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Analysis of Horizontal Axis Wind Turbine Using Blade Element Momentum Theory

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ABSTRACT

Wind energy has been most viable source of renewable energy. A wind turbine is a device which extracts kinetic energy from the wind and converts it into mechanical energy later converts into electrical energy using generators. There are several methods to design the rotor blade of a wind turbine. The most popular amongst them are Blade Element Momentum Theory (BEMT), Vortex Lattice (VT) method and Reynolds-Averaged Navier-Stokes (RANS) method. The current project work is focused on Blade Element Momentum Theory (BEMT) in detail. Blade Element Momentum Theory is based on equating the aerodynamic forces with the momentum forces on a rotating annular stream tube passing through the wind turbine blade in both axial and tangential direction. In practice wind turbine blades are rotated by the wind and the torque is used to drive the generator. In causing the blades to rotate, wind also changes its direction which is the consequence of Newton's second law. This forms the basis for Blade Element Momentum Theory (BEMT). The NACA series models are used for the wind turbine blade analysis. The aerofoil shaped cross section blades are found to be efficient at low Reynolds number. The commercial CFD software is be used to calculate the aerodynamic properties like lift co-efficient and drag co-efficient of the aerofoil models.

Keywords - *Blade Element Momentum Theory (BEMT), Wind Turbine, Turbine Blade, Lift co-efficient and Drag co-efficient.*

1. INTRODUCTION

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 population.

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. By the 1930s, wind generators for electricity were common on farms, mostly in the United States where distribution systems had not yet been installed. In this period, high-tensile steel was cheap, and the generators were placed atop prefabricated open steel lattice towers.

Vertical-Axis Wind Turbines (VAWT) has the main rotor shaft arranged vertically. The main advantages of this arrangement are that the turbine does not need to be pointed into the wind to be effective. This is an advantage on sites where the wind direction is highly variable. With a vertical axis, the generator and gearbox can be placed near the ground, so the tower doesn't need to support it, and it is more accessible for maintenance.

Drawbacks are that some designs produce pulsating torque. It is difficult to mount vertical-axis turbines on towers, meaning they are often installed nearer to the base on which they rest, such as the ground or a building rooftop. The wind speed is slower at a lower altitude, so less wind energy is available for a given size turbine. Air flow near the ground and other objects can create turbulent flow, which can introduce issues of vibration, including noise and bearing wear which may increase the maintenance or shorten the service life. However, when a turbine is mounted on a rooftop, the building generally redirects wind over the roof and these can double the wind speed at the turbine. If the height of the rooftop mounted turbine tower is approximately 50% of the building height, this is near the optimum for maximum wind energy and minimum wind turbulence.

Horizontal-Axis Wind Turbines (HAWT) has the main rotor shaft and electrical generator at the top of a tower, and must be pointed into the wind. Small turbines are pointed by a simple wind vane, while large turbines generally use a wind sensor coupled with a servo motor. Most have a gearbox, which turns the slow rotation of the blades into a quicker rotation that is more suitable to drive an electrical generator.

Since a tower produces turbulence behind it, the turbine is usually positioned upwind of its supporting tower. Turbine blades are made stiff to prevent the blades from being pushed into the tower by high winds. Additionally, the blades are placed a considerable distance in front of the tower and are sometimes tilted forward into the wind a small amount.

Downwind machines have been built, despite the problem of turbulence (mast wake), because they don't need an additional mechanism for keeping them in line with the wind, and because in high winds the blades can be allowed to bend which reduces their swept area and thus their wind resistance. Since cyclical (that is repetitive) turbulence may lead to fatigue failures, most HAWTs are of upwind design.

