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Numerical Study on the Effect of Camber Size on the Performance of NACA 6-Digit Airfoils

Zannatul Mim[1,], Md. Fahim Hasan Ronok[1], Abir Shahorior Emon[1,2], Mim Mashrur Ahmed[1]*

[1]Department of Mechanical Engineering, Rajshahi University of Engineering & Technology, Rajshahi-6204, Bangladesh
[2]Department of Mechanical Engineering, Imperial College of Engineering, Khulna-9000, Bangladesh

ABSTRACT
The purpose of this study is to investigate how camber affects 6-digit airfoils. Three different National Advisory Committee for Aeronautics (NACA) airfoils (63-215, 63-415 and 64-012) have been investigated with three varying camber sizes. A high-fidelity computational fluid dynamics (CFD) approach was employed to determine the optimum angle of attack for the highest value of the lift-to-drag ratio. The results indicate that gradually increasing the camber size of 6-digit airfoils leads to an enhancement in the lift-to-drag ratio, ultimately improving turbine efficiency. NACA 63-215 airfoil was tested at several angles of attack, demonstrating a gradual increase in lift coefficient until the stall angle was reached, after which the lift decreased again. The stall angle and optimal working angle of attack for NACA 63-215 were found to be 15° and 5°, respectively. Among the three airfoils, NACA 63-415 had the highest lift-to-drag ratio at the optimum 5˚ angle of attack, with a maximum camber of 2.2% at 50% chord. This study provides a clearer understanding of how camber size affects aerodynamic performance, leading to enhanced turbine efficiency.

Keywords: Aerodynamics, Computational Fluid Dynamics, Airfoil Camber, Lift Coefficient, Drag Coefficient

1. Introduction

Today’s world is fundamentally dependent on energy, from powering industries and running our homes to communication and transportation. It is estimated that 53 billion kWh of energy are consumed annually worldwide [1]. Around 84.7% of the world’s energy comes from finite, non-renewable sources such as fossil fuels (oil, gas and coal), while 10.15% of global electricity is generated from nuclear power, another non-renewable source with a limited supply [2]. Renewable energy sources only meet a small portion of the global energy demand. Around 15.75%, 2.20% and 4.78% of global electricity comes from hydropower, solar energy and wind energy, respectively [2]. On the other hand, the growth rate of solar power generation is significantly high, with an average increase of 32% growth rate in 2017 [3]. However, wind energy contributes a very small portion of the global energy supply. And wind energy has remained relatively underexplored compared to other renewable energy sources. Fig.1 shows the recent works that have been done on different renewable energy sources like solar energy, wind energy and biomass in the past three years. It is clearly noticeable from Research on wind power is relatively scarce when compared to other renewable sources, as shown in Fig.1.

The efficiency of wind turbines mainly depends on the wind speed or velocity, a slight change in the wind velocity can significantly affect wind power generation. The cube of the wind speed approaching the turbine blade determines how much power the wind turbine produces [4]. As a result, low wind speed regions are not cost-effective for wind power generation and generate very little wind power. Therefore, even at low wind speeds, the wind turbine's blades should be built to maximize power generation. A number of research has been done in past years focusing on increasing the wind turbine efficiency through modifications to the blades. Varol et al. (2001) showed how the position of the blades can enhance rotational speed by 32% and avoid negative effects on the system in their study [5]. In other study, Buckney et al. (2013) explored alternative structural configurations for wind turbine blades using topology optimization to enhance design, reduce weight and cost, improving overall structural efficiency along the blade length [4]. Jureczko et al. (2005) developed a computer program package to enable the optimization of wind turbine blades in different criteria such as vibration reduction, strength compliance, output maximization, cost minimization, structural stability [6].

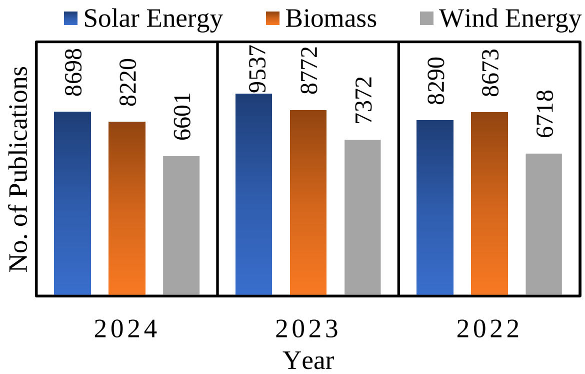


Fig.1 Recent works on various renewable energy sources (solar, biomass and wind)

Fig. 2 shows the trends of publications from 2015-2024, where authors have used ‘wind turbine blade design for maximum efficiency’ keyword whether in abstract or title.

