Fluid Structure Interaction Analysis of Horizontal Axis Wind Turbine

Panchadarla Madhu, Syed Kamaluddin

Abstract*: Wind power is a clean energy source that we can rely on for long term use. A wind turbine creates reliable, cost effective pollution free energy. A Horizontal axis wind turbine (HAWT) with three blades having aerofoil profile NACA 2421 is modelled in CAD software and the performance of the turbine is investigated numerically using 3D CFD Ansys 18.1 software at rotor speeds varying from 1 to 7.5 Rad/sec at wind speeds ranging from 8 to 24 m/s. In order to ensure the turbine blades do not fail due to pressure loads and rotational forces, Fluid structure interaction is carried out by importing the surface pressure loads from CFD output on to static structural module, the rotational velocities are also imparted on the blades and FE analysis is carried out to estimate the equivalent von-Mises stress for structural steel as well as aluminium alloy. It is found that aluminium alloy blades are preferable than the structural steel blades. At high rotor speeds, stresses in the structural steel exceeding the yield strength limit. For aluminium alloy the stresses are below the yield strength limit.

Keywords: wind power, HAWT, aerofoil, equivalent von-Mises stress, Structural steel, Aluminium alloy

I. INTRODUCTION

In the early stage, the research on wind turbine blade design was limited on theoretical study, field testing and wind tunnel testing which need a lot of efforts and resources. Due to development of computer aided design codes, they provide another way to design and analyse the wind turbine blades. Aerodynamic performance of wind turbine blades can be analysed using computational fluid dynamics (CFD). Meanwhile, finite element method (FEM) can be used for blade structural analysis. Comparing to traditional theoretical and experimental methods, numerical method saves money and time for performance analysis and optimal design of wind turbine blades. Currently, General electric company (GE) proposing to build the world's largest wind turbine and proposing to install at outside the city of Rotterdam, Netherlands where abundant wind energy is available throughout the year. The new wind turbine is 850 feet tall and produces 12 MW power.

Manuscript published on January 30, 2020.
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II. LITERATURE REVIEW

H.V Mahawadiwar, et al [1] investigated in detail the effect of varying angle of attack of a wind turbine using GAMBIT and FLUENT CFD software. It was observed that value of numerical power increases as angle of attack increases from 0 to 70°, after 70° the value of numerical power reduced.

Han Cao et al [2] compared aerodynamic performances of different airfoils with help the of two dimensional airfoil modeling in ANSYS Fluent and demonstrated that the DU93 aerofoil has a better aerodynamic performance than the S809 aerofoil.

Kyoungsoo Lee et al [3] performed a static structural linear analysis using a 1-way FSI analysis for the NREL phase VI wind turbine. The entire wind turbine, including the nacelle and tower, was used as the wind turbine structural analysis model. The surface pressure information of the fluid domain from a CFD analysis was directly transferred to the structure using the interface in an FSI analysis.

L Tenghiri et al [4] presented a typical design methodology of the rotor blades of a small wind turbine with a power generation of 11 kW. He determined optimum blade geometry (chord length and twist angle distribution) using optimum rotor theory and the wind turbine blade performance was assessed using Q-blade software.

III. METHODOLOGY

A. Mathematical expression governing wind power

The wind power is generated due to movement of the wind. The energy associated with such movement is the kinetic energy and is given by the following expression.

$$Energy\ (E) = 1/2 \times m \times v^2 \qquad (1)$$

Where m= air mass in Kg

$$m = Volume\ (m^3) \times Density\ (Kg / m^3)$$

$$m = Q \times \rho \qquad (2)$$

Q = Discharge

ρ = Density of air

v = velocity of air in m/s

Hence, the expression for power can be derived as follows:

$$Power = dE/dt \qquad (3)$$

$$= 1/2\ d/dt\ (mv^2)$$

$$= 1/2\ d/dt\ (\rho Q v^2)$$

$$= 1/2\ \rho\ dQ/dt\ v^2$$

Here, dQ/dt = rate of discharge (m/s)

$$= A\ (m^2) \times v\ (m/s) \qquad (4)$$

Where A = area of cross section of blade

Power = 1/2 ρ A v^3 (5)

We know that for given length of blades, A is constant and so is the air density (ρ).

