CITY COLLEGE

CITY UNIVERSITY OF NEW YORK

Final Project

ME 572: Aerodynamic Design

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Prof. Amir Elzawawy

CFD Analysis on Aerodynamic Design Optimization of Wind Turbine Rotor Blades

Submitted By:

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Nomenclature

$X = x - coordinate\ of\ position\ along\ the\ Airfoil$

$Y = y - coordinate\ of\ position\ along\ the\ Airfoil$

$V_\infty = Unifrom\ Upstream\ velocity\ in\ x - direction$

$\rho = Density$

$p = Pressure$

$U = x - coordinate\ of\ velocity$

$V = y - coordinate\ of\ velocity$

$T = Temperature$

$C_d = Drag\ Coefficient$

$C_L = Lift\ Coefficient$

$\vartheta = Dynamics\ viscosity$

$\alpha = Angel\ of\ Attack$

$C_p = Pressure\ Coefficient$

$c = Chord\ Length$

$\alpha = Angel\ of\ Attack$

Abstract

Wind energy is one of the most viable sources of renewable energy with lot of prospect future to redeeming energy demand. With current technology, the low cost of wind energy is competitive with more conventional sources of energy such as coal and other non renewable resources. Most blades available for commercial grade wind turbines incorporate a straight span-wise profile and airfoil shaped cross sections. This project is about the study of a wind turbine blade design made of multiple cross sections airfoil. These cross sections airfoils were first simulated in Qblade software to evaluate the stall angle and then the blades was modeled in solidworks and later its aerodynamics properties were evaluated using CFD software. This paper explores the possibility of increasing the efficiency of the blades by incorporating the winglets at the tip and tubercles at the leading edge. The blade for the project simulated for 7 m/s free stream air speed and 16 degree of angle of attack. Performance was investigated using the computational fluid dynamics (CFD).

Background

The first electricity generating wind turbine, was a battery charging machine installed in July 1887 by Scottish academic James Blyth to light his holiday home in Marykirk, Scotland. Some month's later American inventor Charles F Brush built the first automatically operated wind turbine for electricity production in Cleveland, Ohio. Although Blyth's turbine was considered uneconomical in the United Kingdom electricity generation by wind turbines was more cost effective in countries with widely scattered populations. In Denmark by 1900, there were about 2500 windmills for mechanical loads such as pumps and mills, producing an estimated combined peak power of about 30 MW. The largest machines were on 24-metre (79 ft) towers with four-bladed 23-metre (75 ft) diameter rotors. By 1908 there were 72 wind-driven electric generators operating in the US from 5 kW to 25 kW. Around the time of World War I, American windmill makers were producing 100,000 farm windmills each year, mostly for water-pumping.

Introduction

A wind turbine is a device that is able to convert the kinetic energy forced upon it to mechanical energy. It does so by means of aerodynamic blades. These blades which may be attached and oriented in varying positions, distributes the incident wind unevenly, creating a pressure distribution. The net pressure distribution creates net forces in accordance with the conservation principles causing rotation about an axis. This mechanical work may then be converted into other energy forms. This project mimics closely the loads exerted on the blades of a horizontally oriented axis turbine due to wind velocity in a specific area. From these loads, the pressure distribution and net resultant forces can be found on the blades as well as the mechanical work produced. In general the rotor is not of the optimum In general, a rotor is not of the optimum shape because of fabrication difficulties. Furthermore, when an 'optimum' blade is run at a different tip speed ratio than the one for which it is designed, it is no longer 'optimum'. Thus, blade shapes must be designed for easy fabrication and for overall performance over the range of wind and rotor speeds that they will encounter. In considering non-optimum blades, one generally uses an iterative approach.

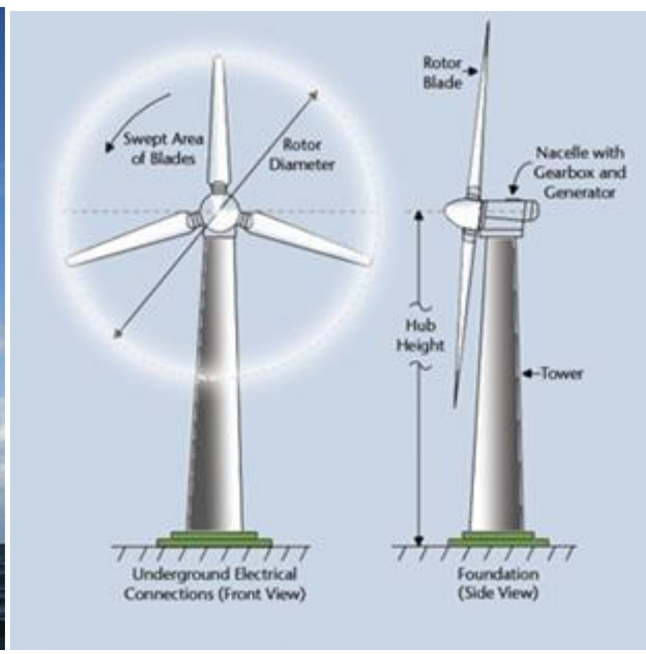


Figure 1a: Showing the horizontal axis wind turbine

Figure 1b: showing some features of the mill

The angle of attack is the angle at which an airfoil passes through the air. This angle is measured between the chord of the airfoil and the relative wind, as shown in figure 1.0. The chord is an imaginary line from the leading edge to the trailing edge of an airfoil. Increasing the angle of attack deflects the airstream and causes an upward pressure on the underside of the airfoil. This in turn increases the speed of the airflow over the topside of the airfoil. As air-flow-speed increases, pressure on the foil's top side is further reduced which furnish the lift upward in this case.

