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Parametric Optimization of the Selig (S1223-il) Airfoil for Enhanced Performance of Vertical Axis Wind Turbines

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Abstract— This study investigates the optimization of the Selig (S1223-il) airfoil to improve the performance of vertical axis wind turbines (VAWTs) using the QBlade software. The efficiency of wind turbines heavily relies on the design of their airfoils, as they play a critical role in capturing energy from the wind. Parametric optimization methods are employed to simultaneously reduce the thickness and camber of the airfoil. Specifically, the airfoil thickness is reduced from 12.14% to 8.5% at the maximum thickness position of 19.80%, while the camber is decreased from 8.87% to 8.46% at the maximum camber position of 49%. These optimizations result in improved aerodynamic performance of the airfoil. Simulation results demonstrate significant enhancements in the coefficients of lift (C_L), drag (C_D), moment (C_m), and lift-to-drag ratio (C_L/C_D) at an optimal angle of attack of 10º. The optimized airfoil exhibits C_L and C_L/C_D ratios increased from 1.988 to 2.121 and 33.370 to 55.356, respectively, while C_D and C_m are reduced from 0.063 to 0.038 and -0.226 to -0.244, respectively. Thereby, the coefficient of power (C_P) is improved from 23% to 34% due to these optimizations. The findings of this study suggest that employing parametric optimization methods to enhance the Selig (S1223-il) airfoil represents an effective approach to improving the performance of VAWTs. This approach contributes to the promotion of wind energy utilization as a sustainable and environmentally friendly power source.

Keywords— Vertical axis wind turbine, Selig (S1223-il) airfoil, QBlade, Parametric optimization methods

I. INTRODUCTION

Wind turbines have emerged as a popular source of renewable energy. There are two main types of wind turbines: HAWTs and VAWTs. Although VAWTs were developed before HAWTs, they are currently less aerodynamically efficient due to their complex behaviour in unsteady wind conditions [1]. Among multiple factors, the shape and dimensions of the blade of VAWTs critically influence its efficiency [2]. However, blade design can be challenging, and finite element analysis (FEA) software has been used to make it more feasible and cost-effective [3]. Among various computational techniques, QBlade software is an open-source tool for the design, simulation, and analysis of both horizontal and vertical axis wind turbines, based on the Blade Element Momentum Theory (BEMT), and allows for aerodynamic and structural analysis of wind turbine blades [4]. According to BEMT, the aerodynamic performance of VAWT blades is determined by small segments of lift and drag forces, which can be used to calculate the overall performance of the blades, as illustrated in Figure 1. VAWTs offer several advantages over HAWTs, such as lower manufacturing costs, easy installation, lower maintenance, lower noise, and the ability to generate power in urban areas where the wind direction is variable and unpredictable. However, the aerodynamic efficiency of VAWTs remains a significant concern that necessitates attention to enhance the power extraction potential of this technology.

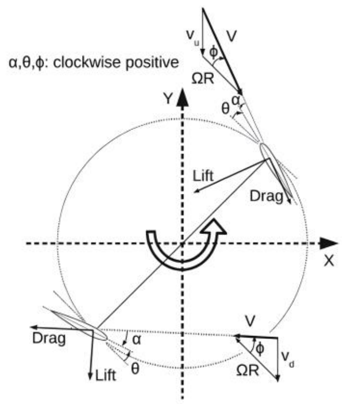


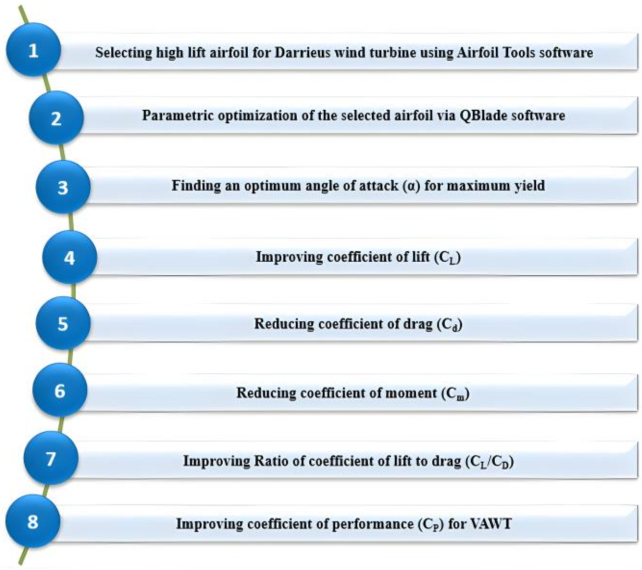
Figure 1. Schematic diagram of forces acting on VAWT blades based on BEMT

