The International Journal of Engineering and Information Technology (IJEIT)
ijeit.misuratau.edu.ly
MISURATA UNIVERSITY

Design and Power Coefficient Investigation of Small Scale Horizontal Axis Wind Turbine Blade with Three Different Airfoils

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Article History

Received 01 Mar, 2026
Revised 24 May, 2026
Accepted 21 June, 2026
Online 23 June, 2026

DOI:
https://doi.org/10.36602/ijeit.v14i2.611

Index Terms

Horizontal Axis Wind Turbine, Small Scale, Airfoils (S821, S819, S820), Blade Design, BEM, Power Coefficient.

Abstract

This work is based on the design study of a small-scale horizontal axis wind turbine blade combined with three airfoils using Blade Element Momentum Theory (BEM). In this study, the aerodynamic characteristics of three different airfoils selected and distributed along the blade length were analyzed to obtain optimum design parameters for the wind turbine blade. The BEM theory was implemented for wind turbine blade design and computed the power coefficient. The paper presents the design of a blade that is 6 m in length, which is combined with three airfoil types: S821, S819, and S820, distributed along the blade regions-root, primary, and tip, respectively. In the blade design, techniques were used to linearize the chord length and twist angle for blade optimization. The power coefficient was computed at an angle of attack of 5 degrees through axial and angular induction factors calculations for the blade sections, and the result obtained for the power coefficient is 44.42%. This value does not include the generator efficiency, so this result agrees with the estimated power coefficient for the blade design of 38.25%. This study presents a good power coefficient prediction to motivate continuous research in the wind energy sector.

التصميم والتحقق من معامل القدرة لشفرة توربين الرياح ذات المحور الأفقي صغيرة الحجم بثلاثة جنيحات هوائية مختلفة

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الملخص

يستند هذا العمل الى دراسة تصميم شفرة توربين رياح ذات المحور الافقي صغير الحجم ومدمجة بثلاث جنيحات هوائية باستخدام نظرية زخم عنصر الشفرة. في هذه الدراسة تم تحليل الخصائص الديناميكية الهوائية للثلاث الجنيحات الهوائية المختلفة والموزعة على طول الشفرة للحصول على معاملات التصميم المثالية لشفرة توربين الرياح. تم تطبيق نظرية زخم عنصر الشفرة نفذت لتصميم شفرة توربين الرياح وحساب معامل القدرة لها. تقدم الورقة تصميم للشفرة بطول 6 متر وهذه الشفرة مدمجة بثلاثة أنواع من الجنيحات الهوائية اس 821، اس 819، اس 820 والتي تم توزيعها على مناطق الشفرة، منطقة جذر الشفرة، المنطقة الاساسية ومنطقة الطرف على التوالي. في تصميم الشفرة استخدمت تقنيات لخطية طول الوتر وزاوية الالتواء لتحسين اداء الشفرة. تم حساب معامل القدرة عند زاوية هجوم 5 درجات وذلك من خلال حساب معاملات الحث المحوري والزاوي لمقاطع الشفرة، وكانت النتيجة التي تم الحصول عليها لمعامل القدرة 44.42%، وهذه القيمة لا تشمل كفاءة المولد. لذا تتفق هذه النتيجة مع معامل القدرة المقدر لتصميم الشفرة، وهو 38.25%. وقد قدمت هذه الدراسة تنبؤا جيدا لمعامل القدرة، مما يحفز على مواصلة البحث في قطاع طاقة الرياح.

الكلمات المفتاحية

توربين رياح افقي، حجم صغير، اجنحة (اس 821، اس 819، اس 820)، تصميم الشفرة، نظرية زخم عنصر الشفرة، معامل القدرة.

I. Introduction

Wind energy is one of the most important applications of renewable energy that captures the kinetic energy of wind to generate electricity. The rotary blades of the wind turbine transform wind motion into rotary motion of a shaft, which is connected to the generator to generate electricity. The electricity generated can be fed into the electrical grid for wider distribution to be used to power homes and other facilities.