For Instance NACA 2415

2 - The maximum camber of the mean line is 0.02c. (First digit)

4 - The position of the maximum camber is at 0.4c. (Second digit)

15 - The maximum thickness is 0.15c. (Third and fourth digits)

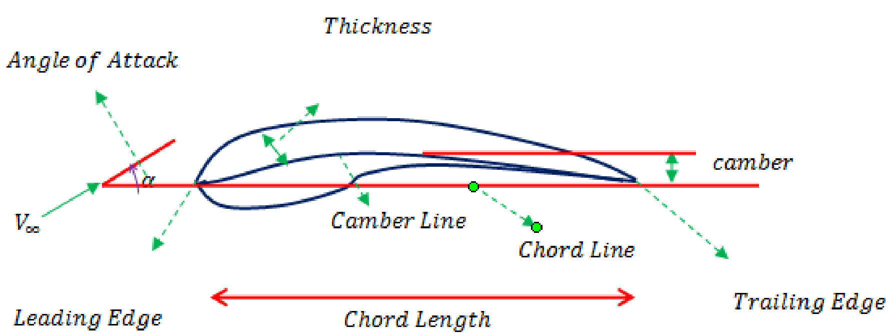


Figure 2: Showing the Components of Airfoil

An airfoil is a section of a wing, as depicted in figure 1.0 as show above and the shape of the airfoil is determined by the following geometric parameters.

- The *chord line*, defined as the straight line connecting the leading edge to the trailing edge.
- The *chord*, defined as the distance from the leading edge to the trailing edge.
- The *camber line*, defined as the locus of points located halfway between the upper and lower surface of the airfoil.
- The *camber*, defined as the maximum distance of the camber line from the chord line. If the camber is zero, the airfoil is symmetric.
- The angle subtended between the incoming wind and the chord line, α, is defined as the *angle of attack*.

Design Procedures

Step 1:

Table 1.0 Model Selection

Model	Blade length (R)	Hub Height (h)	Total Height (H)	Area Swept by Blades (A)	Angular velocity of wind turbine rotor (Ω)	Characteristic Velocity (U)
GE 1.5sle	38.5 m	80 m	118.5 m	4,657 m^2	15 rpm	7 m/s

Step 2:

Using Free Software called Qblade the Airfoil were generated and chosen with respect to the chord thickness so that the root has higher inertial mass so cope the higher stress generated by static mass and rotational forces produce during high wind gust.