Hence, we can say that the wind power is directly proportional to the cube of wind speed. Albert Betz concluded that no wind turbine can convert more than 16/27 (59.3%) of the kinetic energy of the wind into mechanical energy turning a rotor. This is known as the Betz Limit. The theoretical maximum power efficiency of *any* design of wind turbine is 0.59 [6].

$C_{p\,max} = 0.59$.[6]

Also, wind turbines cannot operate at this maximum limit. The *Cp* value is unique to each turbine type and is a function of wind speed that the turbine is operating in. Once we incorporate various engineering requirements of a wind turbine - strength and durability in particular – the real world limit is well below the *Betz Limit* [6]

B. Lift and Drag

Lift is the force used to overcome gravity and is defined to be perpendicular to direction of the oncoming airflow. It is formed as a consequence of the unequal pressure on the upper and lower airfoil surfaces.

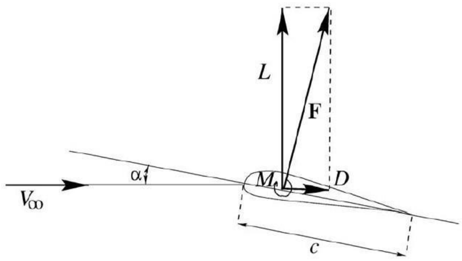


Fig. 1 lift and drag [2]

The drag force is defined as a force parallel to the direction of oncoming airflow. The drag force is due both to viscous friction forces at the surface of the aerofoil and to unequal pressure on the airfoil surfaces facing toward and away from the oncoming flow. The lift is the force used to overcome gravity and the higher the lift the higher the mass that can be lifted off the ground. For an aerofoil, the lift to drag ratio should be maximized. As a result, it can improve efficiency. Lift and drag coefficients C_L and C_D are defined as follows:

Lift coefficient $(C_L) = 2F_L / \rho v^2 c$ (6)

Drag coefficient $(C_D) = 2F_D / \rho v^2 c$ (7)

Where ρ is the air density and c is the length of the aerofoil.

C. Tip speed ratio (TSR):

$\lambda = \omega R/v$ [2] (8)

Where ω is angular velocity of wind turbine rotor

R = radius of the rotor

v = wind speed

Generally a low speed wind turbine chooses value of TSR from 1 to 4 and high speed wind turbine chooses from 5 to 9.

D. Method of flow analysis:

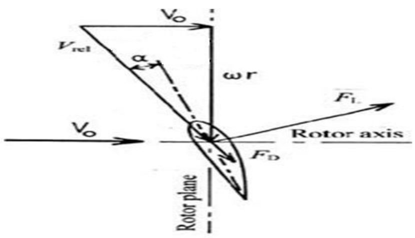


Fig. 2 blade velocity triangle [1]

From the above figure it can be seen that,

$v_r = (v^2 + v_0^2)^{1/2}$

$v = r \times \omega$ (9)

Lift force $= 1/2 \times \rho \times v_r^2 \times C_L$ [2] (10)

Drag force $= 1/2 \times \rho \times v_r^2 \times C_D$ [2] (11)

$F_R = (F_D^2 + F_L^2)^{1/2}$

Numerical power $(P_N) = F_R \times v$

$= F_R \times r \times v$

$= T \times \omega$ [1] (12)

Where; T = Torque

Analytical power $(P_A) = 1/2 \times \rho \times A \times v^3 \times C_P$ [1] (13)

Power coefficient $(C_p) = P_N / P_A$ [1] (14)