The term upwind rotor and downwind rotor denote the location of the rotor with respect to the tower. The downwind turbines were favored initially in the world, but the trend has been toward greater use of upwind rotors with a current splint between 55% upwind and 45% downwind configurations. Wind generators are usually of the upwind type for two principle reasons: 1. a simple tail vane is all that is needed to keep the blades pointed into the wind. 2. A furling mechanism that turns the blades out of the wind stream to protect the machine from high winds is easier for design and fabricate for an upwind rotor. The downwind configuration is usually preferred for larger machines, where a tail vane would not be practical. One problem with the downwind configuration is tower shadow. The tower acts as a barrier to the wind stream and each time a rotating blade passes the tower it is subjected to the changes in wind speed, which causes stresses that vary with the exact amount of wind blocked by the rotor.Since a tower produces turbulence behind it, the turbine is usually positioned upwind of its supporting tower. Turbine blades are made stiff to prevent the blades from being pushed into the tower by high winds. Additionally, the blades are placed a considerable distance in front of the tower and are sometimes tilted forward into the wind a small amount.Downwind machines have been built, despite the problem of turbulence (mast wake), because they don't need an additional mechanism for keeping them in line with the wind, and because in high winds the blades can be allowed to bend which reduces their swept area and thus their wind resistance. Since cyclical (that is repetitive) turbulence may lead to fatigue failures, most HAWTs are of upwind design.

As of 2012, Danish company Vestas is the world's biggest wind-turbine manufacturer. Indian Company Suzlon Energy is a good competitor in the global market in wind turbine manufacturing.

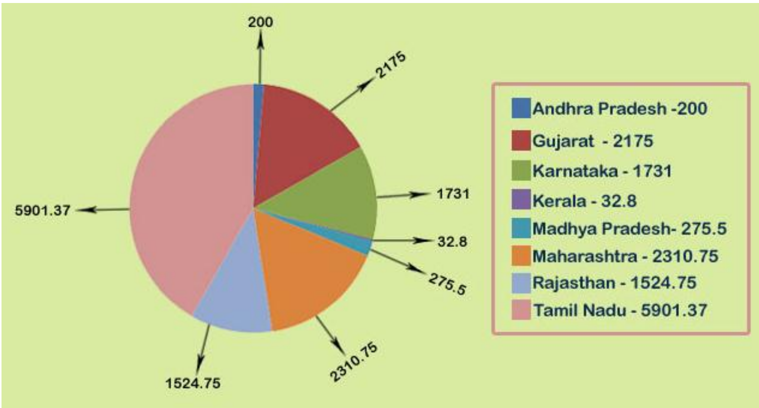


Fig 1**:** Wind Energy Installed capacity in India and state wise distribution.

The development of wind power in India began in the 1990s, and has significantly increased in the last few years. Although a relative newcomer to the wind industry compared with Denmark or the US, India has the fifth largest installed wind power capacity in the world. In the early 1980s, the Indian government established the

Ministry of Non-Conventional Energy Sources (MNES) to encourage diversification of the country's energy supply, and satisfy the increasing energy demand of a rapidly growing economy. In 2006, this ministry was renamed the Ministry of New and Renewable Energy (MNRE). In its 10th Five Year Plan, the Indian government had set itself a target of adding 3.5 GW of renewable energy sources to the generation. In reality, however, nearly double that figure was achieved. In this period, more than 5.4 GW of wind energy was added to the generation, as well as 1.3 GW from other RE sources. The Indian Ministry of New and Renewable Energy (MNRE) estimates that there is a potential of around 90,000 MW for the country, including 48,561 MW of wind power, 14,294 MW of small hydro power and 26,367 MW of biomass. In addition, the potential for solar energy is estimated for most parts of the country at around 20 MW per square kilometer of open, shadow free area covered with 657 GW of installed capacity. The total potential for wind power in India was first estimated by the Centre for Wind Energy Technology (C-WET) at around 45 GW, and was recently increased to 48.5 GW. These figures were also adopted by the government of India as the official estimate.

2. LITERATURE SURVEY

Grant Ingram [1], in this report derives equations for the analysis of wind turbines using the blade element method. These equations are then used in an example performance calculation. Although used for analysis these equations could be equally applied to design activities.