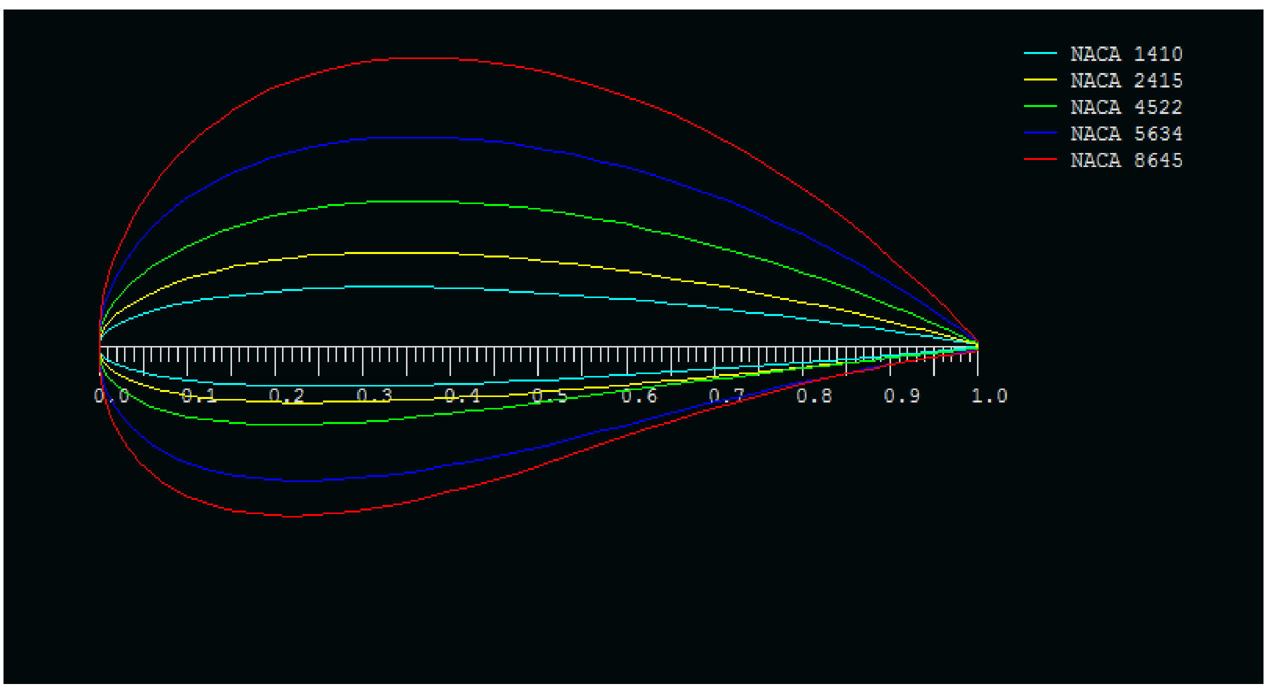


Figure 3: Showing the Components of Airfoil

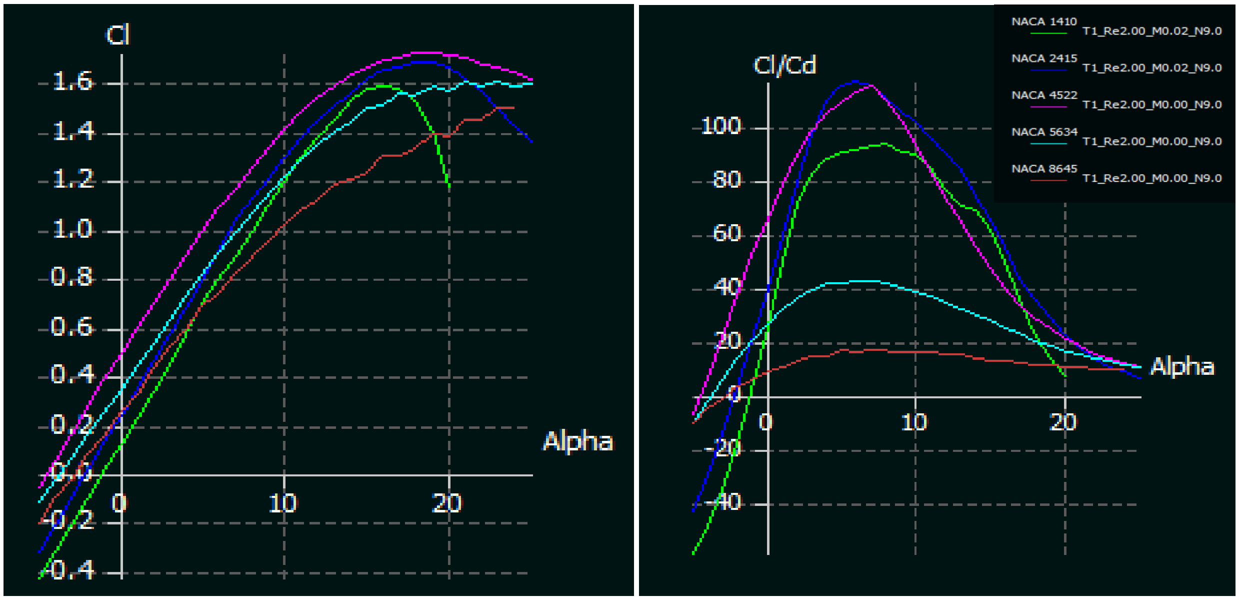


Figure 4: Numerical evaluated Lift/Drag Curve generated from Qblade Program.

Step 3: Ref 3.

Mathematics modeling of Ideal Turbine Rotor without Wake rotation

$$Number\ of\ blade\ (B) = 3$$

$$Tip\ wind\ speed\ (\lambda) = omega * \frac{R}{U}$$

$$local\ speed\ ratio\ (\lambda_r) = \lambda * \frac{r}{R}$$

$$the\ angle\ of\ the\ relative\ wind\ and\ the\ chord\ of\ the\ blade\ for\ each\ section\ of\ the\ ideal\ rotor$$

$$(\varphi) = \tan^{-1}\left(\frac{2}{3\lambda_r}\right)$$

$$= \phi_p + angle\ of\ attack$$

$$Section\ Pitch\ angle\ (\phi_p) = Angle\ between\ chord\ and\ the\ plane\ of\ Rotation$$

$$the\ blade\ twist\ angle\ (\ \phi_T) = \phi_p - \phi_{p_0}$$

- Chord Length and twist angle was determined Using Appendix (2).
- Each section airfoil with variable chord length given by the formula was found using Appendix (1).

Table 2.0 Airfoil Section and Radial Location:

Section	r	Chord Length	Blade Twist Angle	Section
1	0	0	0	Circle
2	3.2	3.9793	38.4612	NACA8645
3	6.5	3.9793	20.1507	
4	9.5	2.4598	12.9533	NACA 5634
5	13	1.8361	8.4602	
6	16	1.5045	6.1064	
7	19	1.2732	4.4744	
8	23	0.9433	2.9476	NACA 4522
9	26	0.8360	2.1061	
10	29	0.7686	1.4367	NACA 2415
11	32	0.6972	0.8916	
12	35	0.6662	0.4392	NACA 1410
13	38.5	0.6060	0	

Step 4:

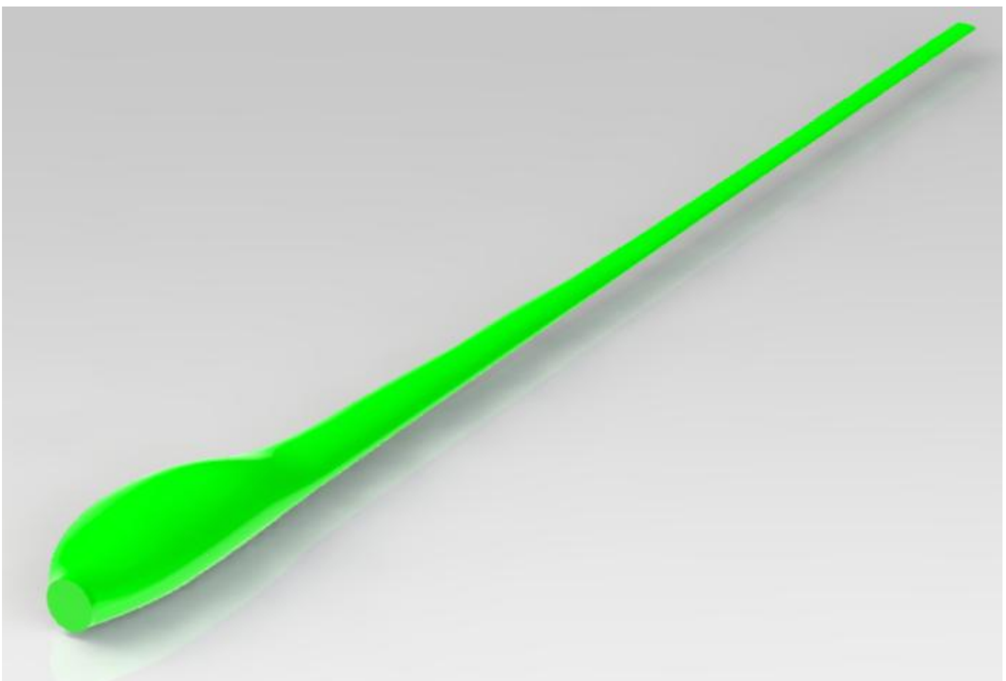


Figure 5.0 Solid Modeling in Solidworks

Mesh Generation

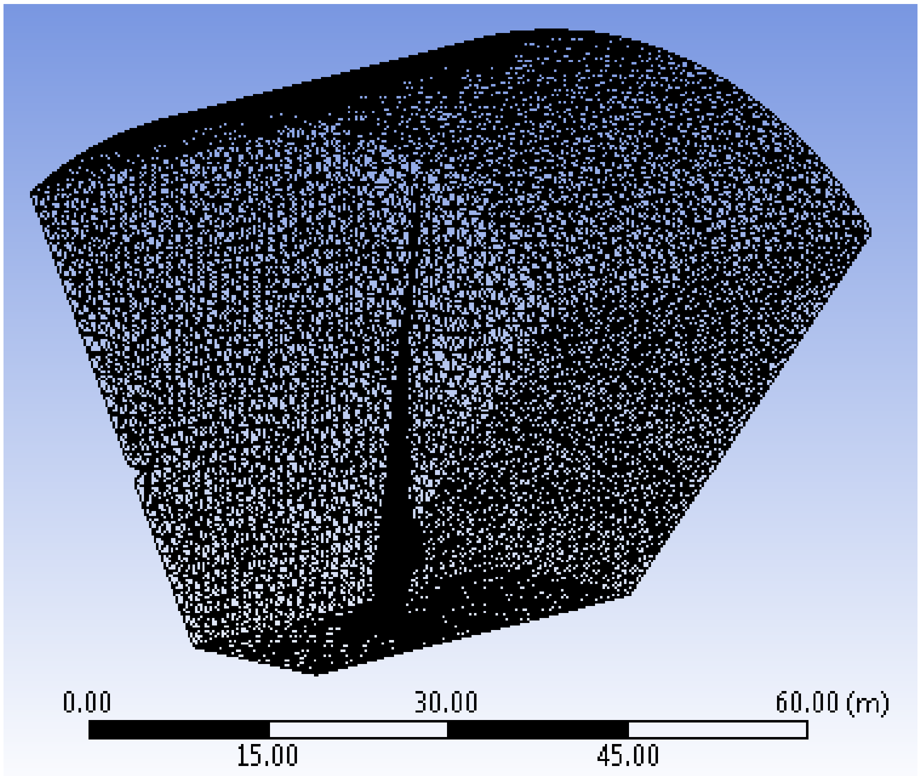


Figure 6.0 Tetrahedral Elements Mesh for Flow Domain

Table 3.0 Mesh Information for NACA2415

Domain	Nodes	Elements
Blade Design 1	396589	284389

Results

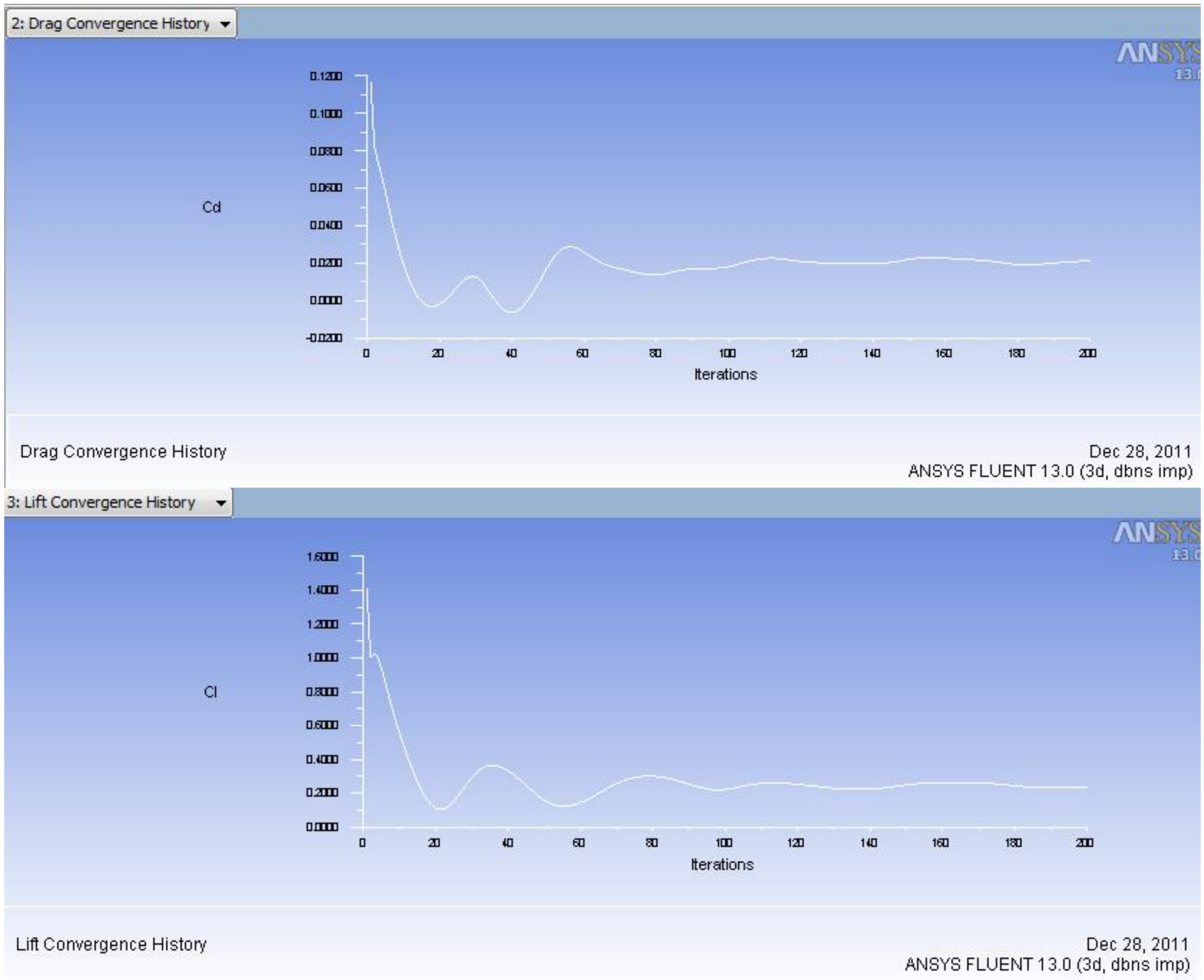


Figure 4.0 Convergence Graph

The graph above shows how the iterative value of lift and drag coefficient is fluctuating over time or number of iteration and final comes to steady value near the stop to values of 0.2 and 0.03 respectively giving $\frac{C_l}{C_D} = 6$,.which is very low value compare to 2d airfoil profile assumed in the beginning given by Qblade software. Over the references area and location of pressure difference matters the most to produce the rotational forces. And also in three dimensional simulation references area dictates the lift and drag coefficients.

