Designing, Optimizing, and Manufacturing of Horizontal Wind Turbine Blades Using the Available Resources.

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***Abstract*—The research aims to enhance wind turbine blade performance by utilizing available technologies and considering constraints such as limited resources. The focus is on developing blade designs that optimize material use, manufacturing techniques, and performance while reducing costs. Alternative and cost-effective materials are considered for blade manufacturing. Analytical models and computational simulations are deployed to validate the initial design and analyze multiple parameters. Simulations and mold production are conducted before manufacturing the blades. Assembly, installation, and testing processes evaluate blade performance.**

***Keywords*— Wind turbine blades, Blade design, Blade manufacturing, Performance improvement, Aerodynamics, Blade optimization, Simulation**

I. Introduction

Since 1973, small-scale wind generators have gained traction in residential and farming sectors, especially in off-grid regions [1] [2]. However, the efficiency of wind turbines hinges on blade design, optimization, and manufacturing [3] [4] [5]. While most turbine components are recyclable, blades pose challenges due to energy-intensive disposal methods. This research aims to explore cost-effective design, optimization, and manufacturing of wind turbine blades using accessible resources and techniques, potentially advancing wind technology and renewable energy adoption.

A. Background and Problem

Horizontal-axis wind turbines are vital for renewable energy but face challenges in costly and technologically sophisticated blade enhancement, hindering adoption in resource-limited regions. Researchers encounter constraints like limited technology and materials, hampering advanced designs and access to resources. Addressing these constraints can lead to more efficient designs and cost reduction.

B. Objectives and Significance

The objective is to enhance blade performance using available technologies, alternative materials, and simplified manufacturing techniques. This research can drive technological advancements, promote affordable renewable energy, and stimulate innovation in wind turbine blade technology.

II. Literature Review

A. Wind Turbines

Wind turbines are integral to sustainable construction, particularly in urban settings [6]. They are categorized based on various factors such as configuration, capacity, and installation location [7].

1) Classification of Wind Turbines

Wind turbines are broadly classified as horizontal-axis or vertical-axis, with the former being more prevalent due to their efficiency and cost-effectiveness [7]. Additionally, turbines can be categorized as upwind or downwind, each presenting unique operational considerations [7].

2) Small Wind Turbines

Small wind turbines, typically with rotor areas less than 200 square meters, find utility in low to moderate wind speed areas near energy demand centers [8]. Design considerations include blade geometry, material selection, and aerodynamic performance [9] [10].

B. Aerodynamic Principles of Turbines

1) Blade Sweep Area: Describes how increasing blade length enlarges the swept area, impacting energy values.

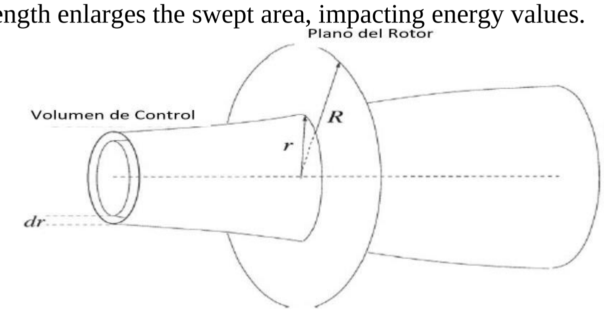

Fig. 1. Depiction of the Sweeping Area. [11]

2) Wind Energy Parameters: Introduces the energy coefficient (C_p) for turbine efficiency, typically ranging from 30% to 45%, with reference to the Lanchester—Betz Limit [11] [12] [7].

3) Lanchester—Betz Limit: Sets the maximum turbine efficiency at 59.26%, influenced by the axial induction factor (a), which peaks at 16/27 when the factor a is 1/3 [7] [13].

4) Speed Ratio Maximum: Highlights the importance of speed ratio (λ) in turbine design, typically ranging from 6 to 9 for 3 bladed turbines [14].