N.S. Çetin1, M.A. Yurdusev2, R. Ata3 and A. Özdemir1, [2] they have described how to select the optimum tip speed ratio for horizontal axis wind turbine. Various speed ratios could be chosen for different types of profiles with different number of blades. An optimization procedure should be applied to find the best ratio since this directly affects the energy generated from the turbine and in turn the investment made. study presents a procedure to assess the optimum speed ratios for various profile types used in practice with various numbers of blades.

Nicolette Arnalda Cencelli [3] describes the range of wind speeds, within which optimal performance of the wind turbine is expected, was selected. The optimal performance was assessed in terms of coefficient of power, which rates the turbine blades ability to extract energy from the available wind stream. The optimization methods employed a means of tackling the multi-variable problem such that aerodynamic characteristics of the blade were ideal through the wind speed range. The optimization involved representation of the rotor as a simplified model and use of the Blade Element Moment method for analysis.

R. Lanzafame, M. Messina [4] carried out mathematical model for fluid dynamics wind turbine design based on the blade element momentum theory has been implemented and improved. The simulation was performed for the whole wind velocity range, in on-design and off-design conditions .The mathematical simulations have been compared with experimental data found in the literature.

Yukio Watanabe1, Hidetsugu Iwashita, and Masamitsu Ito [5] described the shape optimum design of a horizontal axis wind turbine (HAWT) blade operating in low Reynolds number range (Re < 106). The objective is to maximize the power coefficient, rotor power per air flow momentum through the rotor disk area, under the constraints on the torque and the angle of attack in terms of chord length and twist angle distributions where the power-required is evaluated by boundary element method (BEM).

J Laursen, P Enevoldsen, S Hjort [6] applied to a rotor at stationary wind conditions without wind shear, using the commercial multi-purpose CFDsolvers ANSYS CFX 10.0 and 11.0. And local airfoil profile coefficients have been computed and compared with BEM airfoil coefficients.

3. AERODYNAMICS OF HORIZONTAL AXIS WIND TURBINES

Practical horizontal axis wind turbine designs use airfoils to transform the kinetic energy in the wind into useful energy. The airfoil is 2D form of wind turbine blade or wing (aircraft) with infinite span. Wind turbine blades are long and slender structures where the spanwise velocity component is much lower than the streamwise component, and it is therefore assumed in many aerodynamic models that the flow at a given radial position is two dimensional and that 2D aerofoil data can thus be applied.

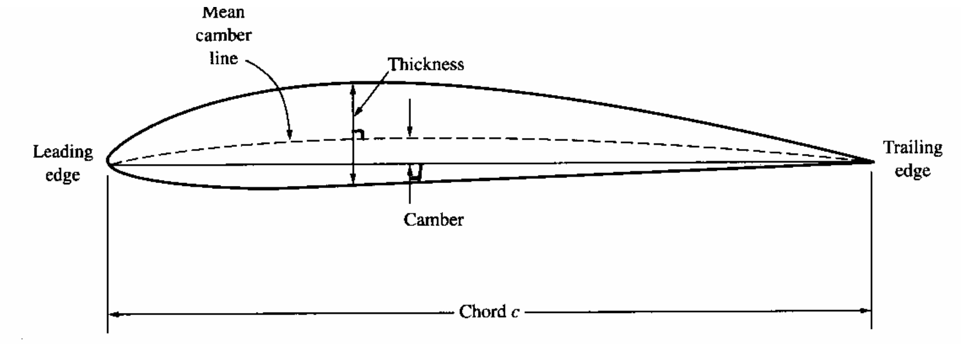


Fig 2: Nomenclature of airfoil.

3.1 ONE-DIMENSIONAL MOMENTUM THEORY AND THE BETZ LIMIT

Consider a control volume whose boundaries are the surface of a stream tube and two cross-sections of the stream tube. The only flow is across the ends of the stream tube. The turbine is represented by a uniform "actuator disc" which creates a discontinuity of pressure in the stream tube of air flowing through it. So this is also called the Actuator Disc Theory.