E. Simulation of wind turbine in Ansys CFX:

The horizontal axis wind turbine (HAWT) used in the present study has three blades with maximum diameter of 3.2 meters. The aerofoil profile of the blade is of NACA series to obtain maximum aero dynamic efficiency. HAWT'S uses lift force generated by the aerofoil to produce torque while VAWT'S uses drag force to produce the torque. The CAD model of the turbine is imported to geometry module of Ansys CFX software. A rotating domain is created for the turbine rotation and a stationary domain (S.D) enclosing the rotating domain (R.D) is created for necessary flow from inlet to outlet. The rotating domain is suitably placed in the stationary domain for effective and smooth fluid flow from inlet to outlet. The rotating domain is suitably placed in stationary domain for effective and smooth fluid flow from inlet to outlet through the rotating domain. The following figure shows the both the stationary and rotating domains.

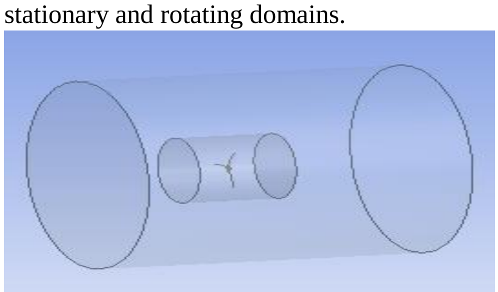


Fig. 3 Stationary and rotating domains

Suitable fluid interfacing is created between stationary and rotating domains for fluid flowing into and out of the rotating domain. The complete model with stationary and rotating domains along with necessary boundary conditions i.e. inlet, outlet etc is meshed. The meshed model is shown in figure 4

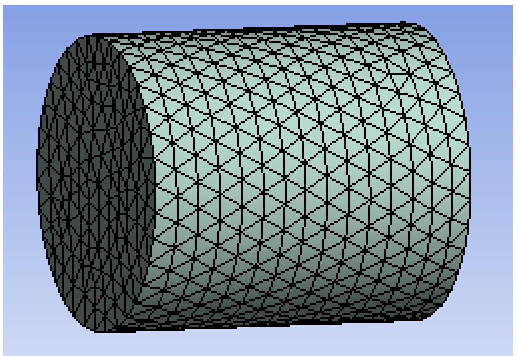


Fig.4 meshed model

The meshed file is imported into CFX module and necessary physical parameters inlet and outlet boundary conditions are given as stated below:

- Inlet (S.D) – wind speeds (8 to 24 m/s)
- Outlet (S.D) – average static pressure (0 Pa)
- Rotor (R.D) – rotational velocity (1 to 7.5 rad/sec)
- Top (S.D) – opening
- Turbulence model – k-ω turbulence model

The CFX setup file is ready for simulation. The setup file with necessary boundary conditions is shown in below figure.

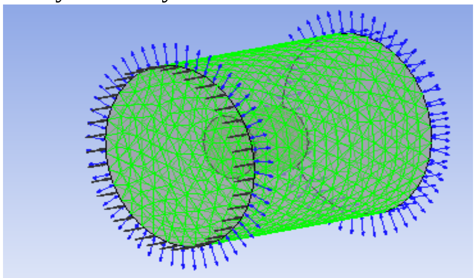


Fig. 5 Boundary conditions

Simulation is executed for suitable number of iterations and the result file created in CFX is analyzed in CFD post for torque values on the blades and power output is calculated by using obtained torque values. In order to ensure the turbine blades do not fail due to pressure loads and rotational forces, fluid structure interaction (FSI) is carried out by importing the surface pressure loads from CFD output on to static structural module, and rotational velocities are also imparted on the blades and FE analysis is carried out to estimate the equivalent von-Mises stress for both structural steel and aluminum alloy. The pressure loads on blades can be seen in figure 6