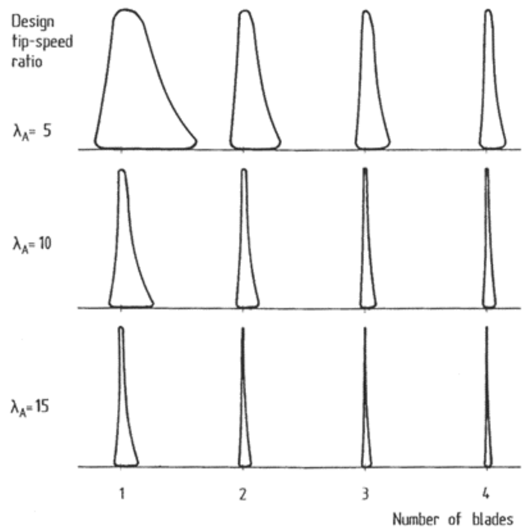

Fig. 2. Displays the ratios of maximum speeds in relation to the number of blades [14]

5) Blade Geometry: plays a crucial role in turbine performance, with variations in shape and aerodynamic profile impacting efficiency and power generation [15] [16].

C. Analysis of Aerodynamic and Aeroelastic Characteristics of Wind Turbines

The behavior of wind turbines is influenced by aerodynamic principles, often simplified in theoretical frameworks. Models like the classic Blade Element Momentum (BEM) method are used for evaluating power coefficients, involving computational simulations [11].

1) Theoretical Framework for Aerodynamic Behavior

A simplified one-dimensional concept is often applied to wind turbine aerodynamics, neglecting friction and rotational speed components [11]. Equations derived from conservation principles provide insights into power generation and drag force [11]. The power coefficient, critical for turbine design, reaches its maximum at the Betz limit [11].

2) Conventional Blade Element Moment Theory

Analyzing wind turbine blade behavior is complex, involving particle interactions and load determination for each element [12]. Equations describe the drag and torque forces on the blade, with coefficients derived from literature [12]. The Prandtl correction factor is utilized to account for tangential forces [12].

D. Composite Materials

Wind turbine blades require careful manufacturing to meet operational demands, with various methods like pre-impregnated materials and resin infusion employed [17]. Laminate composites and sandwich compounds are common in modern turbines, with material selection guided by composite mechanics knowledge [7].

1) Reinforcements

Composite materials rely on natural or non-natural fibers for reinforcement, with glass fibers and carbon fibers being predominant choices [18]. The properties of these fibers dictate their suitability for different blade requirements [18].

2) Natural Fibers

Natural fibers offer an eco-friendly alternative, though with lower mechanical properties compared to glass or carbon fibers [3][19]. Despite this, they find utility in certain applications due to their specific characteristics [19].

E. Previous Studies and Related Research

Research has explored the utilization of natural fibers in turbine blade construction, alongside bamboo-based compounds, and investigations into novel fibers like Stipa Obtusa [3][19][20][21]. Studies across various domains have demonstrated the benefits of optimal blade designs, composite material utilization, and innovative manufacturing techniques [22][23][24][25].

III. Methodology

The methodology encompasses verifying the initial design through analytical models and computational simulations to ensure fluid behavior and aerodynamics are considered [21][20]. Design simplicity and performance efficiency are prioritized, with various parameters analyzed for validation [21][20]. After design and analysis, simulations of the blades and molds precede manufacturing, followed by assembly, installation, and testing processes [21][20].

A. Conceptual Design of the 5kW Blade

1) Wind Velocity

The wind velocity is crucial in determining energy potential, with data obtained from the Wind Atlas for the Republic of Yemen. A wind speed of 8m/s, typical in Al Hudaydah Governorate, serves as the basis for design considerations.

2) Geometric Parameters

The 3-blade configuration adheres to industry standards, with a sweeping area compatible with small wind turbines [21][20]. Initial design parameters are summarized in TABLE (II).

B. Choosing the Optimal Profile for Aerodynamic and Structural Performance

The selection of the optimal profile involves a comprehensive analysis considering aerodynamic performance, structural stability, weight, durability, manufacturing, assembly, and economic factors.

C. Simulation and Analysis of the Rotating Blade

1) Aerodynamic Dynamic Simulation Processes

Simulation processes ensure the blade design achieves its intended purpose, focusing on streamlined shape and aerodynamic efficiency.

TABLE I.

THE ANNUAL AVERAGE WIND SPEED IN SEVERAL YEMENI GOVERNORATES AT A HEIGHT OF 10M.