*Corresponding Author Email Address: mim.zannat208@gmail.com

As observed only a few publications have focused on enhancing the efficiency of wind turbine blades for maximum performance in low wind speed areas. Moreover, the effect of camber position and size on the aerodynamic performance of the NACA 6-digit blades is not investigated in the literature. Hence, the purpose of this study is to investigate how varying the camber of a NACA 6-digit airfoils affects the overall aerodynamic performance of them.

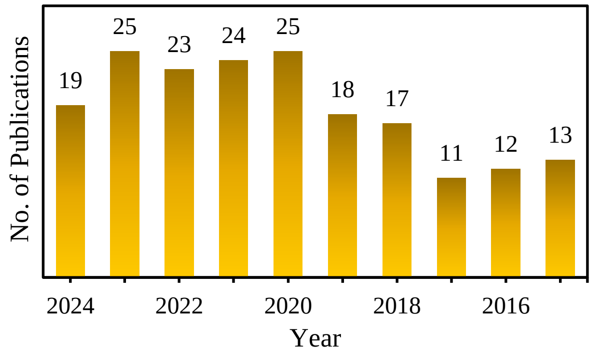
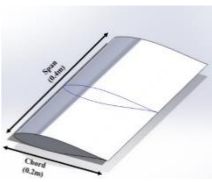


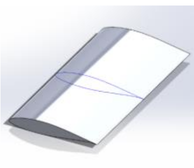
Fig.2 Recent trend in the publications on wind turbine blade design for maximum efficiency

2. Methodology

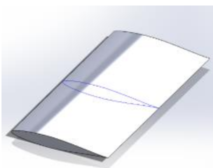
NACA six-digit airfoils are a series of airfoils developed by the National Advisory Committee for Aeronautics (NACA) with a focus on enhancing aerodynamic performance by reducing drag and maximizing laminar flow. They are more advanced than NACA four-digit airfoils due to their advanced design goals and improved control over aerodynamic properties. This paper analyzes the model using ANSYS simulations on the NACA 63-215, NACA 63-415 and NACA 64-012 turbine blades with varying camber sizes. To analyze aerodynamic performance across different camber sizes, single-blade geometries were initially modeled in SolidWorks software with a chord length (C) of 0.20m and span of 0.40m. In Fig.3, the geometry of all three blades is shown.



(a) NACA 63-215



(b) NACA 63-415



(c) NACA 64-012

Fig.3 Single-blade geometries of VAWT blade configurations considered in this study

Fig.3 illustrates the geometries of all three blades. For this study, three distinct six-digit airfoils, each with a unique camber profile, were selected. The camber sizes for NACA 64-012, NACA 63-215 and NACA 63-415 are respectively 0% of 0% chord, 1.1% of 50% chord and 2.2% of 50% chord. These variations allowed for a comparative analysis of performance by differing the camber. Fig.4 illustrates the geometry of the airfoil. The domain sizes are listed at Table 1.

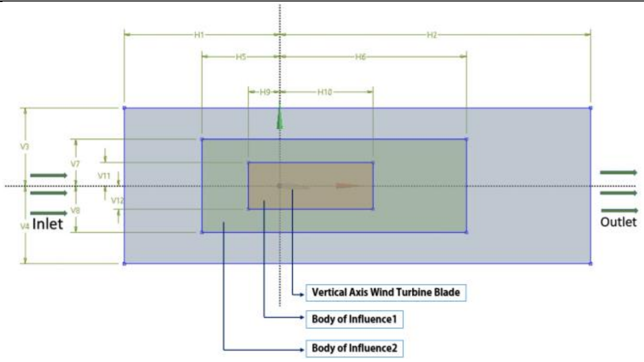
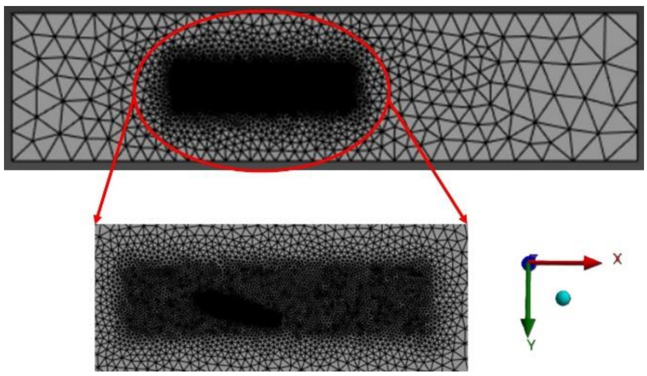


