CFD Analysis of Small Scale Wind Turbine Blade Under Low Reynolds Number

Midhun Arockiyam. M
M. Tech: Machine Design
Mechanical Department
NCERC Pampady, Thrissur

Ajay Thomas
Assistant Professor
Automobile Department
NCERC Pampady, India

Dr. S. Sankar
Associate Professor
Mechanical Department
NCERC Pampady, Thrissur

***Abstract* - The main aim of this project is to increase the lift force of the wind turbine blade with different airfoil profiles under low Reynolds number. This project describes the aerodynamic performance of wind turbine blade before and after modification of airfoils to increase the coefficient of lift of the horizontal axis wind turbine blade. In this study, a one meter long wind turbine blade suitable for 1.6 KW is designed standard and modified airfoils using SOLIDWORKS software. And Computational Fluid Dynamics analysis had done by using Software version (ANSYS WORKBENCH 16.2) to evaluate the performance between them at 15 m/s wind velocity. The outcome of the analysis study revealed that there was improvement in the coefficient of lift for the wind turbine blade with modification.**

I. INTRODUCTION

This project having two correlated goals of designing and CFD analyzing of standard and modified airfoil profiles ,the procedure required for modeling of an accurate CAD model for the new blade geometry, and structural integrity verification procedure for the new blade via Computational fluid dynamics under several operating scenarios. The modified rotor blades airfoils were designed to perform at high efficiency at a much lower wind speed and incorporated a CFD verification process which will perform on the both standard and modified rotor blade design. With an increased magnitude of wind energy being captured the aerodynamic force on the rotor blades at the same time increased which necessitated a structural analysis step to be implemented, with the assistance of an adequate CFD program, to ensure the modified rotor blades will not fail under normal or extreme wind conditions. With the completion of this project the new rotor blade designed and analyzed in this report may be finalized and defined throughout this project may be used to design an entirely different aerodynamically modified rotor blade, including a CAD model and CFD structural integrity verification.

II THEORY

A. Airfoil Terminology

A number of parameters are used to describe an airfoil. The mean camber line is the center line between the upper and lower surfaces of the airfoil. The most leading and end points of the mean camber line are the leading and trailing edges. The straight line joining the leading and trailing edges is called chord line of the airfoil, and the distance between leading and trailing edge measured is chord c, of the airfoil. The maximum distance measured between the chord line and the mean camber line is called camber, which is measured perpendicular to the chord line. The thickness of airfoil is the distance between the upper and lower surfaces, also measured perpendicular to the chord line. The angle between the wind direction and the chord line is defined as angle of attack α, the geometric terms that have an effect on the aerodynamic performance of an airfoil include: the maximum thickness, leading edge radius, mean camber line, the trailing edge angle and thickness distribution of the profile.

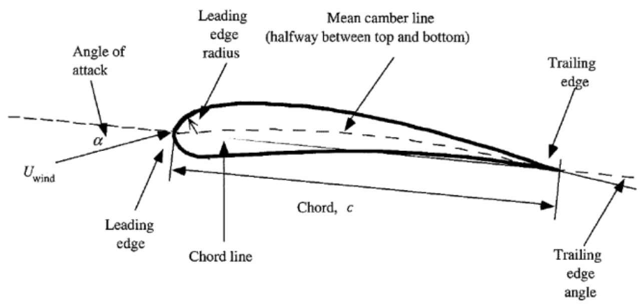

Fig 1: Airfoil terminology

B. Lift force and Drag force

Airflow over an airfoil causes a forces distribution over the airfoil surface. The flow wind velocity increases over the convex surface of airfoil and also lower average pressure on the 'suction' side as compared with the concave or 'pressure' side of the airfoil. In the moment, viscous friction between the air and surface of the airfoil slows the airflow to some extent next to the surface, the resultant of these pressure and friction forces will be resolved into two forces.