A three-bladed wind turbine design with a 4-meter diameter, incorporating two different airfoils distributed along blade sections S1210 and S1223, where result demonstrates a high performance at low velocities, achieving a power coefficient (Cp) exceeding 40% at a wind speed of 5 m/s. at the wind speed increases to 5.5 m/s of tip speed ratio 6.5, the power generated is 650 W with power coefficient (Cp) 0.445. Where the wind speed increases to 7 m/s, the power generated rises to 1.18 KW at a solid power coefficient (Cp) 40% [1].

The blade geometry for a 20-kW wind turbine was optimized using the Blade Element Momentum (BEM) method, with MATLAB employed to calculate critical design parameters. These parameters included the chord length, twist angle, lift and drag coefficients, and induction factors. The results analysis reveals a reduction in both chord length and twist angle along the blade span. Furthermore, the maximum values of the axial induction factor (a) and the angular induction factor (a') are 0.3325 and 0.175, respectively [2].

The small wind turbine blade designed with a airfoil type SG6043 was evaluated by using DEM and CFD approaches. The study achieved a maximum power coefficient (Cp) of 0.46 at tip speed ratio 5 and rotor speed of 267.5 rpm [3].

In aerodynamic design of wind turbine rotor, the chord and twist angle of a blade typically follow non-linear profiles. While these profiles are often linearized to simplify the manufacturing process, such adjustments do not inherently degrade performance. In fact, because an optimum rotor theory only ensures high efficiency at a specific design wind speed, a linearized blade can often perform better than the initial nonlinear model. In this specific case study, linearizing the chord and twist angle profiles (while maintaining fixed values at the tip) results in an increase in annual energy production of 3.33% at a mean wind speed of 5 m/s [4].

According to the NREL guidelines, a horizontal axis wind turbine (HAWT) blade was developed using a "mixed airfoil" approach to enhance aerodynamic performance. The design of the blade combined three various airfoils from the S-series-S823, S833, and S822- at different sections of the blade. The design achieved a higher coefficient of performance compared to blades utilizing a single airfoil. This transition to a multi-airfoil configuration of the rotor demonstrates a clear improvement in the power coefficient [5].

Research indicates that mixed-airfoil configurations are particularly effective for small-scale horizontal axis wind turbines (HAWTs). Furthermore, the SST k-omega turbulence model provides precise results for blade analysis, provided that the mesh is suitably refined within the boundary layer to capture complex flow [6].

Research indicates that incorporating two various airfoil profiles into a hybrid blade design significantly enhances start-up response at low wind speeds. As well, this design achieved a high-power coefficient of 34% at a tip speed ratio (TSR) of 3.7. When compared to other small-scale wind turbines in literature review, this design demonstrated perfect performance. Furthermore, experimental wind tunnel data showed strong correlation with the numerical results generated by the Blade Element Momentum (BEM) code [7].

The design process involved evaluating multiple notations for blade chord and twist angle to identify the most efficient configuration. Performance metrics, including lift, drag, and power coefficients were calculated using Blade Element Momentum (BEM) theory. Furthermore, the impact of varying air densities on the power curves was analyzed, revealing that various densities increased power output. To validate these findings, Computational Fluid Dynamics (CFD) simulations were conducted in Ansys Fluent *for* different angles of attack. The CFD results demonstrated strong correlation with the BEM analysis, confirming the reliability of the design [8].

To improve the design of a 5-kW residential wind turbine, researchers investigated the blade's aerodynamics alongside the optimal conditions for the drivetrain and electrical generator. Utilize the Blade Element Momentum (BEM) theory to establish design parameters and analyze aerodynamic properties; this study found that the turbine reached its capacity of 5 kW at a wind speed of 8.1 m/s while its rated wind speed design was 9 m/s [9].

Horizontal Axis Wind Turbine blades with different airfoils were designed based on BEM for fixed - pitch variable speed. As a result, the BEM theory is efficient for predicting rotor aerodynamic characteristics [10].