The static pressure far upstream and far downstream of the rotor is equal to the undisturbed ambient static pressure.

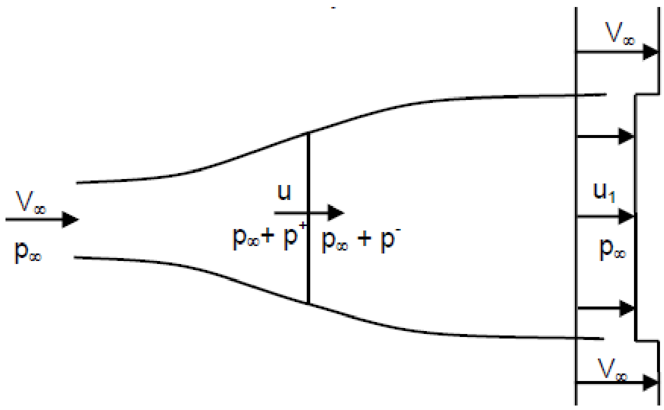


Fig 3: Flow over actuator disc.

Apply the Bernoulli Equation to the upstream and downstream of the stream-tubes separately.

$$\Delta P = P^{+} - P^{-} = \frac{1}{2}\rho\left(V_{\infty}{}^{2} - u_{1}{}^{2}\right) \quad (1)$$

The thrust on the actuator disc (+ve to the right) is the product of pressure difference multiplied by area.

$$\Delta PA = \frac{1}{2}\rho A\left(V_{\infty}{}^{2} - u_{1}{}^{2}\right) \quad (2)$$

Now applying the Newton's Second Law

$$T = \rho A u\left(V_{\infty} - u_{1}\right) = \frac{1}{2}\rho A\left(V_{\infty}{}^{2} - u_{1}{}^{2}\right) \quad (3)$$

On solving, we get

$$u = \frac{V_{\infty} + u_{1}}{2} \quad (4)$$

We define the axial induction factor, a, which is the fractional decrease in wind velocity between the free-stream and the rotor plane, i.e.

$$a = \frac{V_\infty - u}{V_\infty} \Rightarrow u = V_\infty \left(1 - a\right) \quad (5)$$

$$\dot{W}_s = \frac{\rho A V_\infty{}^3}{2} 4a\left(1-a\right)^2 \quad (6)$$

It is useful to compare this amount of useful power with the actual power which would pass through a disc of area A. The power passing through such a disc is the product of the kinetic energy per unit mass of air multiplied by the mass flow rate.

$$\dot{W}_{air} = \frac{1}{2}\dot{m}V_\infty{}^2 = \frac{1}{2}\rho A V_\infty{}^3 \quad (7)$$

The ratio of power produced to the power of the air is called the power coefficient.

$$C_{pw} = \frac{\dot{W}_s}{\dot{W}_{air}} = \frac{\frac{\rho A V_\infty{}^3}{2} 4a\left(1-a\right)^2}{\frac{1}{2}\rho A V_\infty{}^3} = 4a(1-a)^2 \quad (8)$$

We get the maximum power coefficient at a=1/3.

$$C_{pw} = 4a(1-a)^2 = 4\frac{1}{3}\left(1-\frac{1}{3}\right)^2 = \frac{16}{27} = 0.593 \quad (9)$$

This number is known as the Betz limit.

3.2 BLADE ELEMENT-MOMENT METHOD

According to the BEMT, the procedure of blade design begins with dividing the blade length into N elements, select the airfoil profile and the tip speed ratio according to the maximum power coefficient.

