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Optimal Design and Analysis of Wind Turbine Blade and Hub Coupled System

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Abstract-*Wind turbines are one of the renewable energy resources. Wind turbines will be best solution to decrease the pollution produced byfossil fuel operated power generators. In this paper typical 1.7MW wind turbine is designed and performance analysis is carried out on the same. The aerodynamic contour design is one of the important thing to be noticed in wind turbine blade. So for the horizontal axis wind turbine blade the program for optimization design of the blades aerodynamic contour has been solved using MATLAB tool based on design process of Wilson method. According to the space coordinate transformation theory, the space coordinates of the blade elements have been calculated. From the coordinates generated wind turbine blade is modelled in CATIA. Then hub is also designed in CATIA. The first 6 order inherent frequencies and vibration modes of Blade and Hub are solved in ANSYS to verify the design. Modal analysis is selected in ANSYS to solve the inherent frequencies and vibration modes in ANSYS.*

Keywords— *Optimization design, Aerodynamic contour design, Wilson method, Wind turbine blade.*

I. INTRODUCTION

It is difficult to calculate the axial and circumferential inducible factor of wind turbine blades, which is critical in the aerodynamic contour design. The shape of the blade is complex; in addition, today's high performance wind turbine blades are made of glass fibre or carbon fibre composite layer structure, so how to model the blade precisely so as to describe the layer structure becomes a difficult problem, which is also important in mechanical analysis.

To obtain a good wind turbine, the wind turbine structure should be designed theoretically first. Then with the help of modal analysis methods the wind turbine design results can be verified. It is necessary to analyse the vibration characteristic of wind turbine structure, especially the Blade and hub coupled system. In this article studied the design and modelling of wind turbine Blade and hub using MATLAB tool where the coordinates of the wind turbine blade are optimized. Each blade section is modelled in CATIA from the obtained values of MATLAB tool. Finite element method is used static strength analysis of the blade with the shell element discretisation over the skin and three dimensional 'sandwich' element to simulate the spar web.

Finally a computer program that would enable optimization calculation of blade inducible factor is developed to build the blade modal precisely. Which describes the actual shape of the blade.

II. WIND TURBINE STRUCTURE DESIGN

Wind turbines can be divided into two types, named horizontal axis wind turbines and vertical axis wind turbines. On the otherhand, they can also be divided into offshore wind turbine and landwind turbines. Nowadays, typical horizontal axis wind turbineshave gained more attentions from the world.

The basic wind turbine structure designed in this paper is shown in Fig.1 below there are mainly 4 parts in the large wind turbine,named wind wheel, tower, base and cabin, in which the wind wheelcan be divided into blade and hub.

As shown in Fig.1 , parameter D is the wind wheel diameter. Strictly speaking, D is the encircle diameter of wind wheel when wind turbine is running. The swept area of the wind wheel and the choice of blade length have some relationship with this parameter D. Therefore, the wind wheel diameter D is one of the main parameters in wind turbine design.

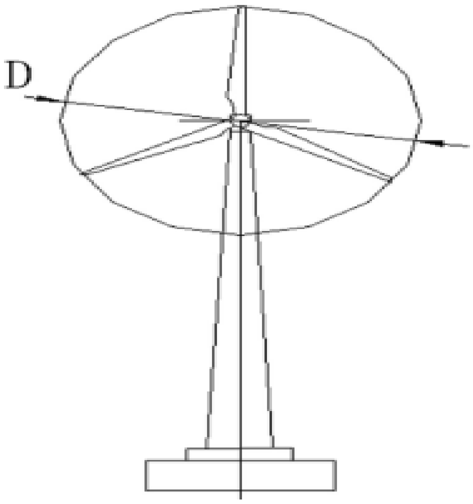

Fig.1 Wind wheel diameter

III. OPTIMAL DESIGN OF AERODYNAMIC CONTOUR

Referring to the data of 1.7MW which is provided by a company. The parameters of the blade are as follows rated power 1.7MW, cut in wind speed 3m/s, cut out wind speed 25m/s, rated wind speed 9m/s, number of blades 3. According to the tip speed ratio range of high-speed wind turbines, λ is 8. Optimum angle of attack α=3º with corresponding lift coefficient C_f=0.72 and drag coefficient C_d=0.006.