The power performance of small horizontal axis wind turbines (HAWTs) was analyzed utilizing the Blade Element Momentum (BEM) methods. The blade design parameters took into consideration factors such as tip loss, hub loss, drag coefficient, and wake. The design focused on wind turbine type selection, limited blade airfoil, twist angle, and chord length distribution. Results indicated that 3-, 5-, and 7-bladed rotors achieved maximum power coefficients of 0.46, 0.50, and 0.48 at tip speed ratios of 7, 5, and 4, respectively. The analysis exposed that the number of blades has a minor impact, while solidity significantly influences the power coefficient. At the pitch angle of 3°, performance peaked with 5 blades but declined with an increase in the number of blades. Maximum efficiency was found at 4%-6% solidity for 3-bladed rotors and a tip speed ratio of 7, and 5%–10% solidity for 5 and 7-bladed rotors at tip speed ratio 5 and 4 respectively [11].

II. Blade Design Parameters

A. Design Wind Speed and Rated Wind Speed

At design wind speed, the wind turbine rotor power coefficient achieves its maximum value. According to IEC61400-2 [12], the design wind speed for wind turbine should be the annual mean wind speed multiplied by 1.4. In this case study, the annual mean wind speed is assumed to be 5.7 m/s, therefore, the design wind speed is 8 m/s.

The required power was set at 13,500 W. The efficiency (mechanical and electrical) was considered to 85%. The design power coefficient range is 40% to 50%, so we chose 45%. The horizontal axis wind turbine has power coefficients about 38.25%. Through these values, the rotor radius was calculated by applying the following equation [13]:

$$P = \frac{1}{2}\, \rho\, A\, V\, C_p\, \eta \qquad (1)$$

The rotor radius of wind turbine was found approximately 6.00 m.

B. Rotor Speed and Design Tip Speed Ratio

Generally, small wind turbines with three blades have a tip speed ratio (TSR) at the design wind speed in the range of 6 to 8. In this case study, we choose a design tip speed ratio of 6 at a design wind speed of 8 m/s, which corresponds to a blade tip speed of 46.8 m/s and a rotor speed of 76.4 rpm.

C. Airfoils Behaviour

A wide arrangement of airfoil geometries has been developed to keep pace with the rapid evolution of the wind energy sector. While airfoil optimization is often more critical for power wind systems, the selection of the right profile remains essential for small-scale wind turbines. Specifically, these small-scale wind turbines require airfoils that perform efficiently at low angles of attack, where the lift-to-drag ratio reaches its maximum value by maintaining a drag coefficient significantly lower than the lift coefficient [14; 15].

Many established airfoil families have been successfully applied to commercial wind turbine blades. These profiles contribute to significant increase in energy production by displaying a high lift-to-drag ratio and reduced sensitivity to surface roughness. Furthermore, for stall-regulated rotors, these airfoils allow for an increased swept area relative to the generator size, maximizing power capture [16].

The NREL has tested various airfoils for wind turbine applications, identifying and accepting only those that demonstrate the highest aerodynamic efficiency. According to the NREL, the rotor diameter of wind turbines from 10 m to 20 m can use airfoils S821, S819, and S820 for the root, primary, and tip regions, respectively.
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The values of lift and drag coefficients of airfoils selected with the angle of attack in the range of -15 to 15 degrees at Reynolds number of 1000000 are described in figures (1), (2), (3) [17]. figure (4) shows the lift to drag ratio of three airfoils selected for the horizontal axis wind turbine.

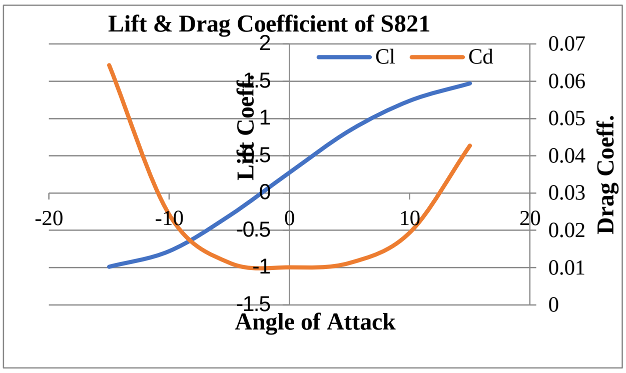

Figure 1. Lift and Drag Coefficient of Airfoil S821 [17]