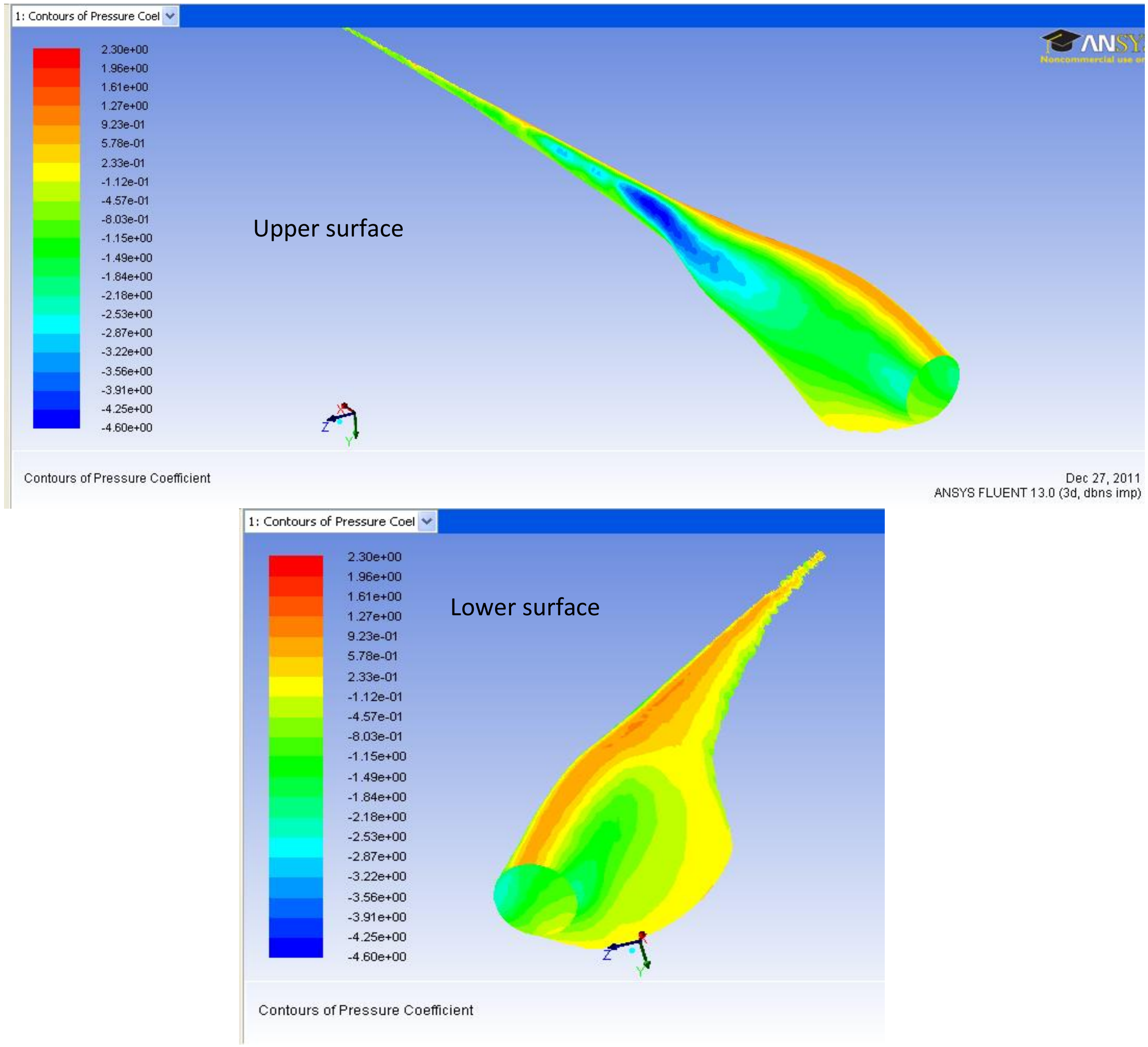
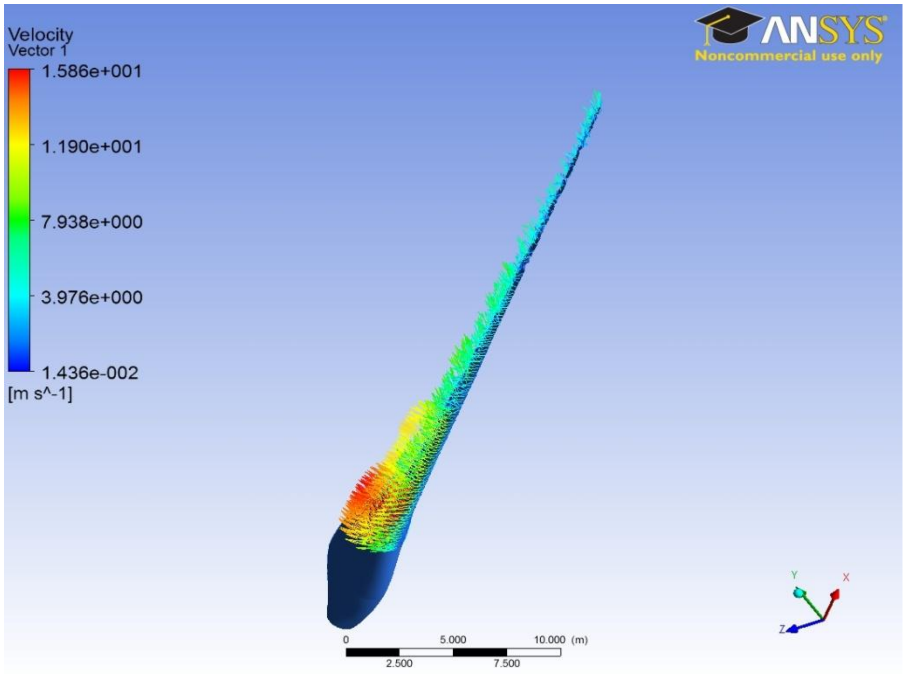
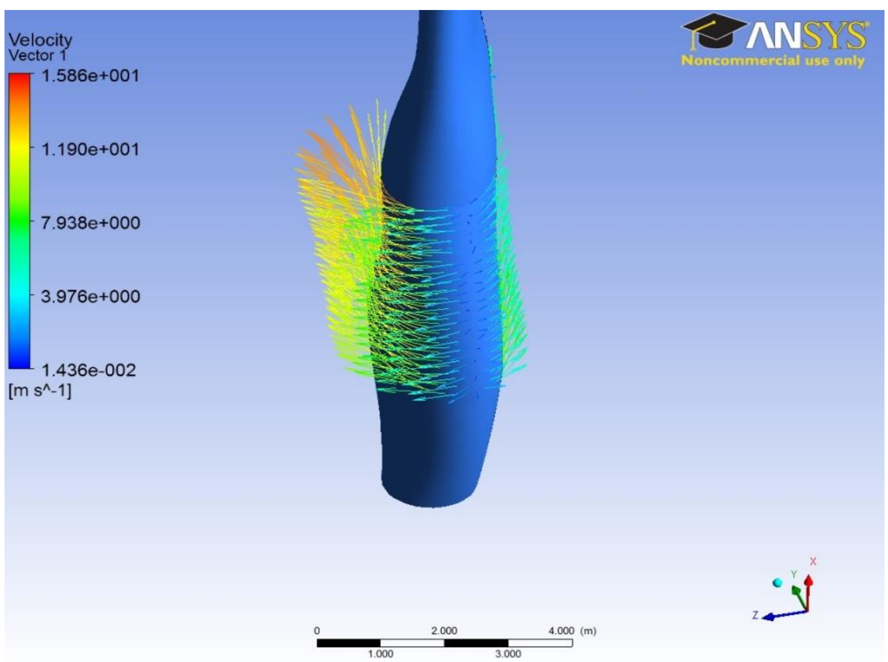