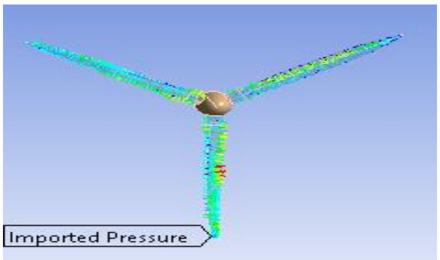
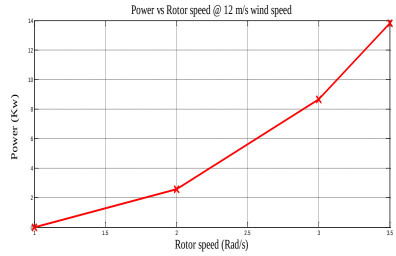


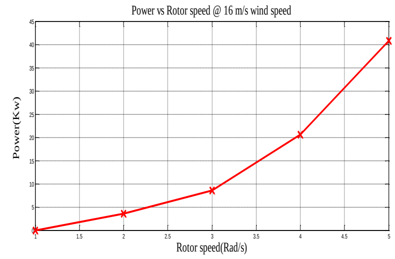
Fig.6 Imported pressure on blades

IV. RESULTS AND DISCUSSION

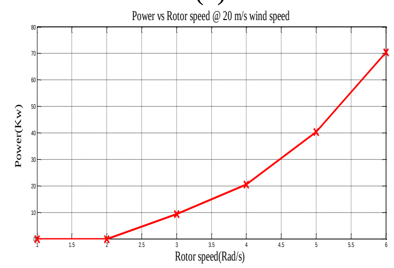
The wind speed generally varies in a day during one particular season in an year. Hence all wind turbines are shut down at the lowest speed in the year called cut-in speed and are again stopped at higher wind speeds at which the stresses exceed the strength of the blade material called cut-off speed. In the present work wind turbine is run at different rotor speeds varying from 1 Rad/s to 7.5 Rad/s at varying wind speeds ranging from 8 to 24 m/s so as to arrive at the cut –in and cut-off speeds of the turbine. The mechanical stresses on the rotor blade are determined using fluid structure interaction. The pressure loads from CFD output are superimposed along with the rotational velocities. The necessary boundary conditions for fixing the rotor are suitably applied in Ansys structural software.



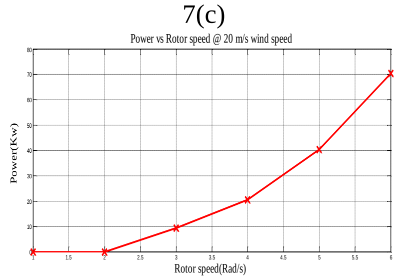
7(a)



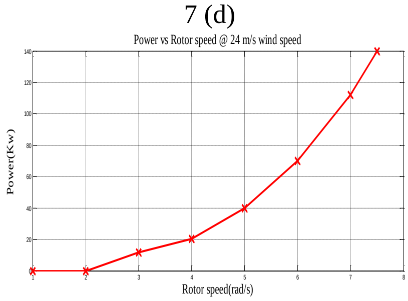
7(b)



7(c)



7 (d)

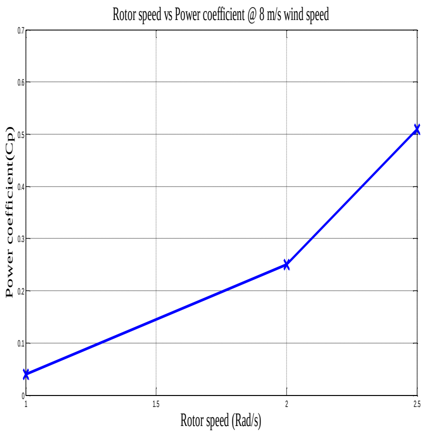


7 (e)

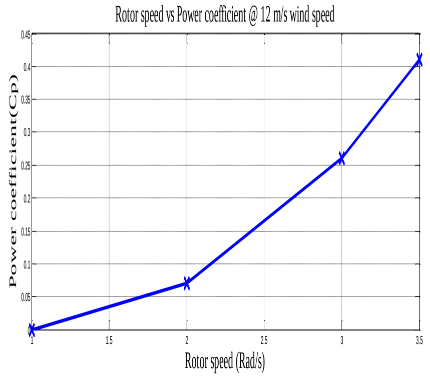
Fig. 7 (a to e) power vs rotor speed plots