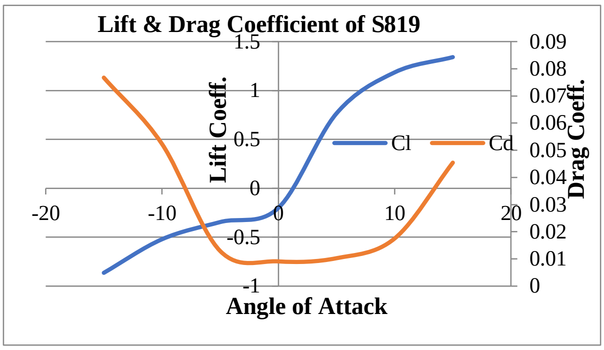

Figure 2. Lift and Drag Coefficient of Airfoil S819 [17]

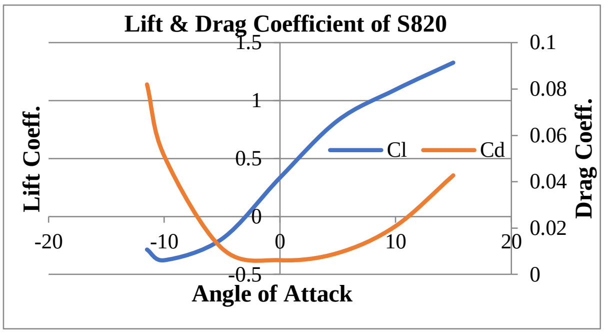

Figure 3. lift and Drag Coefficient of Airfoil S820[17].

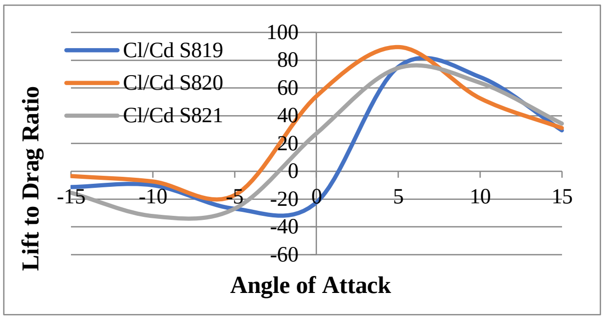

Figure 4. lift to Drag Ratio of Airfoils Selected [17].

D. Airfoils Selection and Design Angle of Attack

NREL suggests designing wind turbine blades with a combination of three different airfoils from the S-series. This approach aims to improve the performance of a horizontal axis wind turbine by optimizing the design of its blade. The blade is essentially divided into three parts, with each section featuring a distinct airfoil to enhance its aerodynamic efficiency.

The blade is designed with three different airfoils and expands along the blade length to be airfoils S821, S819, and S820 for the root, primary, and tip regions respectively. The airfoil's performance is affected by Reynolds number (Re), which is defined as [18]:

$$Re = \rho\, U_{rel}\, c / \mu \tag{2}$$

The Reynolds number for wind turbine fixed speed does not vary significantly, which is the Reynolds number range of 933095 – 1123685 for the variation wind speed from 2 m/s to 16 m/s as it is shown in Table (1). The Reynolds number is chosen as 1000000 for design Reynolds number.

Table 1. Estimated Reynolds number at various operation wind speed

v (m/s)	V_{tan}(m/s)	U_{rel}(m/s)	Re. number
2	23.4	23.5	933,095
4	23.4	23.7	941,036
6	23.4	24.2	960,889
8	23.4	24.7	980,743
10	23.4	25.4	1,008,537
12	23.4	26.3	1,044,272
14	23.4	27.3	1,083,979
16	23.4	28.3	1,123,685

The design of attack angle, as a rule, a high value of lift coefficient contributes to positive torque, and a low of drag coefficient contributes to negative torque. Therefore, the design attack angle is chosen at the critical angle of attack where the lift to drag ratio is maximum. The design angle of attack is set at the critical angle of attack 5°.