Figure 5.0 Stream Line around the airfoil at 5 degree angle of attack

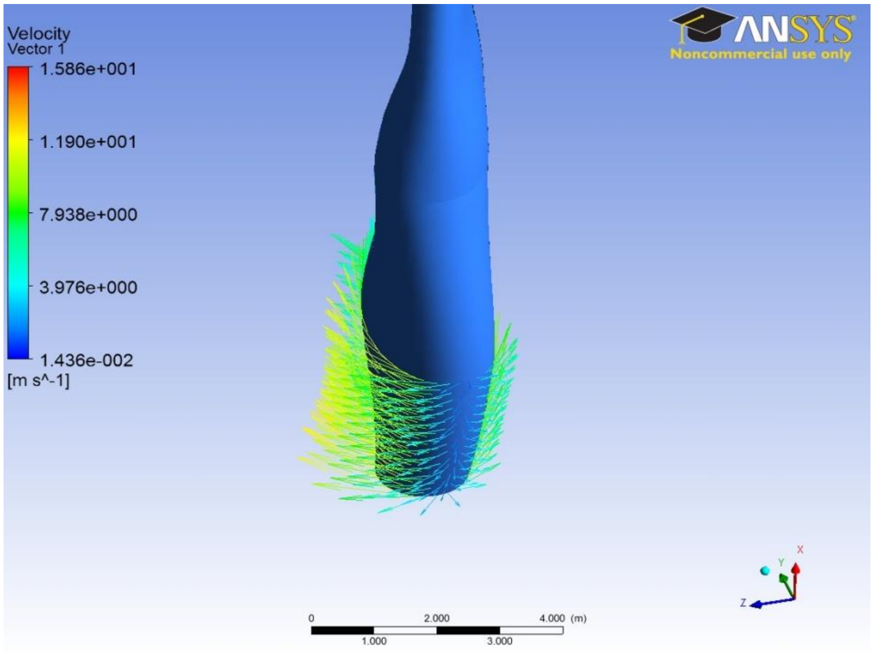
In the Figure above, we can see the plot the pressure coefficient plot around the blade. As we can see the pressure distribution over the airfoil is not symmetric with valid the theoretical prediction the asymmetric geometry of the air body doesn't produce symmetrical distributed pressure over and below the surface and hence the net force act at different location creating the pitching moment. This moment leads to the rotatorary motion of the when subjected at 16 degree of angle of attack for the simulation. The corresponding plot represents the high pressure under the surface than that of upper surface hence the hence creates that pitching moment.


Velocity
Vector 1
1.586e+001
1.190e+001
7.938e+000
3.976e+000
1.436e-002
[m s^-1]
ANSYS
Noncommercial use only
0
5.000
10.000 (m)
2.500
7.500

(a)


Velocity
Vector 1
1.586e+001
1.190e+001
7.938e+000
3.976e+000
1.436e-002
[m s^-1]
ANSYS
Noncommercial use only
0
2.000
4.000 (m)
1.000
3.000

(b)



(c)

Figure 6.0 Absolute Magnitude of Velocity (a) Top (b) mid (c) Bottom

In the Figure above, the velocity plot of the flow over the blade three sections of the blade top, middle and bottom. In figure (c) we can see that the bottom the change in the velocity is not higher relative to the free stream velocity hence the not much higher pressure coefficient. However, as per design we are expecting the change in the velocity to be higher in middle and top section so that I create higher pressure difference and create the pitching moment as desired. This change is velocity is due to change in momentum due to flow separation and compressibility.

Conclusions

The blade design process was conducted and optimized using Qblade software and further aerodynamics analysis were conducted suing CFD software Ansys Fluent. The target was to optimized blade design that will be used to compare the improvement of a system with winglets and tubercles at the leading edge over one without them. Unlike an airplane wing design which usually have one airfoil design through all the length of the wing, However in the case out wind turbines, five different airfoil profiles were used in the same blade varying from the root to the tip of the wind. Also, another important difference can be found in the twist angle of a wind turbine blade. The blade is twisted in a special and optimized manner through the length of the blade, this do not happens on an airplane wing. For this study, several software packages were used independently to create and obtain an optimal blade design. The specific packages used include QBLADE and SolidWorks 2011.

The CFD analysis of blade was very time consuming and complicated process with less understanding of methods and techniques to refined mesh to obtain converging results and to produce fastest and more reliable designs.

At the end disappoint was faced when the design was not successfully meshed in Ansys workbench for optimized as shown in the appendix 3. Further work can be done to study the aerodynamics behavior of optimized blade.