Ranking	Station 10 m above ground	E	N	Estimated Elevation [m.a.s.l]	Mean Wind velocity [m/s]
1	Hodeidah (CAMA/WMO)	45º 02’	12° 50’	12	9.2 / 7.0
2	Taiz	44º 08’	13° 41’	1385	6.6
3	Aden (CAMA/WMO)	45º 02’	12° 50’	3	6.5 / 7.2
4	Sana’a	44º 11’	15° 31’	2190	3.7
5	Ibb	44º 20’	14° 00’	1929	1.5

TABLE II.

THE VALUES OF THE INITIAL DESIGN PARAMETERS

Parameter	Unit	Value
Power	KW	5
Velocity	m/s	8
Cp		0.45
ρ	kg/m^3	1.2

2) Structural Blade Design/Model Analysis

Blade structure and materials, whether hollow or solid, plate thickness, and material properties are defined to determine weight and corresponding frequencies for different speeds.

3) Static Blade Loads and Deflection

Structural design verification includes withstanding static loads and stresses at various speeds without permanent deformation.

D. Modeling Blades and their Manufacturing Mold

Blades and molds are modeled using three-dimensional software, with attention to segmentation for manufacturing ease . Mold design is verified before producing the final blade model, ensuring accuracy and quality.

IV. Computational Simulation Results

A. Choosing the Optimal Profile for Aerodynamic and Structural Performance

Upon determining the Reynolds number, various airfoil surface models were considered, including S809, NACA4412, S823, S822, among others as shown in Fig. 3. The QBlade program facilitated a comparison of these surfaces, ultimately selecting S822 for its maximum Cp coefficient of 0.425 under design conditions. S-Series surfaces, like S822, are favored in small wind turbine blades due to their enhanced stiffness.

B. Aerodynamic Analysis with BEM

Using the Blade Element Momentum (BEM) methodology, tangential and axial induction coefficients were determined to signify the energy extracted from the air for blade motion also the simulation results for the airfoil shape of the blade was obtained as shown in Fig 4. Through 1058 iterations, values for these coefficients and results were obtained.

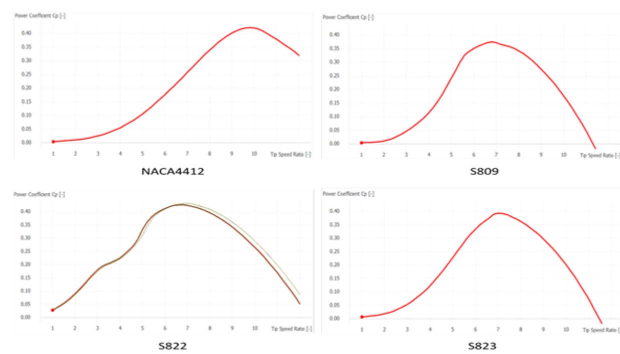

Fig. 3. Cp values for each type of tested airfoil surface

C. Blade Structure and Material Analysis Results

The blade structure, identified as hollow with varying thicknesses, was analyzed along with material properties for cavity filling. Blade weight and corresponding frequencies for rotational speeds were established.

D. Static Blade Load and Deflection Analysis Result

Loads acting on each part of the blade at different wind speeds were defined to ascertain stresses, pressures, and deflection as shown in Fig 5. These loads and forces were based on previously obtained results.

E. Simulation Using Computational Fluid Dynamics (CFD) Software

After BEM simulation, blade modeling in SOLIDWORKS preceded CFD simulation in ANSYS. A computational domain representing the fluid medium, air, was defined along with boundary conditions and parameters using the CFX tool as shown in Fig. 6. Simulations were conducted for various wind speeds and rotational velocities, with torque results compared to prior analyses and ANSYS software as shown in Fig. 7 and TABLE III.

