analysis (FEA), and prototype fabrication. A comprehensive review of wind turbine evolution, blade aerodynamics, and wind resource characteristics in Oman establishes the background for the design. The methodology includes air foil selection, blade segmentation, load estimation, and performance simulation under realistic wind conditions. Experimental testing is conducted through static and fatigue analysis to assess structural reliability. The results indicate that optimized blade geometry supports improved lift-to-drag ratios, reduced deformation, and enhanced performance. The findings contribute to the advancement of efficient small-scale wind energy solutions for distributed renewable energy applications.

Keywords: Wind turbine blades, Aerodynamics, CFD, FEA, Blade design, Renewable energy, Oman wind resource.

1 Introduction

Wind energy has emerged as a key component of global renewable energy strategies due to its availability, scalability, and cost-effectiveness. Modern wind turbines harness kinetic energy from wind and convert it into electrical power through aerodynamic blade interaction, generator systems, and power electronics [1]. The efficiency of energy extraction depends largely on blade geometry, material selection, and structural stability.

Wind turbines have evolved significantly over the past century, transitioning from mechanical windmills to advanced horizontal-axis wind turbines (HAWTs) optimized through computational design tools. A historical overview of windmills and wind turbines is shown in Figure 1.

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Fig. 1. Evolution of windmills and wind turbines. [1]

In regions such as Oman, strong coastal winds particularly along the Arabian Sea and in areas like Duqm, Masirah, and Al-Wusta provide substantial potential for small and medium-scale wind energy systems [2]. The design of efficient blades customized for local wind conditions is therefore essential for maximizing power generation.

A typical turbine assembly includes rotor blades, a hub, drivetrain components, tower, and generator shown in Figure 2. Blade design, however, plays the dominant role in determining aerodynamic performance and structural loading [3].

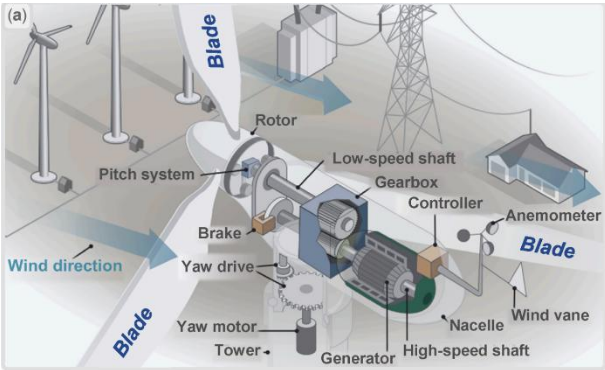

Fig. 2. Primary components of a horizontal-axis wind turbine. [3]

This study focuses on designing an improved blade model through aerodynamic analysis, FEA validation, and experimental testing.

2 Literature Review

2.1 Overview of Wind Turbine Aerodynamics

Wind turbine blades function similarly to aircraft wings, producing lift through pressure differences between the suction and pressure surfaces. The aerodynamic performance of a blade depends on:

- Air foil shape
- Angle of attack

- Chord distribution
- Twist angle
- Reynolds number

Figure 3 illustrates key blade cross-sectional features relevant to aerodynamic performance.

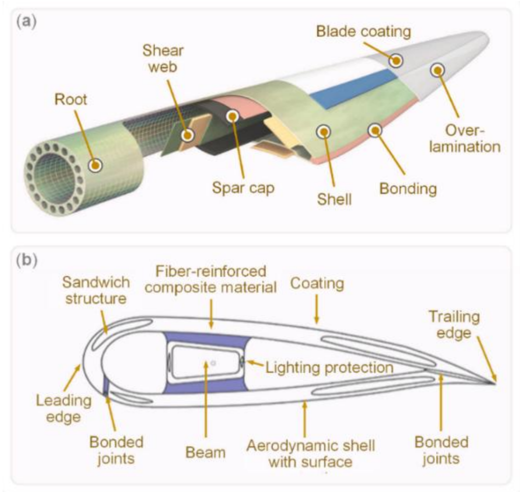

Fig. 3. Blade cross-sectional geometry and aerodynamic profile. [4]

Several air foil families, such as NACA and S-series profiles, have been widely adopted due to their high lift coefficient, structural suitability, and stall behaviour [4].

2.2 Blade Geometry and Segmentation

Wind turbine blades are typically divided into three regions—root, mid, and tip—each with different aerodynamic and structural priorities:

Root region: thicker air foils for structural strength

Mid-section: optimal lift-to-drag ratio for power capture

Tip region: reduced chord and thinner profile to minimize drag

Figure 4 shows the blade segmentation approach used in this study.