- Lift force – force acting perpendicular to direction of the airflow. The lift force is an outcome of the irregular pressure on the lower and upper airfoil surfaces.
- Drag force – force acting parallel to the direction of the airflow. The drag force is due to both viscous friction forces at the surface of the airfoil and to irregular pressure on the upper and lower airfoil surfaces.

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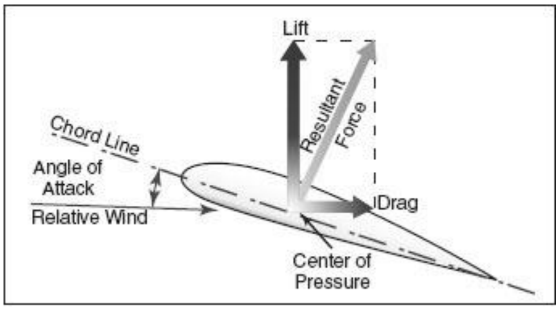

Fug 2: Lift and Drag force

C. Reynolds number

The Reynolds number can be defined generally include the fluid properties of viscosity, density, a characteristic dimension or characteristic length and plus a velocity. This dimension is a matter of convention – for example diameter and radius are equally valid to describe circles or spheres, but one is chosen by convention. For ships or aircraft, the width or length can be used. For flow in a sphere moving in a fluid the internal diameter or a pipe is generally used today. Other shapes such as non-spherical or rectangular pipes objects have the same diameter defined. For fluids having variable density such as compressible fluids or gases of variable viscosity such as non-Newtonian fluids, special rules apply. The Reynolds number is defined as,

Re = inertial forces/viscous force

$= \rho v L/\mu$

$= (1.225 x 15 x 0.175)/(1.81 x 10^{-5})$

Re =182009.66 < 200000, (low Reynolds number)

where:

- v is the maximum velocity fluid (SI units: m/s)
- L is a characteristic linear dimension, (m)
- μ is the dynamic viscosity of the fluid
- ρ is the density of the fluid (kg/m^3).

III METHODOLOGY AND PROCEDURES

A. Nomenclature

A	Swept area of rotor
α	Angle of attack
CD	Drag coefficient
CL	Lift coefficient
D	Drag force
L	Lift force
N	RPM of the rotor
P	Power developed by rotor
r	Radius of rotor
R	Resultant force acting on the airfoil
V	Free stream velocity
VT	Tangential velocity
VR	Resultant velocity
ω	Angular velocity

B. Rotor blade profile selection and design:

Different airfoil types were designed to suit a multitude of unique wind turbine propeller, blade, and aircraft wing designs. The general procedure to selecting airfoils for a wind turbine rotor types to afford for two key goals aerodynamic and structural performance. The first goal is to be as aerodynamically efficient at the outer surface blade in order to get the required lift force with as low wind speed The second goal is to have a structurally analysis of blade, which required the use of a airfoil that having more thickness to endure the large bending moment caused by the aerodynamic and intrinsic gravity loads exerted on the blade during the wind turbines operation at the root of the blade. In this project the selected airfoil profiles are NACA 2414, NACA 2421 and NACA 4421 from www.airfoiltools.com.

Fig 3: Airfoil NACA 2414 Chord = 175mm, Thickness = 100%, Origin = 0%

Fig 4 :Airfoil NACA 2421, Chord = 175mm, Thickness = 100%, Origin = 0%

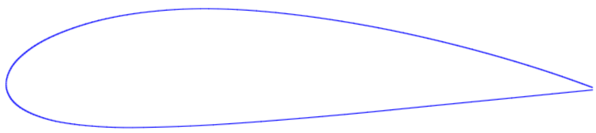

Fig 5: Airfoil NACA 4421, Chord = 175mm, Thickness = 100%, Origin = 0%

C. Cad Modeling

To designing a new rotor blade is modeling a perfect 3D CAD model of the blade's overall geometry designed as well as to be export into an importable file for the CFD process. Solidworks was used to CAD modeling process, the importance CAD modeling in Solidworks that ability to make changes easily and quickly throughout the drafting process. Solidworks models can be easily modified if there is any changes to the design are required when the initial CAD model is finished.