The general steps followed for blade design based on BEMT are:

Define the parameters for which the wind turbine blade is designed namely power, aerofoil design parameters (Cl, Cd, angle of attack (α), maximum tip speed (λ), wind velocity (V∞), number of blades B, no. of sections, density(ρ) and axial induction factor a

Calculate the local tip-speed ratio for each blade element by using the relation given below.

$$\lambda_r = \lambda\left(\frac{r}{R}\right) = \lambda\mu \quad (10)$$

Calculate the tangential induction factor a' from the relation as given below.

$$a'(1+a') = \frac{a(1-a)}{\lambda_r{}^2} \quad (11)$$

Calculate the angle between the mean relative velocity and tangential direction by using the relation.

$$\tan\phi = \frac{(1-a)}{(1+a')\lambda_r} \quad (12)$$

Calculate twist distribution for each section of the blade element.

$$\theta_r = \phi_r - \alpha_{design} \quad (13)$$

The tip-loss factor can be calculated from the equation

$$F(\mu) = \frac{2}{\pi}\cos^{-1}\left[\exp\left(\frac{-\frac{B}{2}(1-\mu)}{\mu\sin\phi}\right)\right] \quad (14)$$

Axial thrust coefficient can be calculated by using the relation which is given below.

$$C_T = 4F(\mu)(0.04 + 0.6a) \qquad \text{if } a>0.2 \qquad (15)$$

Calculate chord distribution for each section of the blade, by using the relation.

$$\frac{c}{R} = \frac{C_T 2\pi\mu \tan^2\phi}{B(1-a)^2 C_l \cos\phi} \qquad (16)$$

Calculate the length of the blade, where Cpw is taken from the figure 4.1, according to λ .

$$R = \sqrt{\frac{power(W)}{\frac{1}{2} C_{pw}\rho\pi V_\infty^3}} \qquad (17)$$

By using the above procedure, for NACA4412 airfoil whose design value of C_l is 1.074 and corresponding incidence angle =5.50 at Re=1E6. The value of axial induction factor is taken 1/3and the tip-speed ratio is 7 for maximum power coefficient. The blade chord-length and twist distribution for three-bladed rotor of HAWT is tabulated in table1.

Section	$\mu = \frac{r}{R}$	$\lambda_r = \lambda\mu$	***a'(r)***	ϕ **(rad)**	θ_r**(deg)**	C_T	***c/R***
1	0.05	0.35	0.9366	0.777	39.02	0.96	0.28576
2	0.1	0.7	0.3387	0.618	29.93	0.96	0.26162
3	0.15	1.05	0.1720	0.496	22.95	0.96	0.21090
4	0.2	1.4	0.1028	0.408	17.85	0.96	0.17109
5	0.25	1.75	0.0679	0.343	14.13	0.96	0.14226
6	0.3	2.1	0.0481	0.294	11.35	0.96	0.12113
7	0.35	2.45	0.0357	0.257	9.22	0.96	0.10520
8	0.4	2.8	0.0276	0.228	7.55	0.96	0.09285
9	0.45	3.15	0.0219	0.204	6.20	0.96	0.08301
10	0.5	3.5	0.0178	0.185	5.10	0.96	0.07502
11	0.55	3.85	0.0148	0.169	4.18	0.96	0.06840
12	0.6	4.2	0.0124	0.156	3.41	0.96	0.06281
13	0.65	4.55	0.0106	0.144	2.75	0.96	0.05801
14	0.7	4.9	0.0092	0.134	2.18	0.96	0.05379
15	0.75	5.25	0.0080	0.125	1.68	0.95	0.04994
16	0.8	5.6	0.0070	0.118	1.24	0.93	0.04618
17	0.85	5.95	0.0062	0.111	0.85	0.90	0.04206
18	0.9	6.3	0.0056	0.105	0.51	0.83	0.03670
19	0.95	6.65	0.0050	0.099	0.20	0.67	0.02808
20	0.99	7	0.0045	0.095	-0.08	0.25	0.00988

Table1: Blade Chord and Twist Distribution for a Three-Bladed HAWT by BEMT.