Blade length calculation

From the above data power of the wind wheel can be calculated by

$$P=\frac{1}{2}\rho S C_p v^3 \quad (1)$$

$$S=\frac{\pi}{4}D^2 \quad (2)$$

Where ρ=density of air
S= Swept area
C_p= coefficient of power
V= rated wind speed
D= diameter of wind wheel

Therefore from power $S = \frac{2P}{\rho C p v^3}$ (3)

$$S = \frac{2*1.7*10^6}{1.225*0.43*9^3}$$

$$S = 8854.14 \text{ m}^2$$

Then From swept area $D = \sqrt{\frac{4*S}{\pi}}$ (4)

D = 78.2 m

Blade length is equal to radius of the wind wheel diameter.

So blade length l = 38m

IV. SELECTION OF AIRFOIL

From National Advisory committee for aeronautics (NACA), there are various types of airfoils for wind turbine blade. The difference between each airfoil is the thickness. There are four types of airfoils they are symmetrical, NACA 4, 5 digit and NACA 6 series airfoils. The selection of airfoil depends upon the type of wind turbine i.e is whether it is large or small windmill.aerofoil NACA4412 is selected for blade design.

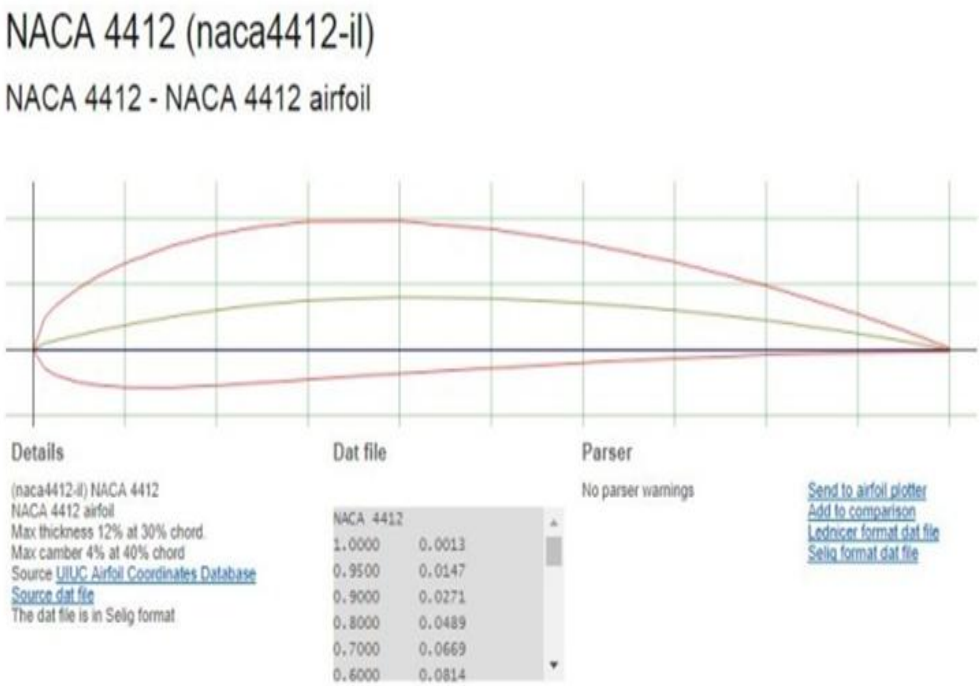

Fig. 2 aerofoil NACA4412

V. OPTIMAL CALCULATIONS OF WIND TURBINE BLADE

Optimization design of span wise shape of the wind turbine blade is obtained by Wilson method which is based on Blade element moment theory. The Blade divided into number of elements here it is divided into 20 elements along the span. The optimization modal is as follows

$$F = \frac{2}{\pi}\arccos\left(e^{-f}\right) \quad (5)$$

$$f = \frac{B}{2}\frac{R-r}{R\sin\theta} \quad (6)$$

$$\tan\emptyset = \frac{1-a}{1+b}\frac{1}{\lambda} \quad (7)$$

Twist angle of each blade element can be calculated as

$$\theta = \emptyset - \alpha \quad (8)$$

Chord length of each element can be calculated as

$$C = \frac{8\pi brF\cos\emptyset}{BC_l(1+b)} \quad (9)$$

Where, λ is tip speed ratio, a is axial induction factor, b is circumferential induction factor, F is tip loss coefficient, f is intermediate variable, R is radius of rotor or blade length, ris distance between blade element cross-section to the rotor centre, ∅ is oncoming flow angle, C_l is blade aerofoil lift coefficient, C is blade element chord length, Θ is twist angle.