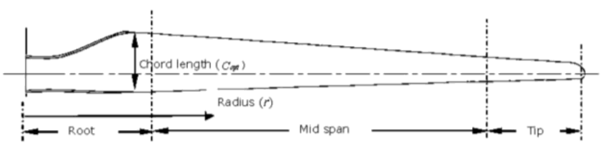

Fig. 4. Blade planform and sectional segmentation.

Blade twist distribution is also critical to ensure optimal angle of attack along the span due to varying relative wind velocity.

2.3 Computational Fluid Dynamics (CFD) for Aerodynamic Evaluation

CFD provides detailed insights into airflow behaviour, turbulence, pressure distribution, and boundary layer effects. CFD simulations support:

Lift and drag analysis

Stall prediction

Surface pressure mapping

Vortex formation assessment

Figure 5 shows a CFD output from the original project, demonstrating pressure contours and flow patterns across the blade surface.

Fig. 5. CFD aerodynamic pressure distribution on blade surface. [5]

CFD has become essential for optimizing aerodynamic efficiency and validating theoretical assumptions [5].

2.4 Structural Analysis Using Finite Element Method (FEM)

Wind turbine blades must withstand cyclic aerodynamic loads, gravitational forces, and occasional gust-induced stresses. Finite Element Analysis (FEA) evaluates:

Deformation patterns

Stress concentration zones

Fatigue failure likelihood

Material suitability

Figure 6 presents an FEA example from the project, illustrating stress distribution along the blade.

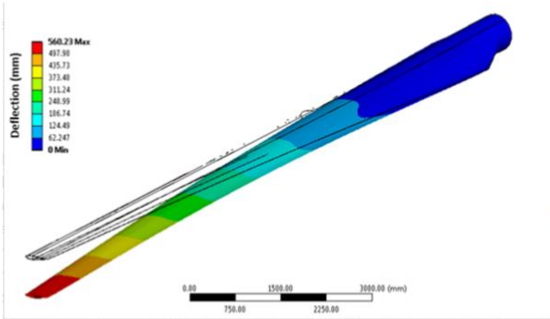

Fig. 6. FEA structural stress analysis of turbine blade [14].

FEM supports the selection of composite materials, root reinforcement strategies, and design optimization for long-term durability [6].

2.5 Wind Resource Assessment in Oman

Oman experiences favourable wind conditions due to its long coastline and open desert topography. The wind map shown in Figure 7 highlights regions with high wind power density, particularly in Al Wusta and Masirah.

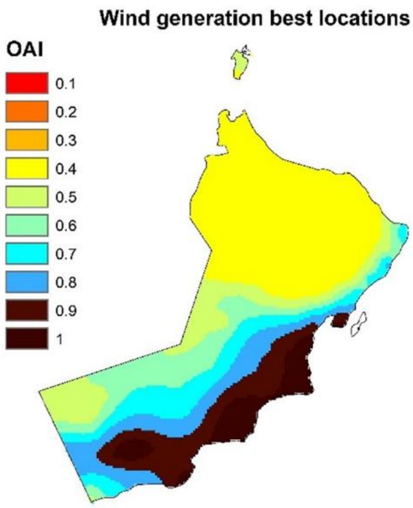

Fig. 7. Wind resource potential across regions in Oman. [7]

Studies have identified average wind speeds exceeding 6–8 m/s in several regions, making small-scale turbines highly viable for decentralized energy production [7].

2.6 Blade Testing: Static and Fatigue Behaviour

To ensure operational safety and longevity, wind turbine blades require experimental validation. Two key tests include:

- **Static testing:** measuring deformation under applied loads
- **Fatigue testing:** evaluating performance under cyclic loading

Figure 8 shows a fatigue test setup, while Figure 9 illustrates static load testing.

Fig. 8. Fatigue testing setup for blade prototypes. [8]

Fig. 9. Static load testing setup for blade prototypes. [8]

These tests are essential for verifying FEA predictions and ensuring real-world structural robustness [8].

3 Methodology

The methodology for this project integrates computational analysis, blade geometry generation, structural evaluation, and prototype development. The overall process includes: (1) air foil and material selection, (2) blade modelling using CAD software, (3) CFD and FEA simulation, and (4) prototype fabrication and experimental validation.