III. Preliminary Blade Design

The initial design of the wind turbine blade focuses on determining the chord and twist angle profiles along blade length. This is based on several parameters: a rotor radius of 6.0 meters, a design tip speed ratio of 6, and 3 blades. The design also utilizes a specific angle of attack (5 degrees) and lift coefficients of three airfoils S821, S819, and S820 selected at the attack angle are 0.8392, 0.7657, and 0.8284 respectively. The blade is divided into 10 sections, and for each section, the chord and twist angle are calculated using an optimum rotor theory [18], which is been detailed as follows:

$$\lambda_{r,i} = \lambda_0 (r_i / R) \tag{3}$$

$$\varphi_i = \tfrac{2}{3} \tan^{-1}(1/\lambda_{r,i}) \tag{4}$$

$$c_i = \frac{8\,\pi\, r_i}{B\, C_{l,design,i}} (1 - \cos\varphi_i) \tag{5}$$

$$\theta_{p,i} = \varphi_i - \alpha_{design,i} \tag{6}$$

Where i is the indication of blade section number, $\lambda_{r,i}$ is the speed ratio in that section, r_i the radius of that section, and φ_i is the relative wind angle at that section. $C_{l,design,i}$ and $\alpha_{design,i}$ are the design lift coefficient and design angle of attack at that section respectively. The design lift coefficient and design angle of attack are taken into account to be constant along blade span. Therefore, for the following blade sections, we use $C_{l,design}$ and α_{design} to represent $C_{l,design,i}$ and $\alpha_{design,i}$ respectively.

Preliminary chord length and twist angle are calculated based on equations (3) - (6). Table (2) describes the blade geometry chord distributions along blade span in blade segment 10. Figures (5) and (6) show the chord length at the root of the blade over 1 m, and the twist angle distributes from 25.41 degrees at blade root to 6.31 degrees at blade tip.

Table 2. Blade Design Specifications

Span (r_i) (m)	Chord (m)	Twist Angle (φ) Deg.	Airfoil Type
0	HUB	-	HUB
1.275	1.231	25.41	S821
1.80	1.017	19.37	
2.325	0.846	15.52	
2.85	0.786	12.89	S819
3.375	0.678	11.00	
3.90	0.596	9.59	
4.425	0.553	8.49	
4.95	0.441	7.61	S820
5.475	0.401	6.90	
6.00	0.368	6.31	

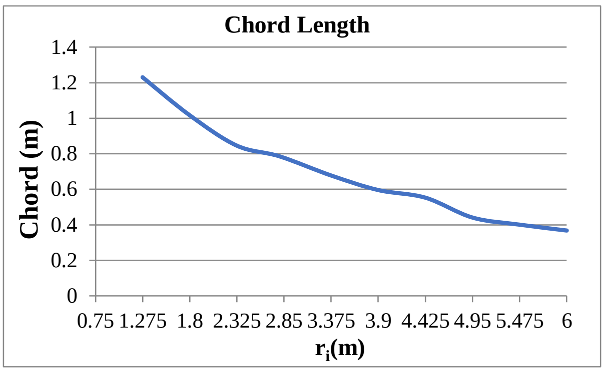

Figure 5. Blade chord length profile

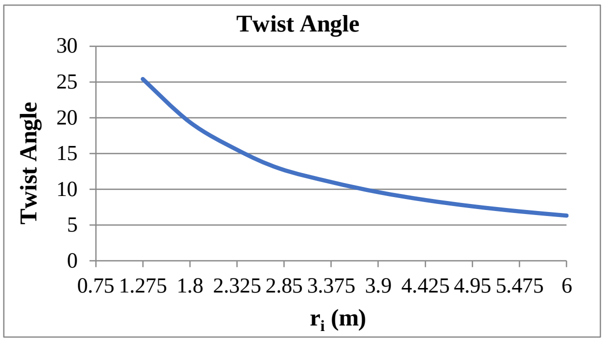

Figure 6. Blade twist angle profile

IV. Performance Analysis

The wind turbine rotor power is contributed by each individual blade element of the three blades; therefore, the calculation is based on each blade element's performance analysis. The performance parameter of each blade element is calculated through an iterative procedure [18, 19], which is summarized in the following steps:

(1) Estimate an initial (the first iterative) value for the axial induction factor a and angular induction factor a':

$$\varphi_{i,1} = {}^{2}/_{3} \tan^{-1}({}^{1}/_{\lambda_{r,i}}) \quad (7)$$

$$a_{i,1} \left[\frac{\sigma_i \, C_n}{4\sin^2\varphi_{i,1} + \sigma_i \, C_n}\right] \quad (8)$$

$$a'_{i,1} \left[\frac{\sigma_i \, C_t}{4 \sin\varphi_{i,1} \cos\varphi_{i,1} - \sigma_i \, C_t}\right] \quad (9)$$

Where i indicates the blade element section, and σ_i is the local solidity, defined by:

$$\sigma_i = \frac{B \, c_i}{2 \, \pi \, r_i} \quad (10)$$

$$C_n = C_l \cos\varphi + C_d \sin\varphi \quad (11)$$

$$C_t = C_l \sin\varphi - C_d \cos\varphi \quad (12)$$

(2) Begin the procedure iteration; for the first iteration follow step (1). Then calculate the relative wind angle and Prandtl tip loss factor:

$$\tan^{-1}\varphi_i = \frac{(1-a_i)}{(1+a_i')\lambda_{r,i}} \quad (13)$$

$$F_i = \frac{2}{\pi} \cos^{-1} e^{-f} \quad (14)$$

Where, $f = \frac{B \, (R-r)}{2 \, r \sin\varphi_i}$

(3) In this step calculate the local angle of attack of the blade section part:

$$\alpha_i = \varphi_i - \theta_{p,i} \quad (15)$$

Then obtained C_l and C_d are obtained from the airfoil lift and drag coefficient curves against the angle of attack as it is illustrated in figures curves (1), (2), and (3) according to the airfoil type used in blade section.

(4) Recalculate the axial induction factor a and angular induction factor a' for next iteration by applying the equations number (8) and (9) [2].

If the deviation between the axial induction factor of this iteration and the previous one is within an acceptable tolerance, then confirm the local relative wind angle φ_i, tip loss factor F_i and angle of attack α_i, which determine the local lift and drag coefficients $C_{l,i}$ and $C_{d,i}$ for the blade element part; (if not, then go back to step 2).

Having obtained the power coefficient for each blade element by applying the following equation [6]:

$$C_p = \frac{8}{\lambda^2} \int_{\lambda_r}^{\lambda} F_i \, \lambda_r^3 \, a'(1-a) d\lambda_r \quad (16)$$

This flowchart as shown in figure (7), illustrates the flow of the process of analyzing power coefficient of rotor blade in this research.

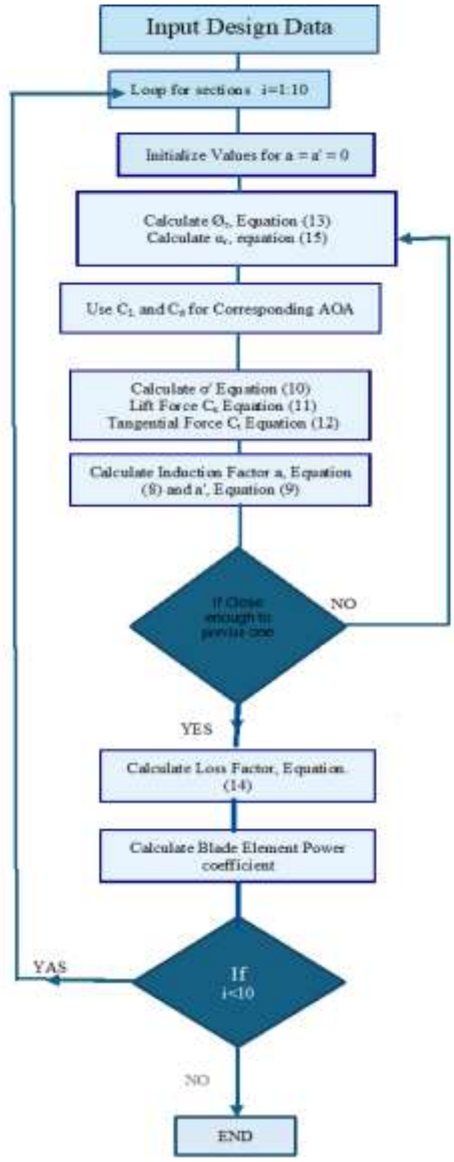

Figure 7. Flowchart for Computation of Power Performance Using an Iterative Procedure