1.7MW wind turbine blade is divided into 20 elements from r to R. each blade element chord length and twist angle iterative calculations done using the above equation using MATLAB tool. M file is created in programming where all the above iterative calculations are done M files. Flow chart is as follows

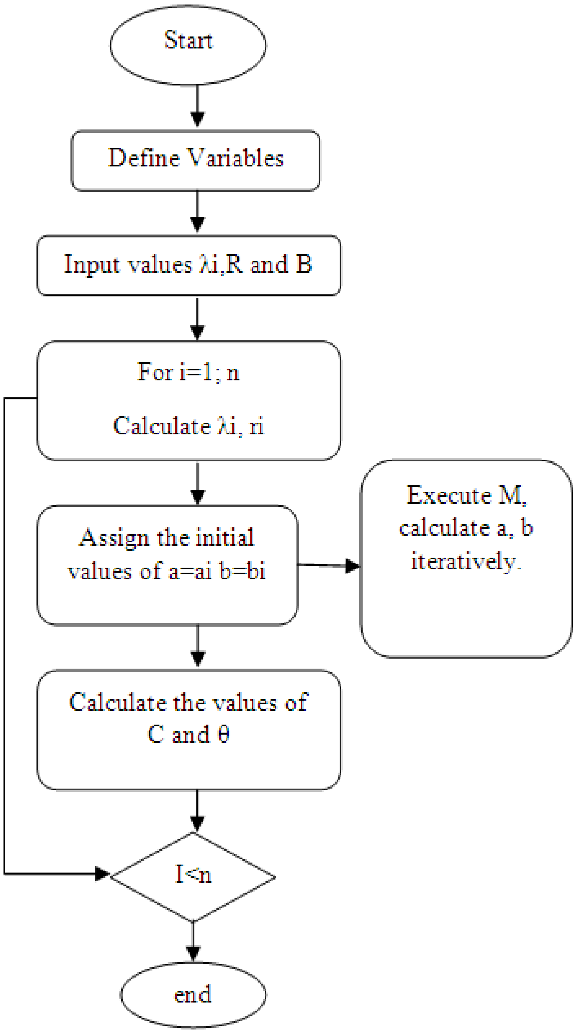

Fig.3 Flow chart for optimization

For the optimum values eq. (10) and eq. (11) are used for oncoming flow angle Φ and circumferential induction factor b respectively. But for obtaining the optimum value of a eq. (12) is used.

$$\Phi = \tan^{-1}\left(\frac{\lambda(1+b)}{1-a}\right) \tag{10}$$

$$b = \left(\frac{\sigma' C_l}{4\lambda \cos\phi}\right)(1-a) \tag{11}$$

$$a = \left(1 + \frac{4 * \cos^2\varphi}{\sigma' C_l \sin\varphi}\right)^{-1} \tag{12}$$

where a is axial induction factor, b is the circumferential induction factor, C_l is coefficient of lift, θ is twist angle, φ isonflow angle onto blade, F is tip loss coefficient, α is inlet angle, B is number of blades.

Therefore finally from the above flow chart in new file define the variables namely axial induction factor a, circumferential induction factor b, initial values of a and b. define all the constants like radius R, power coefficient C_p, lift coefficient C_l, number of blades B. Now start a loop. Enter the equations from 1 to 5 then for every iteration the values of a and be are calculated and these values are stored for next iteration. By all this process we can get the optimum values of a and b which are axial and circumferential induction factor. From these values we can get the optimum values of chord length and twist angle.