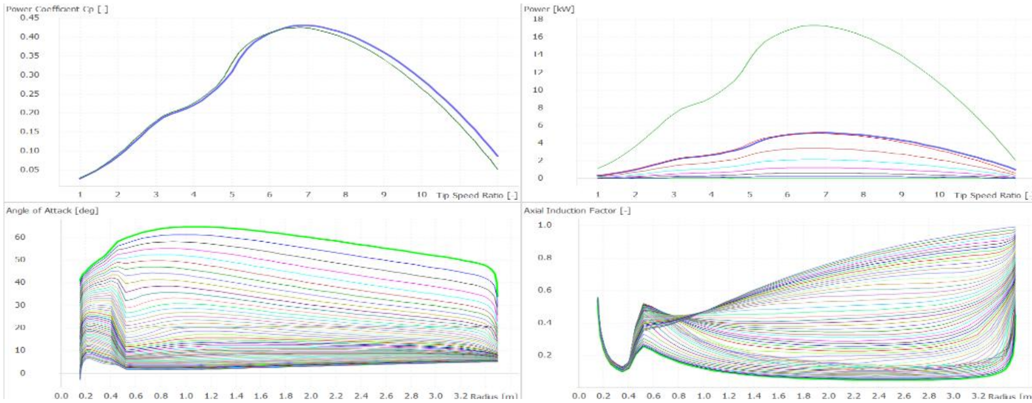

Fig. 4. The simulation results for the airfoil shape of the blade

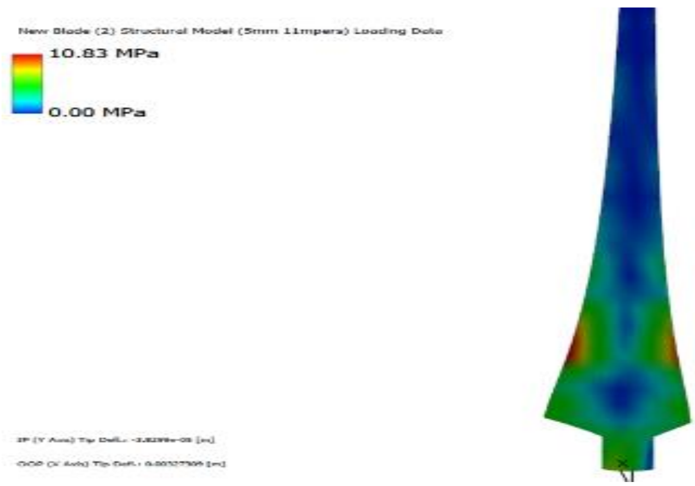

Fig. 5. Displays the corresponding results for the loads acting on each part of the blade at a wind speed of 11 m/s and a thickness of 0.5 cm

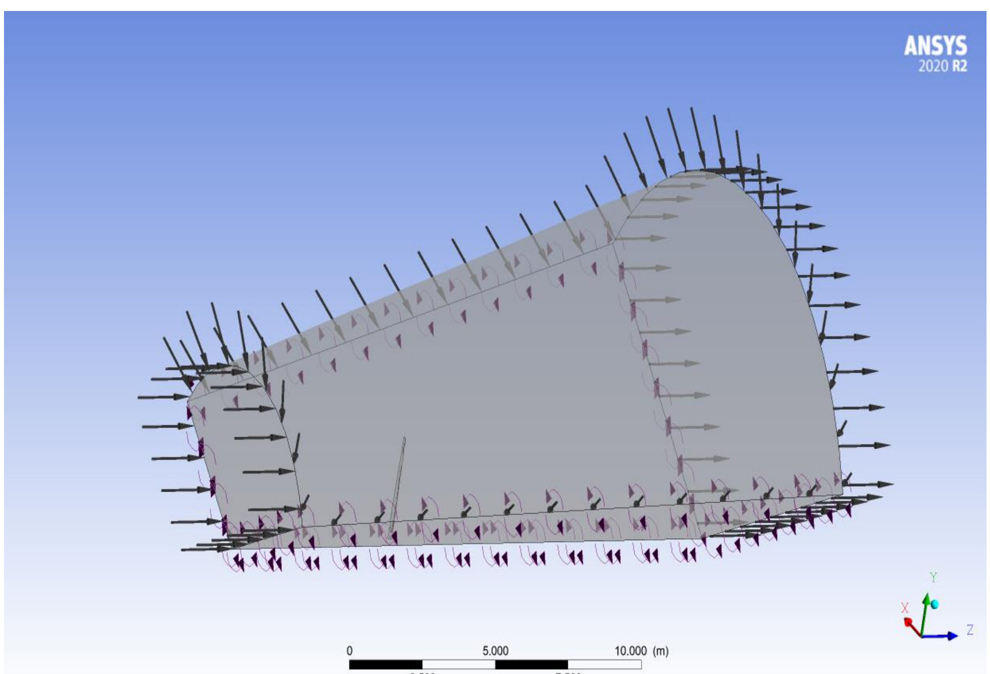

Fig. 6. CFX tool to define boundary conditions and other parameters

TABLE III.