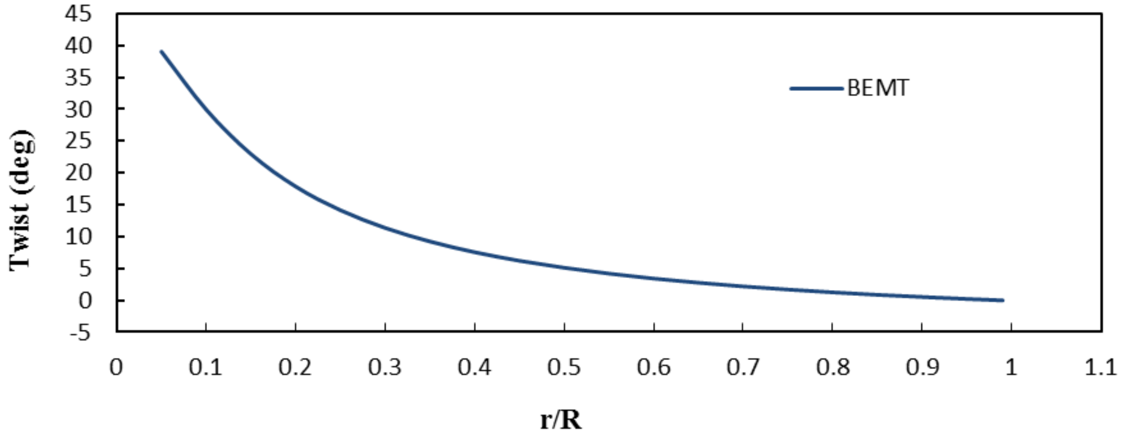


Fig 4: Variation of angle of twist along the blade length by BEMT.

$$[\frac{-\hbar^2}{2m}\nabla^2+V]\Psi=i\hbar\frac{\partial}{\partial t}\Psi \quad (1)$$

4. CFD ANALYSIS OF NACA 4412 ROTOR

4.1 Wake Study

The air that passes through the cross-section of a wind turbine rotor exerts a torque on the rotor shaft, and an equal and opposite torque is imposed upon the flow stream by the rotating blades. Consequently, downstream of the rotor the air flow must rotate in a direction opposite to that of the rotor. The angular momentum is thus increased in the wake, so that each air particle has a tangential velocity component along with an axial one, instead of flowing merely stream-wise. When the wake rotation is introduced, the tangential component of the rotor wake flow produces an increase of its kinetic energy which has to be compensated for by an additional fall in the static pressure. The tangential induction factor a' is zero upstream of the rotor, where the flow is assumed not to rotate. Whereas it is different from zero immediately downstream, due to the tangential component equal to 2Ωra'.

The tangential velocity increases with decreasing radius because a' increases and so the pressure decreases creating a radial pressure gradient. The radial pressure gradient balances the centrifugal force on the rotating fluid. The pressure drop across the disc is caused by the rate of change of axial momentum. This thus causes an additional pressure drop associated with the rotation of the wake; the wind's total available energy is therefore reduced. In figure 5 the axial velocity distribution is shown XY. Near the rotor blade the axial velocity increases due to the effect of rotation of the blade. When moving far from the rotor plane, the axial wake velocity gets stabilized to undisturbed wind velocity.To ensure a high-quality product, diagrams and lettering MUST be either computer-drafted or drawn using India ink.