VI. CHORD LENGTH AND TWIST ANGLE

The calculated values of chord length and twist angle at the blade root are often too large .It is necessary to modify them aiming at easy modelling and saving materials for manufacturing. The data of blade element from r to R is fitted.

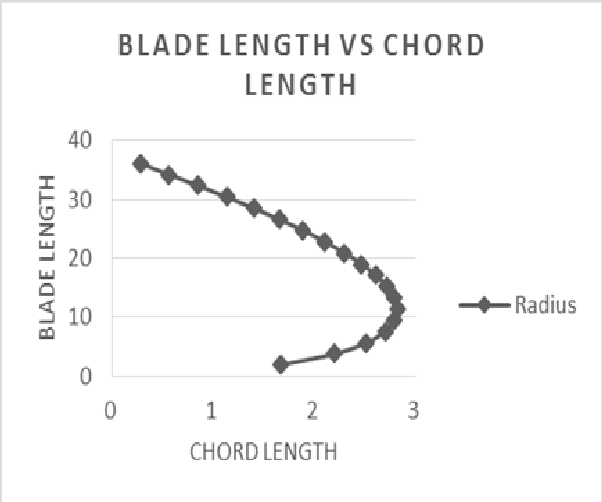

Fig.4 Chord length vs blade length

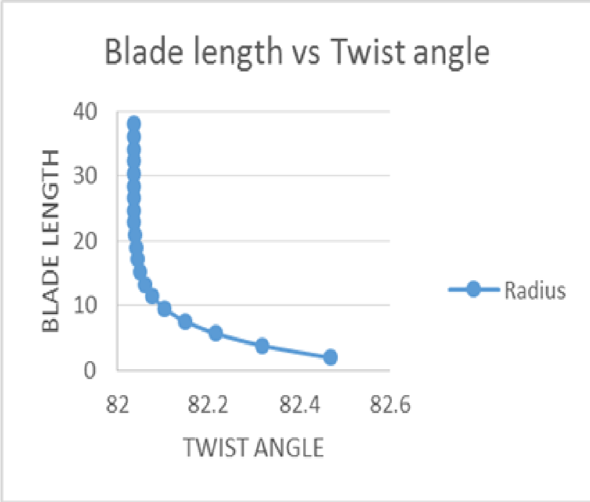

Fig.5 blade length vs twist angle

From root to tip of the blade the along the blade length chord length decreases gradually from fig. 4 it is the graph shows gradual decrease in the chord length upto some level and increases. The increase in chord length is due to the root of the blade that is the root of the blade is made circular to fit into the hub. The graph shows that the obtained values of chord length are good and the blade can be modelled from these values. From fig. 5 it can be observed that there is very small change in twist angle that so an airfoil with less thickness should be used to model the blade.

VII. THREE DIMENSIONAL MODELLING OF WIND TURBINE BLADE, HUB AND ACCESSORIES

The CATIA software was used to carry out the 3-D surface modelling of the blade. The curve of each blade element was created by the calculated coordinate data of discrete points above; subsequently, entire surface of the blade was produced through lofting.Each blade element curve can be automatically generated by selecting the exel file of the coordinate data though steps of 'insert'-'curves'-'curve through XYZ points'. The blade was divided into several parts according to different way of layering. These segmental swept skin surfaces of the blade were created by selecting the cusp of the curve sequentially, using the order 'lofting surface'. Finally made the blade spliced into a whole. Combined with the data of circles at the root, an entire three-dimensional surface model of the blade was created successfully. The model was saved as .igs form, so as to exchange data with the ANSYS software easily.