Pechlivanoglou et al. utilized QBlade to enhance the annual energy production of a 1.5 MW turbine by extrapolating measured wing lift increases from wind tunnel experiments [5]. Thuné et al. analyzed the outer rotor blade section of a virtual 7.0 MW wind turbine with a 165 m diameter. They identified and tested airfoils using XFLR5 (XFoil) and QBlade with the blade element momentum theory, finding that NACA 63-6XX and NACA 64-6XX airfoils performed best for blade designs 2 and 3, with a high-performance coefficient compared to large commercial HAWT rotors [6]. Weinzierl et al. expanded the functionality of QBlade to enable the parameterized study of actively controlled trailing edge flaps, which reduced wind turbine loads [7]. Using QBlade software, Mueller et al. optimized wind turbine blade aerodynamics by incorporating vortex generators (VG), determining the optimal chord position for VGs to be in the range of x/c = 15%-20% [8]. Rahul et al. analyzed a small VAWT at a slow speed using NACA 4412 and NACA 63415 airfoils. They found that wind turbine efficiency can be impacted by parameters such as angle of attack, twist angle, tip velocity ratio (TSR), and chord length [9]. Mustafa Alaska et al. achieved highly accurate results in their research on HAWT blade behaviour and performance using QBlade software and the SG6043 profile for 10 different sections with a blade length of 1.17 m [10]. Zahariea et al. analyzed a small-scale HAWT using QBlade software, focusing on the power curve, pitch angle control curve, and annual energy production. Their structural analysis of three internal structures with natural frequencies was found to be in a safe range, avoiding resonance [11]. Shubham Raut et al. utilized QBlade software to design and optimize the SG6043 airfoil. MATLAB programming was used to determine optimized values for the chord length and the twist angle. The results of the QBlade simulation indicated a maximum C_p of 0.45 at a rated wind speed of 8.4 m/s [12].

The effectiveness of wind turbines is largely determined by the design of the blade airfoil sections, which work together to produce lift and reduce drag. Therefore, selecting the right airfoil is a critical aspect of wind turbine design and optimization as it affects the amount of power generated by the turbine. The Selig (S1223-il) airfoil has been used in various applications due to its superior aerodynamic characteristics, including low C_L and C_L/C_D ratios [13-15]. However, the impact of reducing the thickness and camber of this airfoil on the performance of vertical axis wind turbines (VAWTs) is not well understood. An in-depth investigation of these parameters is necessary to optimize VAWT design and increase efficiency. The objective of this study is to explore the effects of reducing the thickness and camber of the Selig (S1223-il) airfoil on VAWT aerodynamic performance. The study will analyze objective functions, including minimizing C_L, C_L/C_D, and maximizing C_D and C_m at low Reynolds numbers and optimal angles of attack.

II. Research Approach

The performance VAWTs is heavily reliant on the lift generated by their blades, which is directly influenced by the design of the airfoil. An airfoil that can achieve maximum lift at low wind speeds is considered optimal for VAWTs. In this context, the Selig (S1223-il) airfoil stands out as a promising candidate for optimization due to its favourable aerodynamic characteristics, including high lift and low Reynolds number performance. The present study investigated the optimization of the Selig (S1223-il) airfoil design for VAWTs using QBlade simulation software, which is an open-source software developed by the Institute for Technical Thermodynamics and the German Aerospace Center (DLR) [16]. This software offers a user-friendly graphical user interface (GUI) that allows users to create wind turbine designs and simulate their performance using BEMT. Moreover, the software allows the customization of turbine models by adjusting design parameters such as airfoil selection, blade shape, and rotor diameter. The methodology adopted for this study is illustrated in the following flow chart.