Fig.4 Computational Domain

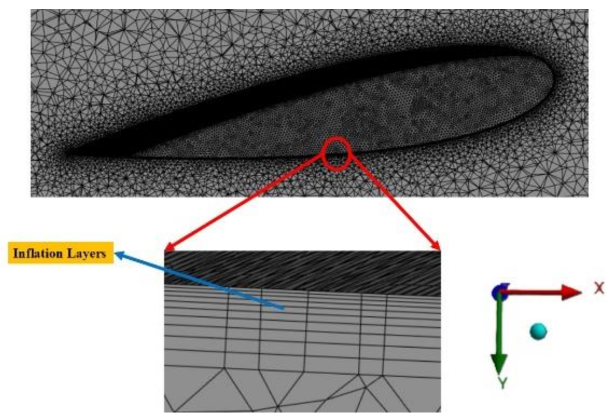
Table 1 Domain sizes

Domain 1		Domain 2		Domain 3	
H1	1m	H5	0.5m	H9	0.2m
H2	2m	H6	1.2m	H10	0.6m
V3	0.35m	V7	0.2m	V11	0.08m
V4	0.35m	V8	0.2m	V12	0.08m

The elements size of the edge sizing, face sizing, body of influence 1 and body of influence 2 were taken 7×10^{-4} m, 1×10^{-3} m, 7×10^{-3} m and 8×10^{-2} m respectively. Ten inflation layers were established with the thickness of the first layer measuring 4×10^{-5} m (see Table 2 for details). In this study a constant fluid flow speed of 7 ms^{-1} was applied. A detailed mesh picture is illustrated in Fig. 5.



(a)



(b)

Fig.5 (a) Final mesh quality and (b) Mesh with inflation layers

Table 2 Overview of the key parameters of numerical investigation

Parameter	Value Type	Parameter	Value Type
Edge sizing	7×10^{-4}m	Viscous Model	SST k-omega
Face sizing	1×10^{-3}m	Fluid density	1.205kgm^{-3}
Body sizing 1	7×10^{-3}m	Fluid viscosity	1.82e-05kgm^{-1}s^{-1}
Body sizing 2	8×10^{-2}m	Velocity	7ms^{-1}
Inflation (first layer thickness)		Reference values	Compute from inlet Area- 0.08m^2 Length- 0.2m
First layer height	4×10^{-5}m	Viscous Model	SST k-omega
Maximum layers	10	Fluid density	1.205kgm^{-3}

3. Results & discussion

After conducting a mesh dependency analysis, we confirmed that the chosen mesh size is appropriate, as a coarser mesh produced similar results (as shown in Fig.6). This ensures the accuracy and reliability of our simulation.