V. Linearization of Chord Length

To make wind turbine blades easier and cheaper to manufacture, it's necessary to linearize the chord lengths and blade angles. This is because the calculated chords and angles naturally vary in a nonlinear way along the blade, which can be difficult to fabricate and uneconomical using materials. To minimize these difficulties, it is needed to linearize the chords and the blade angles.

Chord length linearization without too much deviation is achieved by the following a linear equation as:

$$c=a_1 r+ a_2 \tag{17}$$

Where, r is the radial position along the blade, and a_1 and a_2 are constants. These constants are determined by setting two points on the linear line. A common method is to use the theoretical chord values at r = 0.5R and r = R, to determine the line [20].

The constants a_1 and a_2 can be calculated by solving Equation (17) at two different values of blade radius.

$$a_1= -0.1181 \qquad a_2=1.07657$$

Therefore, c = -0.1181 r + 1.07657

VI. Results and Discussion

Refer to data on literature review; the linearized chord length and twist angle improve power performance and reduce both material and manufacturing costs. The radial profiles of the chord and twist angle of the optimal blade are depicted in Figures (8) and (9).

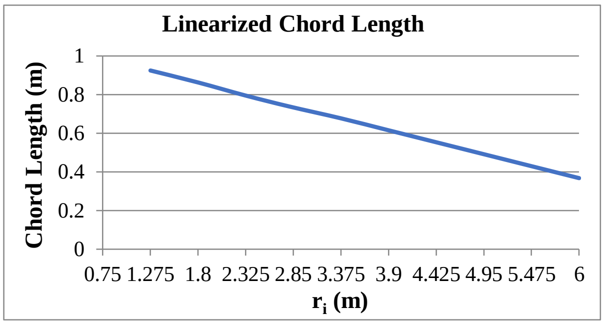

Figure 8. Linearized chord length

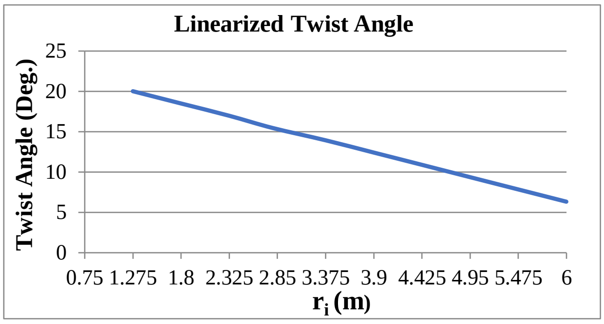

Figure 9. Linearized Twist Angle

The axial induction factor, and angular induction factor for the blade sections were calculated iteratively, and the results are described in Table (3). The results of the axial and angular induction factors are plotted along the blade span in the Figures (10) and (11), respectively. The axial induction factor starts at a high value at the beginning of the root section, which is equal to 0.37680. As the radial span increases, the axial induction factor rapidly decreases up to the blade radius (ri = 2.85) m. This is due to the airflow deceleration induced by the rotor stronger near the root section, and becoming weaker toward the outer blade span. Consequently, the trendline stabilizes at a nearly constant value of about 0.334-0.339 toward the blade tip, indicating a more uniform flow interaction and aerodynamic performance across the outer blade span. Hence, the rotor is operating within a normal aerodynamic regime without excessive induction or flow separation

.

The trendline of the angular induction factor illustrates the variation of values with radial distance along the blade span. At the root section the angular induction factor reaches its maximum value of approximately 0.12283, and as the radial distance increases the factor decreases rapidly. At blade radius approximately ri=3.3 m, the angular induction factor approaches a nearly constant value close to 0.01, indicating a stabilized flow condition along the outer span of the blade. This means the low values of angular induction factor near the tip imply reduced swirl in the wake and improved aerodynamic performance.