Figure 7 (a to e) shows the variation of power output in kilowatts and rotor speed varying from 1 to 7.5 Rad/s at each wind speed keeping wind speed constant. At the lowest rotor speed of 1 Rad/sec only wind speed of 8 m/s , simulation could be carried out giving a power output of 0.5 Kw and convergence could not be attained at higher wind speeds in excess of 8 m/s , indicating that wind turbine could not be run at all of 1 Rad/sec. At rotor speed 2 Rad/sec, power output could be obtained only at 8, 12, and 16 m/s giving maximum power output of 3.5 KW at 16 m/s followed by 2.5 KW at both 12 and 8 m/s wind speed respectively. At 3 Rad/sec, the wind turbine could not be simulated at 8 m/s, due to exceeding of Betz limit beyond acceptable value of 0.59.However simulations could be carried out with acceptable convergence and Betz limit at wind speeds 12 to 24 m/s. The power outputs are 8.6 KW at 12 m/s followed by 8.5, 9.3, 12 KW at 16, 20 and 24 m/s wind speeds. However convergence criteria is satisfied at 2.5 Rad/s yielding power output of 5 KW. From all the above simulations carried out so far ,the cut-in speed can be set as 24 to 29 RPM(2.5 to 3 Rad/s) at which the average power output is around 8 KW. At 4 rad/s, simulations could not be carried out at 8 and 12 m/s wind speed due to exceeding Betz limit accepted value of 0.59. power output at 16 m/s is 20 KW and remained constant though wind speed further increased to 24m/s. However the wind turbine could be run at 3.5 Rad/sec at 12 m/s giving power output of 14 KW. At rotor speed of 5 rad/s , the power output remained constant at 40 KW when wind speed is varied from 16 to 24 m/s . At rotor speed of 6 Rad/sec, 70 KW power output is achieved at wind speeds ranging from 20 to 24 m/s wind speed. While at 7 Rad/sec and 7.5 Rad/sec the wind turbine could be simulated at 24 m/s wind speed only and it was not possible to do simulations at 7 and 7.5 Rad/sec except for 24 m/s wind speed.

The power coefficient (C_p) of a wind turbine depends on the output power developed and available power in the wind which in turn depends on the cube of the velocity of the wind. Higher wind speed results in higher power coefficient value. However the maximum attainable value is limited by Betz limit of 0.59 with maximum velocity not exceeding cut-off speed of wind turbine.

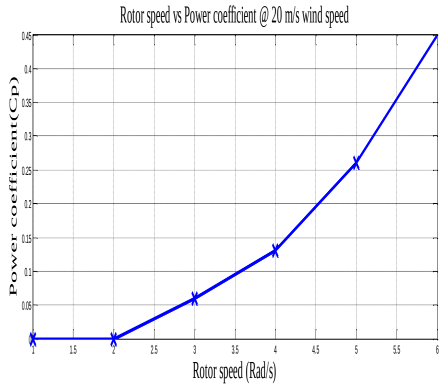


8 (a)

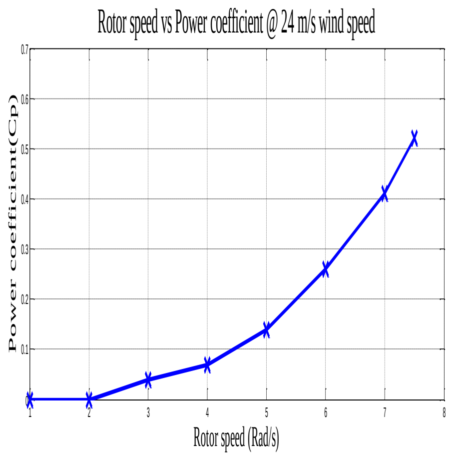


8 (b)

8 (c)



8 (d)



8 (e)

Fig.8 (a to e) power coefficient vs rotor speeds plots

Figure 8 (a to e) shows variation of power coefficient with wind turbine rotor speed varying from 1 to 7.5 Rad/sec at wind speeds ranging from 8 to 24 m/s.