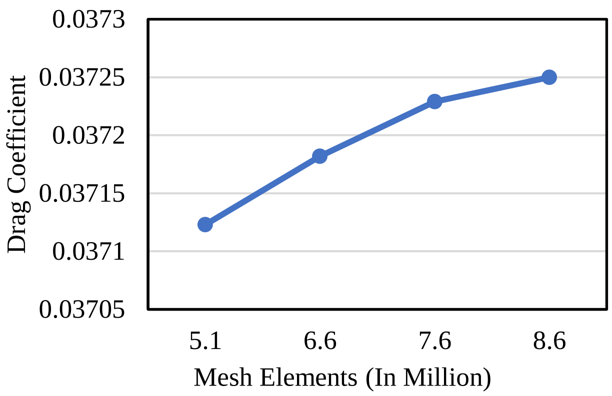
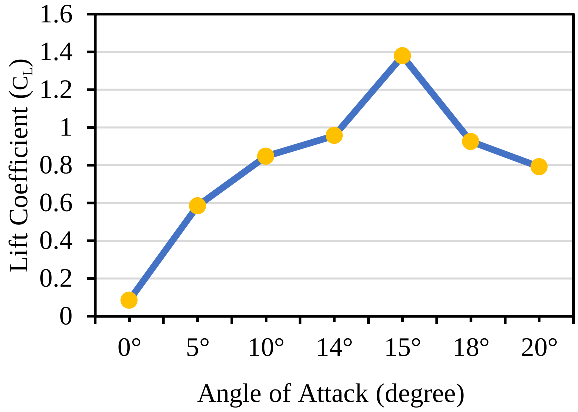
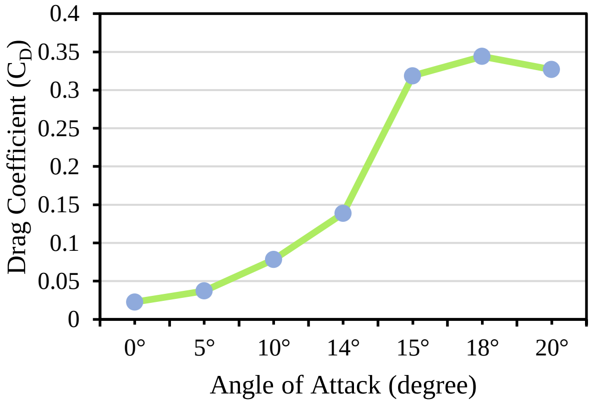


Fig.6 Mesh dependency analysis for NACA63-215 (5 degree AoA)

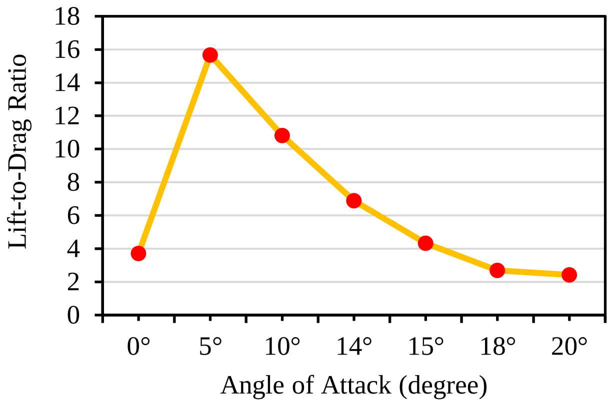
The results of the numerical analysis for the selected airfoils are displayed in Fig.7. NACA63-415 airfoil with the highest camber size significantly surpasses other selected airfoils achieving a higher lift-to-drag ratio. Simulations for the NACA63-215 airfoil was performed across seven different angles of attacks (0˚, 5˚, 10˚, 14˚, 15˚, 18˚ and 20˚) to identify the stall angle. This revealed that the stall angle for NACA63-215 was 15 degrees, where the lift coefficient reached its peak value (≈1.377). Although the drag coefficient for NACA63-215 increased gradually with the rising AoA, the lift coefficient increased steadily up to 15˚ angle of attack i.e. stall angle, after which it begins to decrease. The maximum lift-to-drag (C_L/C_D) ratio was achieved at 5˚ angle of attack for the NACA 63-215 airfoil (≈15.6706). NACA63-415 has the highest C_L/C_D (≈16.609) among the three studied airfoil for 5-degree AoA, which is 9.5% higher than the maximum C_L/C_D offered by NACA64-012 (15.1677). As VAWT is a lift-type wind turbine, the blades with high C_L/C_D generates higher power output compared to the blades with lower C_L/C_D. According to a recent study by Erkan et al. (2020), the NACA63-415 airfoil's optimal operating angle is at 6 degrees AoA [7] while this study identified it at 5 degrees AoA.



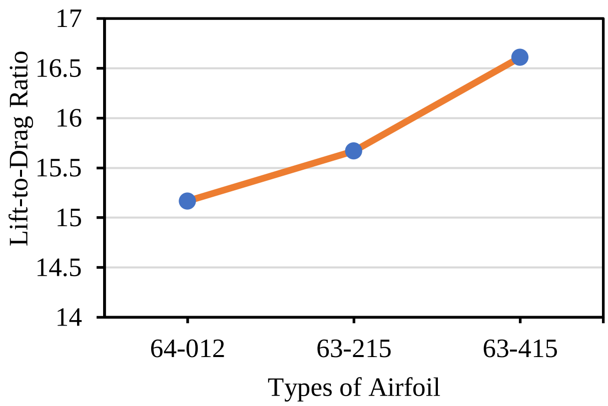
(a) Lift Coefficient vs Angle of Attack (NACA63-215)