In this research, the optimization process aimed to enhance the aerodynamic performance of Selig (S1223-il) by simultaneously reducing its thickness and camber while keeping other design parameters constant, as shown in Table 1. The primary objective of this step was to identify the optimal combination of thickness and camber that would result in superior aerodynamic performance while maintaining a constant chord length and twist.

TABLE 1. PROPERTIES OF ORIGINAL AND OPTIMIZED SELIG (S1223-IL) AIRFOIL

Airfoils	**Thickness (%)**	**Thickness at Maximum Position (%)**	**Camber (%)**	**Camber at Maximum Position (%)**
Selig (S1223-il)	12.14	19.90	8.67	49.00
Optimized Selig (S1223-il)	8.50	19.80	8.46	49.00

Thickness and camber are important parameters that have a significant impact on the airfoil's properties, including lift coefficient (C_L), drag coefficient (C_D), pitching moment coefficient (C_m), and the C_L/C_D ratio. Increasing the airfoil thickness can enhance lift, but it can also increase drag and stall risks. Likewise, increasing camber can also improve lift, but it may also lead to increased drag and stall risks. Therefore, any modifications made to the airfoil design were evaluated based on trade-offs between lift, drag, and stall characteristics, while considering the intended use and the desired performance characteristics. According to the simulated outcomes, the optimized Selig (S1223-il) airfoil has a reduced profile thickness and camber compared to the original Selig (S1223-il) airfoil, as presented in Figure 2.

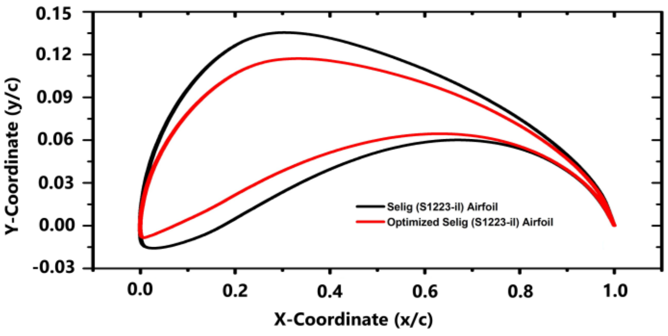


Figure 2: Comparison of thickness and camber of original and optimized Selig (S1223-il) airfoils

III. RESULTS AND DISCUSSION

A. Optimum angle of attack (α)

QBlade utilizes aerodynamics principles to elucidate the optimal angle of attack for an airfoil. Based on aerodynamic theory, the optimal angle of attack for an airfoil corresponds to the angle that generates the maximum C_L/C_D. At this angle, the airfoil achieves maximum aerodynamic efficiency by producing the highest amount of lift with the lowest possible drag.

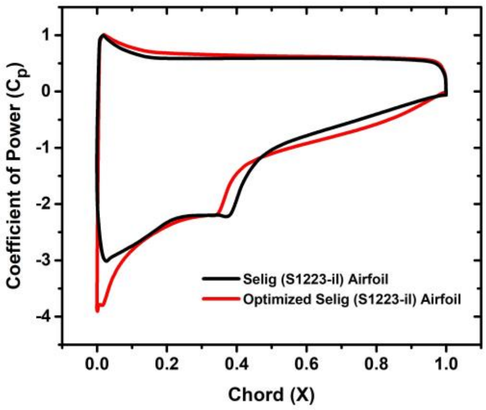


Figure 3. C_p vs Chord-X distribution of the original and optimized Selig (S1223-il) airfoils

The XFOIL direct analysis simulation is employed to identify the ideal angle of attack, covering a range of -10 to 20 degrees with increments of 0.5 degrees. At 10 degrees angle of attack, there is a noticeable pressure variation around the airfoil, resulting in improved C_P, as presented in Figure 3. The C_P values for the original and optimized Selig (S1223-il) airfoils are 23% and 34%, respectively.