It is seen that at wind speed of 8 m/s , maximum C_P of 0.51 is obtained at only 2.5 Rad/sec and delivering very small power output of 10 Kw.

At wind speed 12 m/s, the C_p value dropped down to 0.16 and maximum value of C_p obtained is 0.4 at 3.5 Rad/sec. At constant rotor speed of 3.5 Rad/sec, the C_p value continuously drops from 0.4 at 12 m/s to 0.19, 0.10, and 0.05 at wind speeds of 16, 20, and 24 m/s respectively. On the other hand highest value of C_p that is 0.51 is realised at 2.5, 5, and 7.5 Rad/sec at corresponding wind speeds of 8, 16, and 24 m/s only. Since efficiency is a multiple of C_P with a constant value of 1.68, the highest efficiencies could be realised only at 8, 16, and 24 m/s.

Figure 9 shows the variation of Von Mises equivalent stress for structural steel and aluminium alloy at rotor speeds varying from 1 to 7.5 Rad/sec. The stresses shows increasing trend with increase in rotor speed. The increase is more pronounced for structural steel than aluminium alloy. Considering the yield strengths of 250 MPa and 280 MPa for structural steel and aluminium alloy, the allowable stresses in the wind turbine are limited to half of the yield strength that is 125 MPa and 140 Mpa for structural steel and aluminium alloy respectively. It is seen that the allowable stress value of 125 Mpa for structural steel is beginning to exceed from rotor speeds of 4.5 Rad/sec. And for aluminium alloy the allowable stress value of 140 Mpa is not realised even at highest speed of 7.5 Rad/sec. Hence, it can be concluded that aluminium alloys are more preferable to structural steel due to realisation of higher power output (cut-off speed can be set at maximum value of C_P at particular value of average wind speed throughout the year at the wind turbine location).

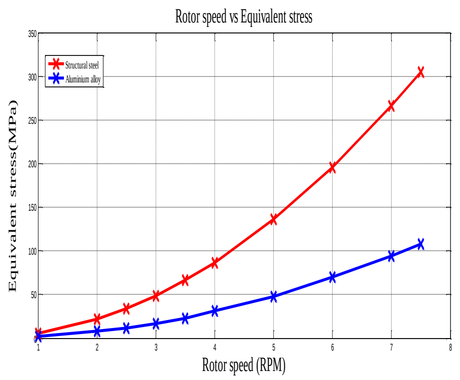


Fig. 9 equivalent stress vs rotor speed plot

V. CONCLUSION

A horizontal axis wind turbine modelled in CAD software is investigated numerically in Ansys 3D software. Since the wind turbine speed varies during different seasons in an year, the simulation is carried out at different wind speeds ranging from 8 to 24 m/s. In order to determine the cut-in and cut-off speeds of the wind turbine, simulation is performed at different rotor speeds varying from 1 to 7.5 Rad/s. The wind turbine is able generate the minimum power output of 2.5 KW at 8m/s wind speed at rotor speed of 2 Rad/sec and maximum power output of 140 KW at 24 m/s wind speed at 7.5 Rad/sec. Fluid structure analysis is carried out to estimate the equivalent von-Mises stress for structural steel as well as aluminium alloy. It is found that the stresses in structural steel shows a increasing trend and maximum stress developed is306 MPa and the stresses in aluminium alloy also shows a increasing trend and maximum stress developed is 108 MPa. It is concluded that aluminium alloy blades are preferable than the structural steel blades. At high rotor speeds, stresses in the structural steel exceeding the yield strength limit. For aluminium alloy the stresses are below the yield strength limit.

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