TABLE OF RESULTS

wind speed [m/s]	Angular Velocity [radian/s]	Torque from QBlade [N m]	Torque from ANSYS [N m]
3	5.828571	46.5422199	46.1755
4	7.771428571	82.74172426	84.4061
4.5	8.742857143	104.7199948	104.531
5	9.714285714	129.2839442	128.215
5.5	10.68571429	156.4335724	154.24
6	11.65714286	186.1688796	184.934
6.5	12.62857143	218.4898656	216.262
7	13.6	253.3965306	250.723
7.5	14.57142857	290.8888744	287.238
8	15.5429	330.9668971	324.573
8.5	16.51428571	373.6305986	367.927
9	17.48571429	418.8799791	411.976
9.5	18.45714286	466.7150384	458.389
10	19.42857143	517.1357767	507.375
12	23.31428571	744.6755184	728.597

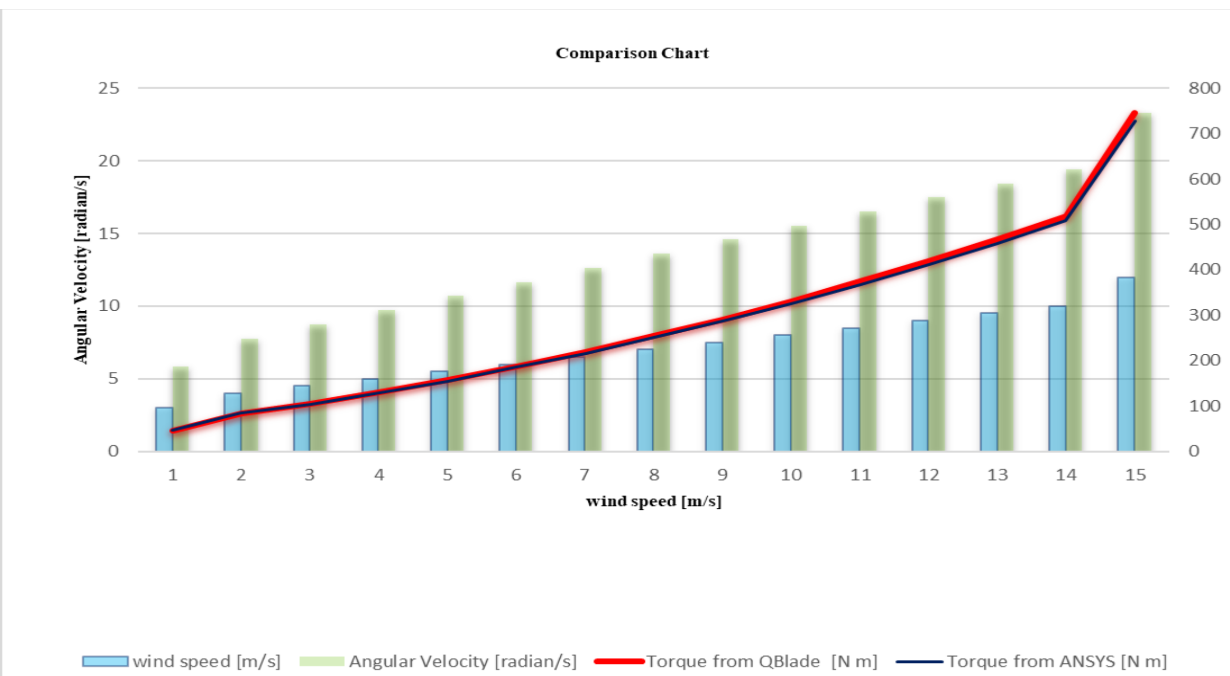

Fig. 7. torque results compared for various wind speeds and rotational velocities.

V. Three-dimensional Modeling and Manufacturing

A. Creating a three-dimensional model for the blades and designing their specific mold

Following the simulation process, the blade was modeled in SOLIDWORKS using data from the QBlade program. Additionally, a mold for the blades, consisting of two sections to accommodate the irregular blade shape, was designed as shown in Fig. 8.