Reference

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- http://wind.nrel.gov/airfoils/Documents/S816,S817,S818_Design.pdf
- http://www.kansasflyer.org/index.asp?nav=Avi&sec=Alti&tab=Theory&pg=2

Appendix 1

```
clear all
close all
clc


m=input('Enter the first of 4 digits of NACA airfoil: ');
p=input('Enter the second of 4 digits of NACA airfoil: ');
t=input('Enter the last two digits of 4 digits of NACA airfoil: ');
c=input('Enter the chord length: ');
n=input('Enter the number the iteration: ');

m=m/100;
p=p/10;
t=t/100;
i=1;
y_c(1,i)=0;


for x=0:c/n:c
    y_t(1,i)=t*c/0.2*(0.2969*sqrt(x/c)-0.1260*(x/c)-
0.3516*(x/c)^2+0.2843*(x/c)^3-0.1015*(x/c)^4);

    if (x>0 || x<=p*c)
        y_c(1,i+1)=(m*x/p^2)*(2*p-x./c);
    elseif (x>pc || x<=c)
        y_c(1,i)=((m*(c-x))/(1-p)^2)*(1+x/c-2*p);
    end
    dyc=(y_c(1,i+1)-y_c(1,i));
    dx=(c/n);
    theta(1,i)=atan(dyc/dx);
    x_u(1,i)=x-y_t(1,i)*sin(theta(1,i));
    x_l_c(1,i)=x+y_t(1,i)*sin(theta(1,i));
    y_u(1,i)=y_c(1,i)+y_t(1,i)*cos(theta(1,i));
    y_l_c(1,i)=y_c(1,i)-y_t(1,i)*cos(theta(1,i));
    z(1,i)=0;
    i=i+1;
  end

plot(x_u,y_u)
hold on
plot(x_l_c,y_l_c)
hold off
axis equal

for a=1:1:n+1
    x_l(1,a)= x_l_c(1,n+2-a);
    y_l(1,a)= y_l_c(1,n+2-a);
end
A = [x_u ;y_u; z];
B = [x_l; y_l ;z];
C=[A B];
C=C';
save airfoil.txt C -ASCII -tabs
```

```
save foo2.dat C -ascii
```

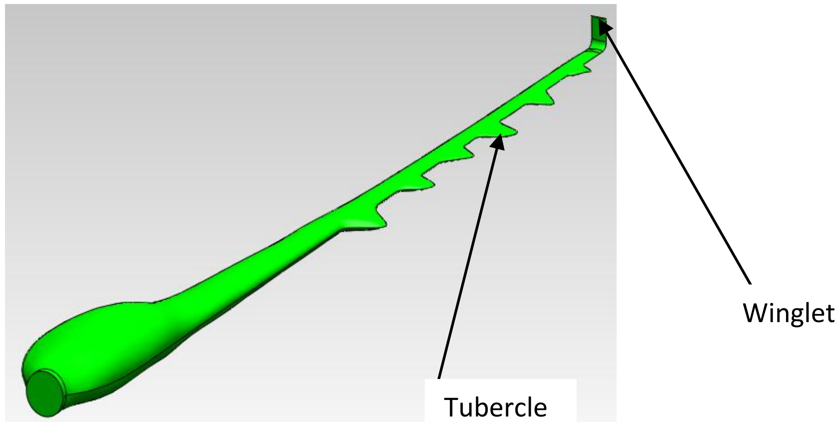
Appendix 2

```
% MODEL GE 1.4 sle
clear all
clc

angle_of_attack = 16;
lift_coff = [1.3 1.3 1.51 1.51 1.51 1.51 1.69 1.69 1.65 1.65 1.58 1.58];
lift_coff=lift_coff';
No_blade=3;                       % number of blade
blade_radius=38.5;                % Overall length of the Blade (m)
hub_height=80;                    % Hub height(m)
total_height=118.5;               % Total Height of the Turbine (m)
area_swept=pi*blade_radius^2;     % Area Swept by the rotor blade (m^2)
angular_velocity=15;              % Rotational Speed of the MAin shaft (rpm)
angular_velocity_rad_s=angular_velocity*2*pi/60; % Rotational Speed of the
MAin shaft (rad/s)
velocity_upstream=7;              % Free upstream velocity of the upstream
velocity (m/s)

tip_wind_speed=angular_velocity_rad_s*blade_radius/velocity_upstream;
r=[3.2 6.5 9.5 13 16 19 23 26 29 32 35 38.5];
r=r';
local_speed_ratio=(tip_wind_speed.*r)./blade_radius;
relative_wind_angle=atan(2./(3.*local_speed_ratio));
relative_wind_angle_deg=relative_wind_angle*180/pi;
section_pitch_angle=relative_wind_angle_deg-angle_of_attack;
section_pitch_at_tip=section_pitch_angle(length(section_pitch_angle),1);
blade_twist_angle=section_pitch_angle-section_pitch_at_tip;
chord_length=(8*pi.*r.*sin(relative_wind_angle))./(3*No_blade.*lift_coff.*loc
al_speed_ratio);
chord_length(1,1)=chord_length(2,1);
a= [ r chord_length blade_twist_angle];
disp('        ')
disp('        r     Chord     Blade Twist')
disp('       (m)   Length(m)   Angle (deg)')
disp(' --------------------------------')
disp(a)
```

Appendix 3


Winglet
Tubercle