The power coefficient of wind turbine blade model combined of three airfoils is computed by applying the trapezium rule for solving the integration function in the equation number (16) [6], The trapezium rule is:

$$\int_{x0}^{xn} f(x)dx \approx \frac{x_n - x_0}{2n}\left[(y_0 + y_n) + 2(y_1 + y_2 + \cdots + y_{n-1})\right] \tag{18}$$

Where, $f(x) = \int_{\lambda_r}^{\lambda} F_i\, \lambda_r^3\, a'(1-a)\, d\lambda_r$

And the results calculated from the integration part of the equation (16) are demonstrated in the table (3). According to these results, the power coefficient analyzed by BEM theory is equal 44.42%.

Table 3. Axial, Rotational Induction Factors

r (m)	a	a'	F	*f(x)*
1.275	0.37680	0.12283	1.00000	0.158658174
1.800	0.35568	0.06360	0.999986	0.238984736
2.325	0.34658	0.03833	0.999934	0.314754139
2.850	0.34198	0.02545	0.999620	0.387522031
3.375	0.33938	0.01803	0.998695	0.457300474
3.900	0.33762	0.01340	0.995134	0.523947045
4.425	0.33664	0.01030	0.983528	0.582254775
4.950	0.33574	0.00830	0.943595	0.630982655
5.475	0.33503	0.00673	0.807023	0.592727940
6.000	0.33468	0.00555	0.000000	0.000000000

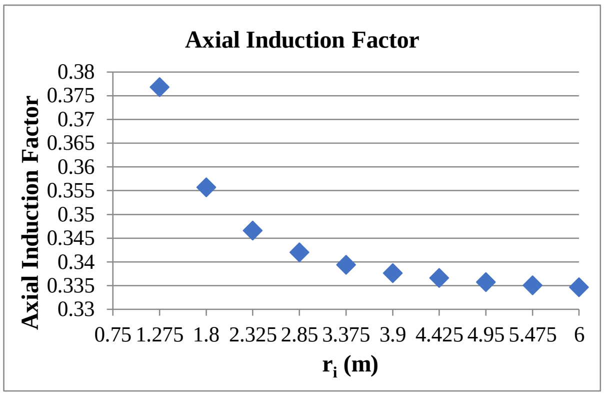

Figure 10 Axial Induction Factor

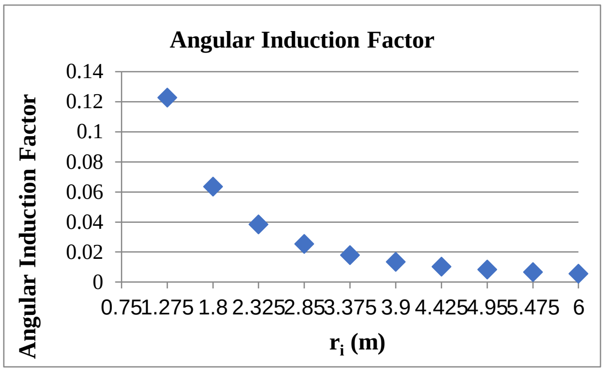

Figure 11. Angular Induction Factor

VII. Conclusion

This present study has utilized Blade Element Momentum (BEM) theory to evaluate the aerodynamic efficiency of small-scale, horizontal-axis wind turbines. The results of this work demonstrated that a three-airfoil blade design can achieve a highly satisfactory power coefficient within the wind energy sector. The chord length and twist angle distributions, axial induction factor, and angular induction factor of the blade design were computed. The obtained result of power coefficient is 44.42% by BEM theory at the design wind speed of 8 m/s, and the blade tip velocity of 46.8 m//s, while the estimated power coefficient for the blade design was 38.25%. Further study of the currently designed wind turbine blade could be conducted using Computational Fluid Dynamics (CFD) to investigate the aerodynamic efficiency and compare results with the present results.

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