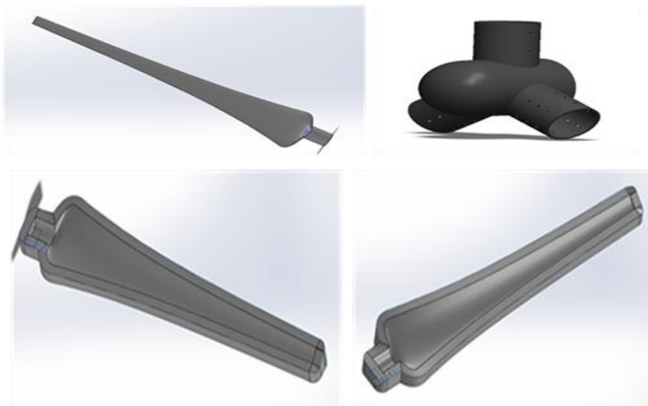

Fig. 8. The mold, blades, and Hub in SOLIDWORKS.

B. Mold Manufacturing

The mold, crafted using a three-axis CNC machine, underwent a two-stage manufacturing process involving part production and assembly.

Fig. 9. The mold for the blades after it has been prepared.

C. Blade Manufacturing

Blade production commenced with layering and laminating fiberglass on each mold part, followed by joining the segments to form complete turbine blades. Subsequent processes included foam filling, emery, sanding, and final touches, resulting in accurately constructed blades.

D. Assembly, Installation, and Testing

1) Assembly: All components were assembled together in preparation for installation.

2) Installation: An initial 4-meter tower was constructed for preliminary testing before mounting the blades on the 20-meter turbine tower.

3) Testing: Initial observations indicated stable blade rotation at low wind speeds. However, precise testing necessitates specialized equipment, currently unavailable due to financial constraints.

Fig. 10. The shape of the blade obtainedafter the completion of the infusion process.

Fig. 11. Final shape of the blades and hub after completing the manufacturing process.

Fig. 12. Assembly of components

VI. Discussion, Conclusions, and Future Work

A. Discussion

Optimal profile selection hinges on factors like aerodynamic performance, structural stability, weight, and ease of manufacturing. Fiberglass emerges as an ideal material for blade construction due to its durability and cost-effectiveness.

B. Conclusions

Efforts focus on developing blade designs that balance performance and cost-effectiveness.

Alternative materials and efficient manufacturing techniques are pivotal in achieving these goals.

C. Future Work

Research avenues include furthering blade design, materials exploration, and manufacturing techniques to enhance performance and reduce costs. Emphasis on long-term durability and reliability warrants attention in future studies.

Fig. 13. The blades after being installed on the test tower

References

[1] J. K. Kaldellis and D. Zafirakis, "The wind energy (r)evolution: A short review of a long history," *Renewable Energy*, vol. 36, no. 7, pp. 1887–1901, Jul. 2011, doi: 10.1016/j.renene.2011.01.002.

[2] A. G. Aissaoui and A. Tahour, *Wind Turbines - design, control and applications*. 2016. doi: 10.5772/61672.

[3] A. K. Mohanty, M. Misra, and L. T. Drzal, *Natural fibers, biopolymers, and biocomposites*. 2005. doi: 10.1201/9780203508206.

[4] K. Larsen, "Recycling wind turbine blades," *Renewable Energy Focus*, vol. 9, no. 7, pp. 70–73, Jan. 2009, doi: 10.1016/s1755-0084(09)70045-6.

[5] J. P. Jensen and K. Skelton, "Wind turbine blade recycling: Experiences, challenges and possibilities in a circular economy," *Renewable & Sustainable Energy Reviews*, vol. 97, pp. 165–176, Dec. 2018, doi: 10.1016/j.rser.2018.08.041.

[6] A. Dilimulati, T. Stathopoulos, and M. Paraschivoiu, "Wind turbine designs for urban applications: A case study of shrouded diffuser casing for turbines," *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 175, pp. 179–192, Apr. 2018, doi: 10.1016/j.jweia.2018.01.003.