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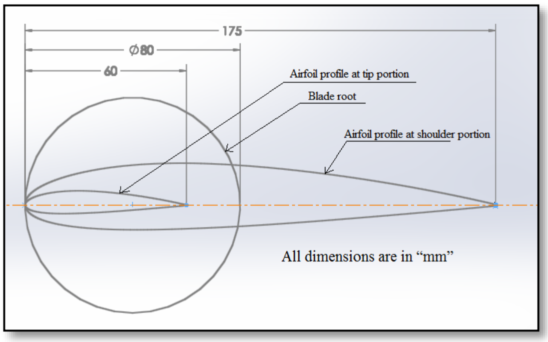


Fig 6: Airfoil profiles

The process of modeling a CAD model for the standard and modified blade geometry was plotted previously from www.airfoiltools.com and import airfoil curves, sketching the required blade components on each individual blade section sketch, leading, trailing edge, the spar, and the hub connection, lofting each blade component separately, and joining all the blade components into one overall single rotor blade. Due to the geometrical difficulty of the rotor blade its three dimensional features are not able to be generated all at once. It was attempting to use a single loft to generate the overall blade shape failed due to the extensive curves of the outer skins which quickly converge at the trailing edge. A single loft also formed invalid and inexact geometry when imported into ANSYS 16.2 which could not analytically model the long, extensive curves and sharp edges properly. The trailing edge where the low and high pressure sides of the blade are joined together without the aid of an internal flange such used at the leading edge.

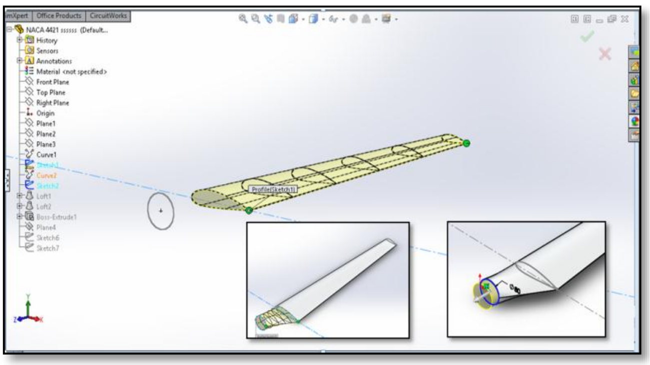


Fig 7: lofting of airfoil profiles

D. CFD Analysis

CFD is a very powerful tool due to its ability to accurately model almost any structure as a large number of elements that are all analyzed and interrelated which provides a clear picture of all the stresses, strains, and other important terms throughout the model. As the number of elements, with their respective nodes, increases the accuracy of the model. Therefore, it is necessary to use enough elements so that accurate results are produced without generating an overly fine mesh which does not much increase the accuracy of the CFD results and is with reason computationally expensive.