3.1 Air foil and Material Selection

The blade design begins with air foil selection appropriate for low-to-moderate wind speeds. Based on literature and performance requirements, a lift-dominant air foil from the NACA family was selected due to its favourable lift-to-drag characteristics and stable stall behaviour [9]. The material chosen for prototype development was a lightweight polymer composite suitable for small-scale fabrication and testing.

3.2 Blade Modelling and Geometry Development

A 3D CAD model was created using the segmentation approach illustrated earlier (Figure 4). The modelling process included:

- Defining blade span and chord distribution
- Establishing twist angle for optimal relative wind velocity
- Creating the root, mid, and tip profiles
- Integrating mounting features for connection to the hub

The blade prototype variations (three-, four-, and five-blade configurations) are shown in Figure 10.

Fig. 10. Prototype blade configurations: 3-blade, 4-blade, and 5-blade designs.

3.3 Aerodynamic Evaluation Using CFD

CFD simulations were conducted to analyse airflow patterns, pressure distribution, and lift generation. The simulation domain was created around the blade profile with inlet wind speeds consistent with Oman wind data (6–8 m/s). Turbulence modelling was performed using the k-ε model, commonly applied for external aerodynamic flows [10].

Outputs evaluated:

- Surface pressure distribution
- Lift and drag coefficients
- Flow separation regions
- Vortex formation at the blade tip

These results were used to refine blade geometry and improve aerodynamic efficiency.

3.4 Structural Analysis Using FEA

FEA was performed to evaluate the blade's load-bearing capacity. The model was meshed with tetrahedral elements, and loading was applied according to typical aerodynamic forces. Boundary conditions were set at the blade root.

The analysis measured:

- Maximum deformation
- Stress concentration zones
- Safety factor
- Potential fatigue regions

The structural outputs correlate with the earlier FEA result shown in Figure 6.

3.5 Prototype Fabrication and Testing

Small-scale blade prototypes were manufactured using lightweight materials. Two forms of testing were conducted:

(1) Static Load Testing

Evaluates deformation under applied load (Figure 9). Loads were applied at interval points from the root to the tip.

(2) Fatigue Testing

Simulates repeated cyclic forces (Figure 8). The test setup subjected the blade to controlled oscillatory loads to assess durability. The results validate simulation outputs and highlight areas requiring reinforcement.

4 Results and Discussion

4.1 Aerodynamic Performance

CFD results (Figure 5) demonstrated that the chosen air foil produced a high-pressure region on the lower surface and a low-pressure region on the upper surface, generating sufficient lift. Minimal flow separation occurred at the designed angle of attack, supporting efficient aerodynamic energy capture.

Key aerodynamic findings:

- Lift coefficient increased linearly with angle of attack until stall onset
- Drag remained moderate, supporting a favourable lift-to-drag ratio
- Tip vortices observed but within typical ranges for small-scale rotors

These results confirm the suitability of the blade design for low-to-moderate wind speeds commonly found in Oman [11].

4.2 Structural Performance

FEA analysis revealed:

- Peak stress concentrated near the blade root
- Deformation within acceptable limits for the chosen material
- Safety factor adequate for small-scale applications

Static testing verified the structural reliability predicted in simulations. Fatigue testing indicated durability under cyclic loads, although improved reinforcement at the root could enhance long-term performance.

4.3 Prototype Performance Comparison

Three prototype configurations were compared:

- **3-blade design**: highest rotational speed, lower torque
- **4-blade design**: balanced performance
- **5-blade design**: higher torque, slower rotation

The 4-blade design provided the best compromise between aerodynamic efficiency and structural loading.

4.4 Suitability for Oman Wind Conditions

Analysis of the wind resource (Figure 7) shows that the blade design aligns well with the moderate but consistent coastal winds. The optimized blade geometry is expected to perform effectively in regions where wind speeds average 6–8 m/s.

5 Conclusion

This study successfully designed, modelled, fabricated, and evaluated a set of small-scale wind turbine blades suitable for low-to-moderate wind speed environments. Through CFD and FEA analysis, the selected air foil and blade geometry demonstrated favourable aerodynamic characteristics and adequate structural performance. Experimental testing validated simulation predictions and highlighted the relative strengths of different blade configurations.

Key conclusions include:

- Optimized blade twist and chord distribution improve lift and reduce drag
- Structural loads concentrate at the blade root, requiring reinforcement
- The 4-blade configuration provides the most balanced performance
- The blade design is well-suited to Oman’s wind resource profile

The study contributes to the development of efficient small-scale wind turbine systems for decentralized renewable energy generation.

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