[7] W. Tong, *Wind power generation and wind turbine design*. WIT Press, 2010.

[8] S. P. Evans, D. Bradney, and P. Clausen, "Development and experimental verification of a 5 kW small wind turbine aeroelastic model," *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 181, pp. 104–111, Oct. 2018, doi: 10.1016/j.jweia.2018.08.011.

[9] C. Herrera *et al.*, "Structural design and manufacturing process of a low scale bio-inspired wind turbine blades," *Composite Structures*, vol. 208, pp. 1–12, Jan. 2019, doi: 10.1016/j.compstruct.2018.08.061.

[10] P. A. C. Rocha *et al.*, "The effects of blade pitch angle on the performance of small-scale wind turbine in urban environments," *Energy (Oxford)*, vol. 148, pp. 169–178, Apr. 2018, doi: 10.1016/j.energy.2018.01.096.

[11] M. O. L. Hansen, *Aerodynamics of Wind Turbines, 2nd edition*. 2013. doi: 10.4324/9781849770408.

[12] V. N. Carlos, "Diseño y construcción de una mini-turbina eólica | Archivo Digital UPM." https://oa.upm.es/36428/

[13] V. M. Lyatkher, *Wind power*. 2013. doi: 10.1002/9781118720851.

[14] P. Schubel and R. Crossley, "Wind Turbine Blade Design," *Energies*, vol. 5, no. 9, pp. 3425–3449, Sep. 2012, doi: 10.3390/en5093425.

[15] D. A. Griffin and T. D. Ashwill, "Blade System Design Studies Volume I: Composite Technologies for Large Wind Turbine Blades," Jul. 2002. doi: 10.2172/800994.

[16] D. Berry, "Design of 9-meter carbon-fiberglass prototype blades : CX-100 and TX-100 : final project report.," Sep. 2007. doi: 10.2172/921145.

[17] D. A. Griffin and T. D. Ashwill, "Alternative composite materials for Megawatt-Scale wind turbine blades: design considerations and recommended testing," *Journal of Solar Energy Engineering-transactions of the Asme*, vol. 125, no. 4, pp. 515–521, Nov. 2003, doi: 10.1115/1.1629750.

[18] E. J. Barbero, *Introduction to Composite Materials Design*. 2010. doi: 10.1201/9781439894132.

[19] D. U. Shah, P. Schubel, and M. J. Clifford, "Can flax replace E-glass in structural composites? A small wind turbine blade case study," *Composites. Part B, Engineering*, vol. 52, pp. 172–181, Sep. 2013, doi: 10.1016/j.compositesb.2013.04.027.

[20] J. W. Holmes, P. Brøndsted, B. F. Sørensen, Z. Jiang, Z. Sun, and C. Xu-He, "Development of a Bamboo-Based composite as a sustainable green material for wind turbine blades," *Wind Engineering*, vol. 33, no. 2, pp. 197–210, Mar. 2009, doi: 10.1260/030952409789141053.

[21] C. M. Samuel, "Diseño estrutural de un álabe de turbina eólica de 5 kw a base de material compuesto con refuerzo de fibras naturales de Stipa Obtusa," 2019. https://repositorio.utec.edu.pe/handle/20.500.12815/110

[22] S. Iswahyudi, S. Sutrisno, Prajitno, and S. B. Wibowo, "Effect of blade tip shapes on the performance of a small HAWT: An investigation in a wind tunnel," *Case Studies in Thermal Engineering*, vol. 19, p. 100634, Jun. 2020, doi: 10.1016/j.csite.2020.100634.

[23] "NREL Explores Innovative Manufacturing Approach for Next-Generation Wind Turbine Blades," *News | NREL*. https://www.nrel.gov/news/program/2021/manufacturing-next-generation-wind-turbines.html

[24] S. S. P. Reddy, Rohan. Suresh, Hanamantraygouda. MB, and B. P. Shivakumar, "Use of composite materials and hybrid composites in wind turbine blades," *Materials Today: Proceedings*, vol. 46, pp. 2827–2830, Jan. 2021, doi: 10.1016/j.matpr.2021.02.745.

[25] CFD analysis of wind turbine blades | Your engineer knowledge Hub." https://beta.yourengineer.in/article/cfd-analysis-of-wind-turbine-blades-73c0.