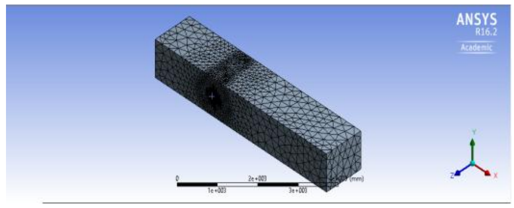


Fig 8: Meshing of rectangular air passage

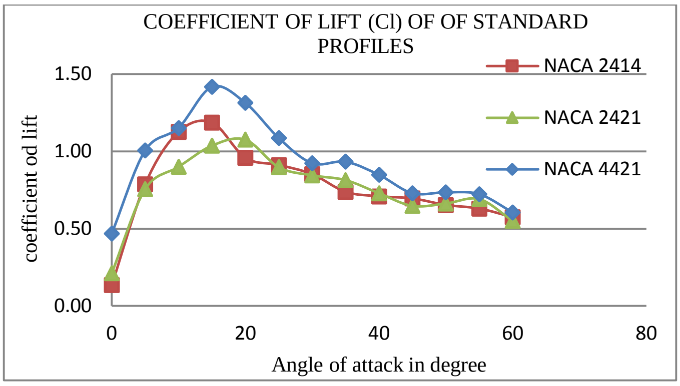
CFD consists of utilizing small elements that consist of a certain number of interconnected nodes which form together in a mesh comprising the total model. This mesh can either be coarse or fine depending on the section of the model being analyzed, with a finer mesh and more perfectly model the high stress areas of the blade or the flow and magnitude of stresses in complex geometrical areas, while a more coarse mesh is used to model areas of the blade that do not show signs of deflection or high stress in order to make the model less computationally expensive. However, care must be taken to not allow the less accurate coarse mesh strain and stress calculations hinder the accuracy of the finer mesh areas. In fluent physics Setup set gravitational acceleration -9.81 m/s2 in y axis. Models and Materials, in viscous model select k-epsilon (2 eqn). And aluminum was selected as blade material. Boundary Conditions Inlet, outlet and no shear wall are constrained. Reference values parameters like compute from inlet, density of air (1.225 kg/m^3), velocity of air (15m/s) and the length of air passage rectangular box 6m were given for CFD analysis.

IV RESULT AND DISCUSSION

The first part of the study involved studying the effects that varying attack angles. As estimated, increasing the attack angle of the airfoil created larger regions of parting causing what is known as the stall effect. At average 15 degree angle of attack the coefficient of lift was at maximum and the coefficient of drag minimum. Increasing the wind speed will caused the separation regions to be more exaggerated with a greater amount of turbulence flow of wind. In this project the wind velocity was kept at constant 15m/s. the value Coefficient of drag of standard modified airfoil profiles NACA 2414, NACA 2421 and NACA 4421 are tabulated below.

TABLE NO 1: COEFFICIENT OF LIFT OF STANDARD PROFILE

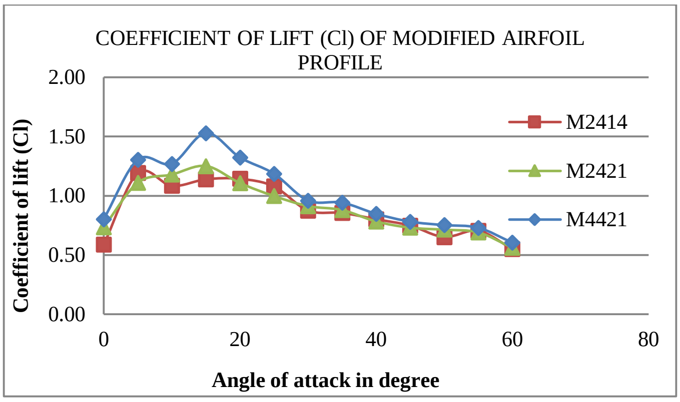
COEFFICIENT OF LIFT OF STANDARD AIRFOIL PROFILES			
Angle of attack in degree	*NACA 2414*	*NACA 2421*	*NACA 4421*
0	0.134929	0.211372	0.467518
5	0.786639	0.755171	1.004780
10	1.125100	0.899854	1.151280
15	1.185710	1.036980	1.417030
20	0.957608	1.076070	1.313690
25	0.911606	0.897540	1.085780
30	0.851919	0.845151	0.922939
35	0.737791	0.814168	0.932476
40	0.708767	0.729504	0.847623