(b) Drag Coefficient vs Angle of Attack (NACA63-215)



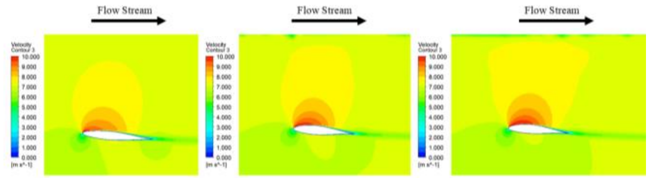
(c) Lift to Drag Ratio vs Angle of Attack (NACA63-215)



(d) Lift to Drag Ratio vs Types of Airfoils (5˚ AoA)

Fig.7 Variation of (a) lift coefficient (C_L), (b) drag coefficient (C_D) and (c) lift-to-drag ratio (L/D) with the angle of attacks of a selected airfoil (NACA63-215), (d) Lift to Drag Ratio (L/D) vs Types of Airfoils (5˚)

Fig.8 presents velocity contour plots for three distinct airfoils analyzed in this study, using the blade's midplane. In Fig.8(c), the NACA63-415 airfoil exhibits a greater velocity distribution compared to the other two airfoils. However, the NACA64-012 (Fig.8(a)) shows higher velocity on the lower surface, resulting in reduced pressure and, consequently, lower lift generation. For NACA63-415, the velocity magnitude on the lower surface is relatively low (Fig.8(c)), which indicates increased pressure on this surface and thus contributes to a higher lift force compared to other blade configurations. Therefore, the NACA63-415 airfoil demonstrates efficient velocity distribution and achieves the highest lift-to-drag ratio among the three airfoils.



(a) (b) (c)

Fig.8 Velocity contour of turbine blades at 5-degree AoA (a) NACA 64-012 (b) NACA 63-215 (b) NACA 63-415.

The pressure contour plot is shown in Fig.9, highlighting the pressure distribution across this central section. Compared to the other three blade types, the NACA63-415 blade has a larger area of negative pressure distribution along the suction surface, as seen in Fig.9(c). The blade's lift increases when there is a greater pressure differential between the upper and lower surfaces. Consequently, NACA63-415 (Fig.9(c)) produces the highest lift, while NACA64-012 (Fig.9(a)) yields the lowest lift among the blades. Thus, the NACA63-415 is the most efficient, achieving the highest lift-to-drag ratio among the three blades.

(a) (b) (c)

Fig.9 Pressure Contour of turbine blades at 5-degree AoA (a) NACA 64-012 (b) NACA 63-215 (c) NACA 63-415.

The results have been validated to ensure their accuracy and reliability. They exhibit close alignment with those reported in other sources [8], confirming the consistency of the findings.

4. Conclusion

The effects of camber on six-digit airfoils have been numerically investigated in this paper. Three different airfoils were used with varying camber sizes from NACA airfoil family. Among the three selected airfoils, the NACA63-415 features the largest camber of 2.2% at 50% chord, while the NACA63-215 has a moderate camber of 1.1% at 50% chord, and the NACA64-012 exhibits no camber (0% at 0% chord). For NACA63-215 the lift coefficient gradually increased until reaching the stall angle, after which it gradually decreased. On the other hand, the drag coefficient showed a gradual increase with the angle of attacks for NACA 63-215 airfoil. Stall angle for NACA63-215 was observed at 15˚ angle of attack. The optimum angle of attack for NACA63-215 airfoil was 5 degrees that offers the highest lift-to-drag ratio (≈15.6706). At 5 degrees AoA NACA63-415 showed the highest value of C_L/C_D (≈16.609). The NACA64-012 airfoil exhibited the lowest lift-to-drag ratio, which was 9.5% lower than that of the NACA63-415. Therefore, the lift-to-drag ratio increases with camber sizes, making NACA (63-415) the most efficient airfoil with the most camber of 2.2%. Besides, pressure contour and streamlines near the airfoil have been illustrated in this study to obtain a better overview. Hence, this study offers key insights to guide researchers and decision-makers in selecting the most efficient turbine blades for lift-type VAWT applications.

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NOMENCLATURE

NACA : National Advisory Committee for Aeronautics
VAWT : Vertical-Axis Wind Turbine