B. Effect of Angle of Attack on Lift Coefficient

The QBlade software employs aerodynamic theory to explain the correlation between the angle of attack (α) and the lift coefficient (C_L) of an airfoil. This theory states that the lift generated by an airfoil is proportional to the dynamic pressure of the air flowing over the airfoil and its area. The dynamic pressure, in turn, is determined by the air density and velocity. The lift force produced by an airfoil increases linearly with the angle of attack, up to a certain point. Beyond this point, the airflow over the airfoil becomes turbulent, resulting in a decrease in lift force known as the "stall condition." The "stall angle" is the angle of attack at which this occurs. Figure 4 demonstrates that C_L increases linearly with α. At 10°, the Selig (S1223-il) airfoil has an approximate C_L of 1.988, while the optimized Selig (S1223-il) airfoil achieves a C_L of 2.121. Reducing both airfoil thickness and camber simultaneously is found to yield an optimal C_L based on the obtained results.

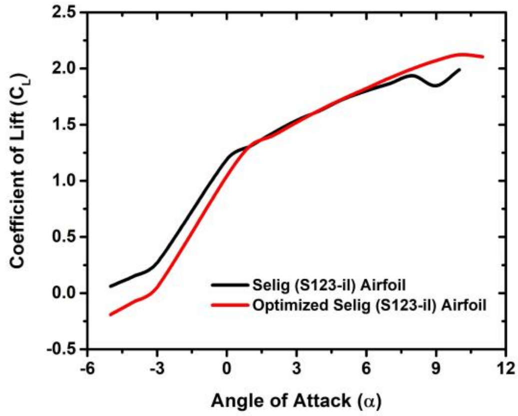


Figure 4. Comparison of C_L for both airfoils at $\alpha = 10^0$

C. Effect of Angle of Attack on Drag Coefficient

The drag coefficient of an airfoil is influenced by various factors, including the angle of attack, airfoil shape, Reynolds number, and surface defects or turbulence. The drag coefficient is typically low at low angles of attack. However, as the angle of attack increases, the airflow over the airfoil becomes more turbulent, which causes an increase in C_D.

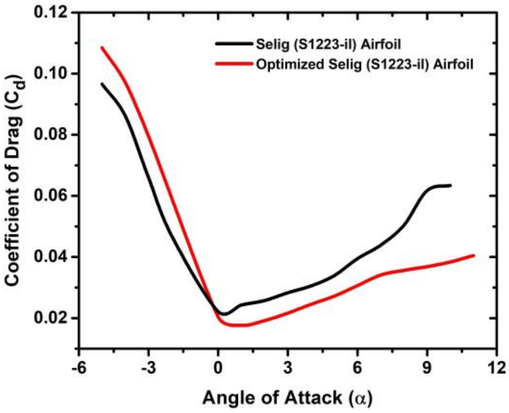


Figure 5. Comparison of C_D for both airfoils at $\alpha = 10^0$

The relationship between α and C_D is illustrated by a curve in Figure 5, which shows a low C_D at small values of α, followed by a sharp increase in C_D at higher angles of attack. It is important to note that even at α equal to zero, a small amount of drag is still maintained due to skin friction and airfoil geometry. The optimized Selig (S1223-il) airfoil exhibits a decreased C_D value at the optimum angle of attack, with C_D decreasing from 0.063 to 0.038.

D. Influence of Angle of Attack on Coefficient of Moment

The pitching moment coefficient, C_m, is a crucial aerodynamic parameter that measures the tendency of an airfoil to rotate around its centre of gravity due to aerodynamic forces. C_m is affected by several factors, such as angle of attack, airfoil geometry, Reynolds number, and surface roughness. At low angles of attack, C_m is generally low. However, as the angle of attack increases, the flow over the airfoil becomes turbulent, resulting in an increase in C_m.

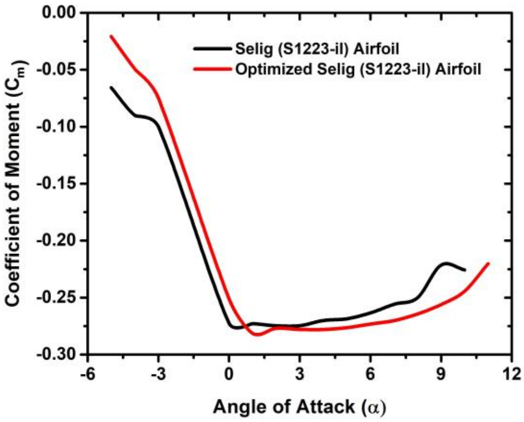


Figure 6. Comparison of C_m for both airfoils at an angle of attack of 10^0

The relationship between C_m and angle of attack can be plotted on a graph, as depicted in Figure 6, which usually displays a low C_m value at small angles of attack, followed by a sharp rise at higher angles of attack. The optimized Selig (S1223-il) airfoil achieved a C_m value of -0.245 at the optimum angle of attack, representing a decrease from the original value of -0.226. The negative C_m value indicates a nose-down moment, which would decrease the angle of attack of the blade without any control input.