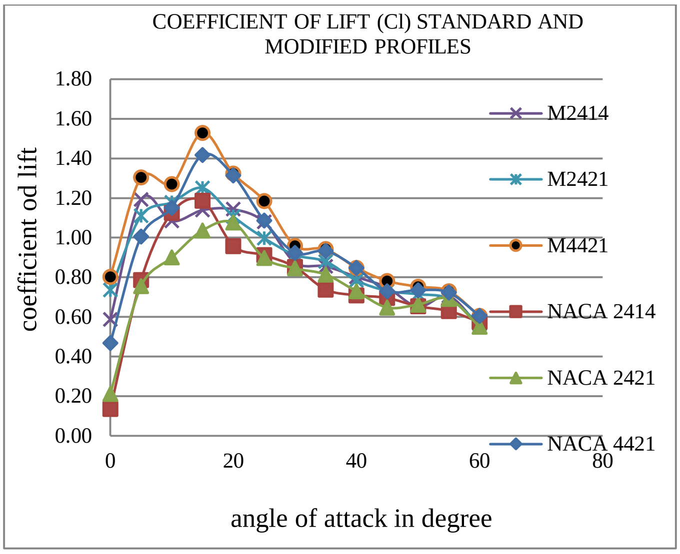
GRAPH NO 1: COEFFICIENT OF LIFT OF STANDARD PROFILE

TABLE NO 2: COEFFICIENT OF LIFT OF MODIFIED PROFILE

COEFFICIENT OF LIFT OF MODIFIED AIRFOIL			
Angle Of Attack (Degree)	M2414	M2421	M4421
5	1.192230	1.109770	1.303630
10	1.084330	1.178600	1.269560
15	1.139660	1.250750	1.528530
20	1.143740	1.107160	1.322750
25	1.079560	0.997981	1.185340
30	0.875959	0.913081	0.959093
35	0.855660	0.880017	0.941911
40	0.802516	0.783822	0.847646



GRAPH 2: COEFFICIENT OF LIFT OF MODIFIED PROFILE



GRAPH 3: COEFFICIENT OF LIFT OF STANDARD AND MODIFIED PROFILE

Lift will opposes directly the downward force of weight. It is produced by the dynamic effect of the air acting on the blade, and acts perpendicular to the air velocity through the blade center of pressure. This is the force that helps to rotate the wind turbine. Lift has both magnitude and direction. Being a force, this is a vector quantity. The pressure act in center of the point where the resultant force crosses the chord line for every angle of attack. Lift acts directly through the center of pressure. Direction of lift is always perpendicular to the wind direction where drag acts longitudinal to the wind direction. If there is no lift, there is no rotation of wind turbine.

Pressure Distributions of standard and modified M4421 airfoil profiles at 0 and 15 Degree Angle Of Attack:

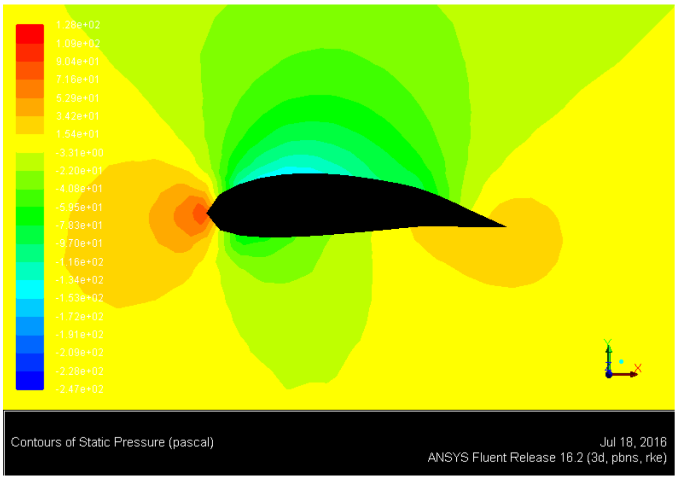


Fig 9: M4421 at 0 Degree Angle Of Attack

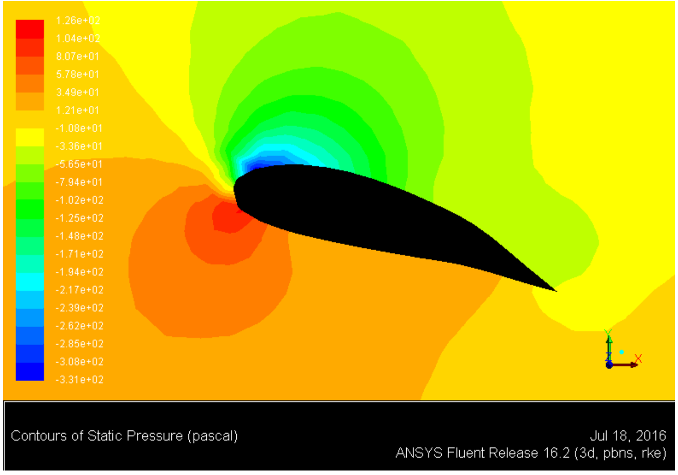


Fig 10: M4421 at 15 Degree Angle of Attack

Velocity contours of standard and modified M4421 airfoil profiles At 0 and 15 Degree Angle Of Attack:

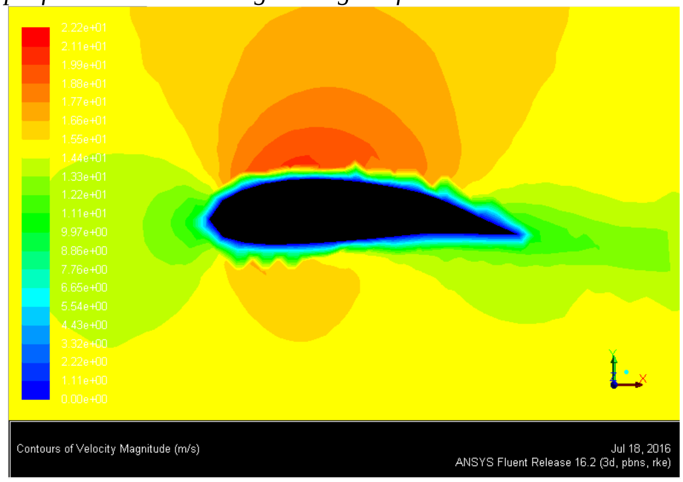


Fig 11: M4421 at 0 Degree Angle Of Attack

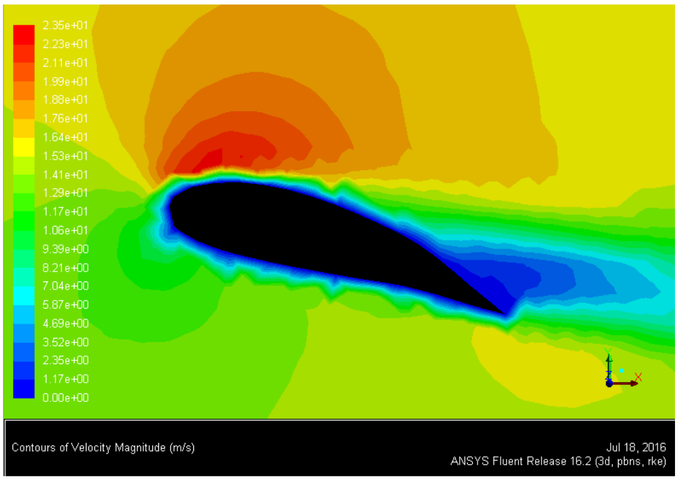


Fig 12: M4421 at 15 Degree Angle of Attack

V: CONCLUSION

This project involved calculating the blade length required for the turbine to operate at peak efficiency with an 15 meter per second incoming wind speed, at approximately sea level, in order to produce the average 1.6 kilowatts of generator power output. This led to the calculation of a total required blade length of one meter. The NACA 2414, NACA 2421 and NACA 4421 airfoil types are chosen for this project, respectively, since they are designed to operate at their peak efficiency when incorporated with a rotor radius and peak generator output. In this way the rotor blades are designed to deliver the appropriate amount of lift force required to operate at high efficiency during low wind speed conditions. Coefficient of lift was improved by modification these airfoil profiles. The CFD analysis software ANSYS 16.2 FLUENT was utilized to get better performance by analyzing of standard and modified airfoil profiles.

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