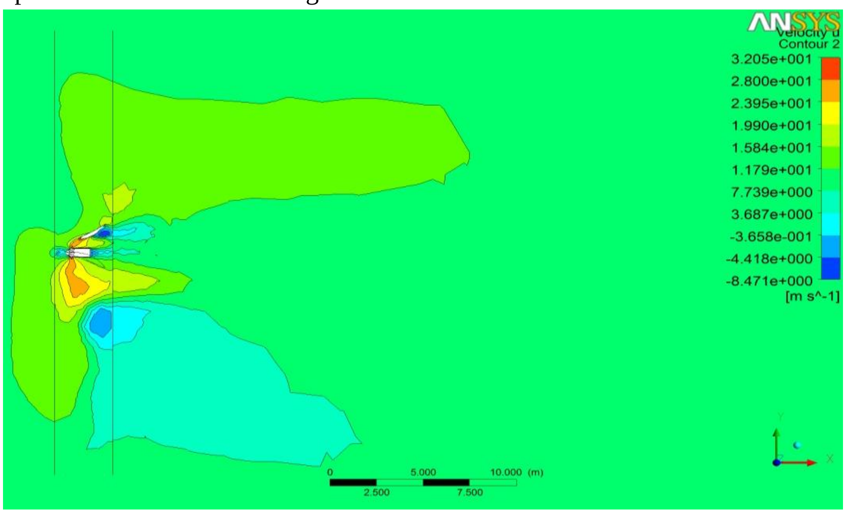
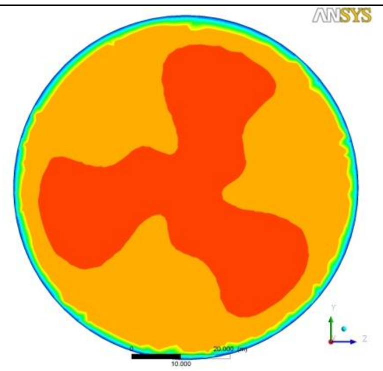
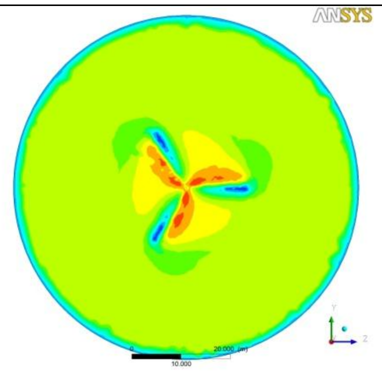


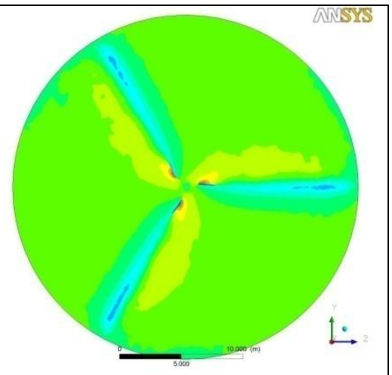
Fig 5: The axial velocity contour in XY plane.



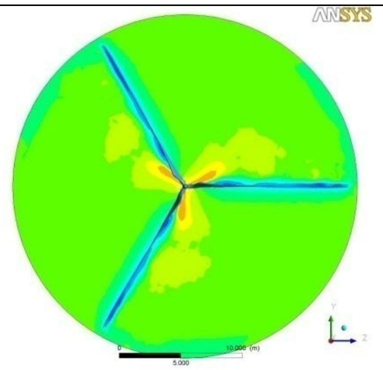
(A) 5m upstream.



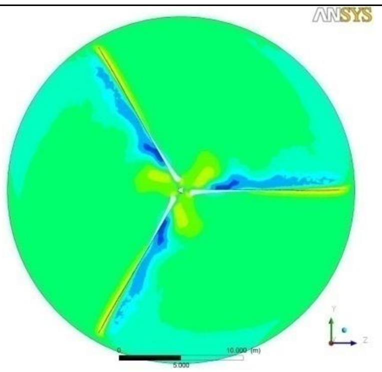
(B) 1m upstream.



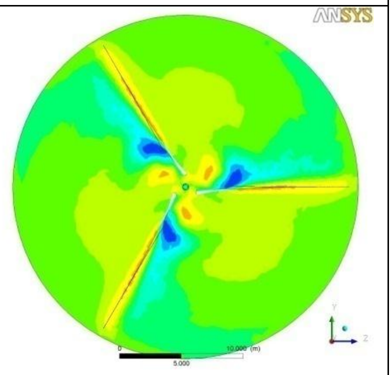
(C) 0.5m upstream.



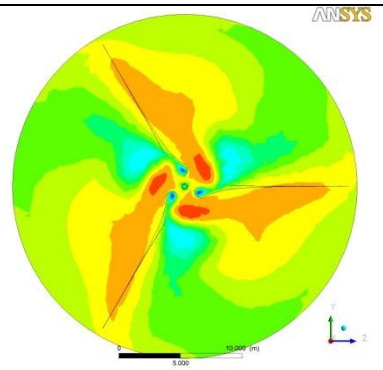
(D) At rotor plane.