E. Impact of Angle of Attack on Ratio of Lift-to-Drag Coefficient

As the angle of attack of an airfoil increases, the lift coefficient initially rises, reaches a peak, and then declines rapidly due to flow separation and stall. Simultaneously, the drag coefficient also increases due to turbulence and flow separation. The aerodynamic efficiency of the airfoil can be measured using the C_L/C_D ratio, which tends to be low at low angles of attack but rises to a maximum value before falling sharply at higher angles due to stall. Based on Figure 7, the optimized Selig (S1223-il) airfoil has a significantly higher C_L/C_D ratio than the Selig (S1223-il) airfoil. Specifically, the optimized Selig (S1223-il) airfoil exhibits a C_L/C_D ratio of 55.353, compared to the Selig (S1223-il) airfoil's ratio of 31.370.

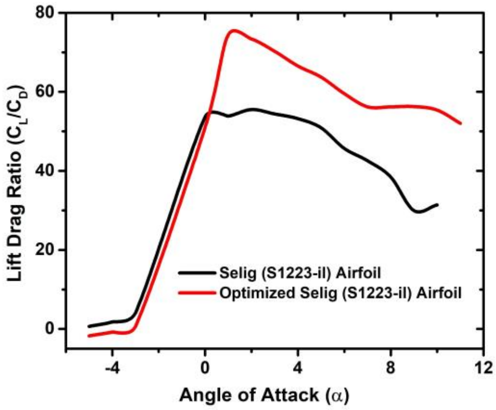


Figure 7. Comparison of C_L/C_D ratio for both airfoils at $\alpha = 10^0$

IV. Comparison of Original and Optimized Selig (S1223-il) Airfoils

Table 2, generated by the XFOIL direct analysis segment, provides a comparison of airfoil properties, including the optimal angle of attack, C_L, the C_D, the C_m, and the C_L/C_D at a specified R_e. The results indicate that the optimized Selig (S1223-il) airfoil outperforms the original Selig (S1223-il) airfoil across all parameters at an optimal angle of attack of 10 degrees.

TABLE 2. PROPERTIES COMPARISON OF SELIG (S1223-IL) AND OPTIMIZED SELIG (S1223-IL) AIRFOILS

Properties of Airfoil	**Selig (S1223-il) Airfoil**	**Optimized Selig (S1223-il) airfoil**
Optimum Angle of attack Alpha (α)	10^o	10^o
Coefficient of Lift (C_L)	1.988	2.121
Coefficient of drag (C_D)	0.063	0.038

Coefficient of moment (C_m)	-0.226	-0.244
Ratio of lift and drag (C_L/C_D)	31.370	55.356
Reynold Numbers	120,000	120,000

CONCLUSION

The purpose of the current study was to improve the aerodynamic performance of VAWTs through parametric optimization of the Selig (S1223-il) airfoil using QBalde software. The selection of the Selig (S1223-il) airfoil was based on its superior aerodynamic properties, particularly its lower C_L and C_L/C_D values. The research investigated the effects of reducing the airfoil's thickness and camber on several coefficients, including C_L, C_D, C_m, and C_L/C_D. The results demonstrated that, at a Reynolds number (Re) of 120,000 and an optimal angle of attack of 10 degrees, reducing the thickness and camber of the airfoil led to improvements in C_L and C_L/C_D, increasing from 1.988 to 2.121 and 31.370 to 55.356, respectively. Additionally, C_D and C_m were reduced from 0.063 to 0.038 and -0.226 to -0.244, respectively. Consequently, the C_P experienced a significant improvement, increasing from 23% to 34%. Overall, the findings of this study highlight the effectiveness of parametric optimization in enhancing the aerodynamic performance of VAWTs, specifically emphasizing the potential of the Selig (S1223-il) airfoil in this context.

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