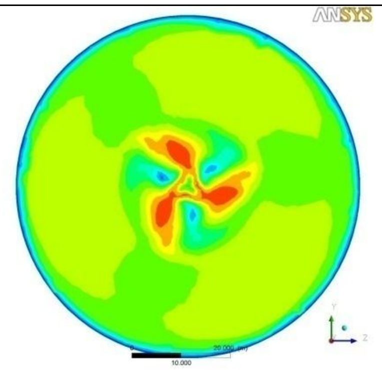
(E) 0.5m downstream.



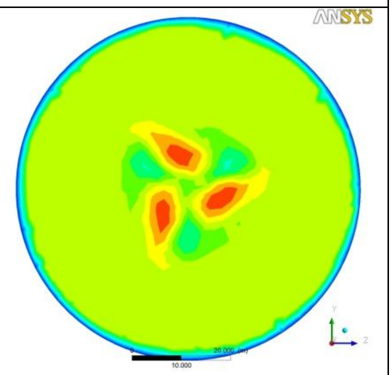
(F) 1m downstream.



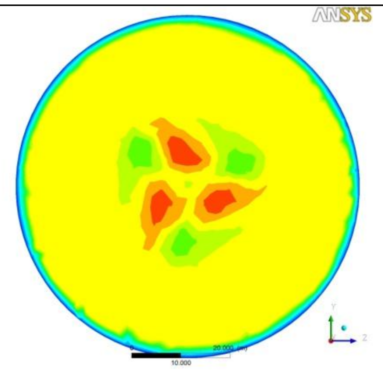
(G) 2m downstream.



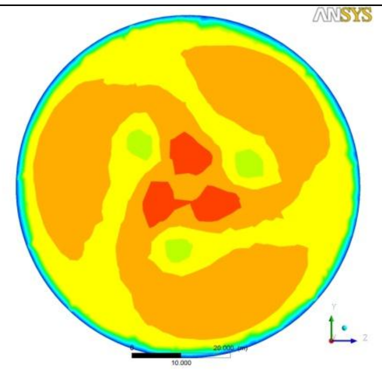
(H) 5m downstream.



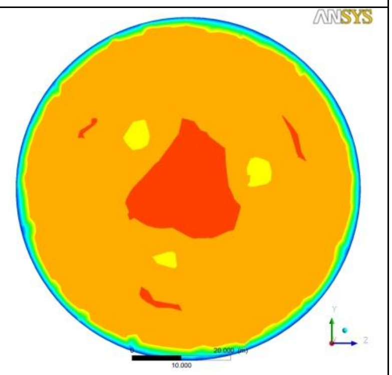
(I) 10m downstream.



(J) 15m downstream.



(K) 20m downstream.



(L) 30m downstream.

Fig 6: Contours of axial velocities in the wake region near to the rotor plane.

Axial velocity contours can be used to study the flow from the near wake to the far wake. In figure 6 the axial velocity component is plotted on radial cut sections at different position within the wake. Close to the rotor the presence of each blade perturbations is clear. As well, at each tip the trailing vortex path is recognizable. Moving downstream, the wake becomes a pitch wise uniform field, which gradually expands. The power is calculated on the rotor plane is 189.79 KW, which was design for 200 KW.

5. CONCLUSION

Out of the different blades used, aero foil shaped cross section blades were found to be efficient. The Reynolds number is below 10^6 for wind velocity of 10 m/s. The wake region becomes weak and sheds a uniform field 30 m downstream of the turbine; this is an indication of the distance to be maintained between the wind turbines. NACA 4412 rotor designed using BEM theory and CFD analysis is performed to predict the output. Shear stress transport turbulence model is used to capture the turbulence effects around the wake region. CFD results matched with the theoretical calculations with 7% error.

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