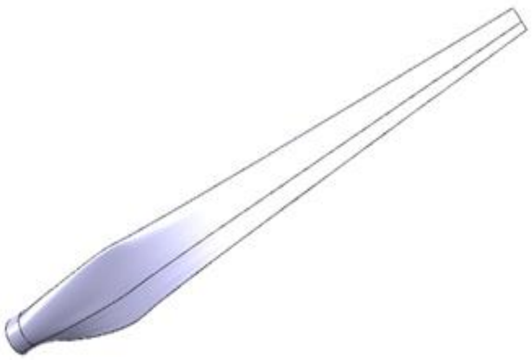

Fig. 6 Wind turbine blade

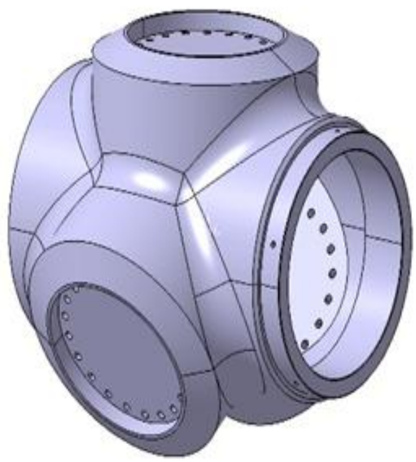

Fig. 7 Wind turbine hub

Fig. 9 Assembly of wind turbine rotor

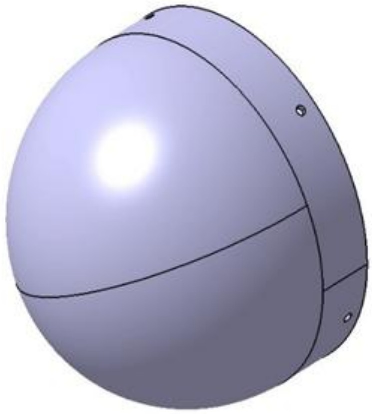

Fig. 8 Cup of hub

As shown in fig.6 the wind turbine blade is designed in CATIA by importing the co-ordinates points of each airfoil of the blade. These points are joined by using a spline and then these splines are joined by using loft option in CATIA. All this procedure is done in generative shape design so blade profile with zero thickness is formed. Now this surface is converted into volume then the wind turbine blade as shown in fig.6 is formed. Hub and cup are the two components dependent on the diameter of the blade root. In design process of the blade we can come across the diameter of the root of the blade. For assembling of the blade into the hub the hub inner diameter is same as the root diameter of the blade. Same procedure is followed for the cup too. In CATproduct file all these components are constrained with nuts and bolts. Hub is fixed with anchor option. All other components are constrained to hub. As shown in fig.9 the assembly is done in CATIA.

VIII. FINITE ELEMENT ANALYSIS OF BLADE AND HUB COUPLED SYSTEM

Dynamic finite element analysis of the blade mainly refers to the vibration modal analysis using the finite element theory. Modal analysis is used to identify natural frequencies, especially low-order frequencies and vibration modes of wind turbine blades. From the modal we can learn in which frequency range the blade will be more sensitive to vibrate. Blades should be designed to avoid the resonance region with the tower and other components in order to prevent some destruction of related components. The finite model of the blade has been established in ANSYS by importing the blade surface model created previously. Fig. 10 shows the modal imported into ansys.

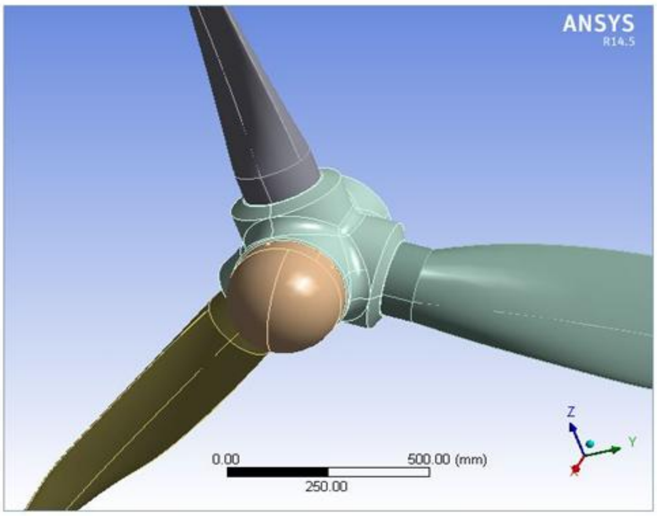

Fig.10 modal analysis modal

There are many ways for ANSYS modal analysis, of which the tetrahedron method is most widely used because of its powerful features. Moreover, it is frequently applied with model of solid units or shell units. Tetrahedron method uses patch conforming algorithmThe vibration modes of the first six orders were extracted with the frequency range of

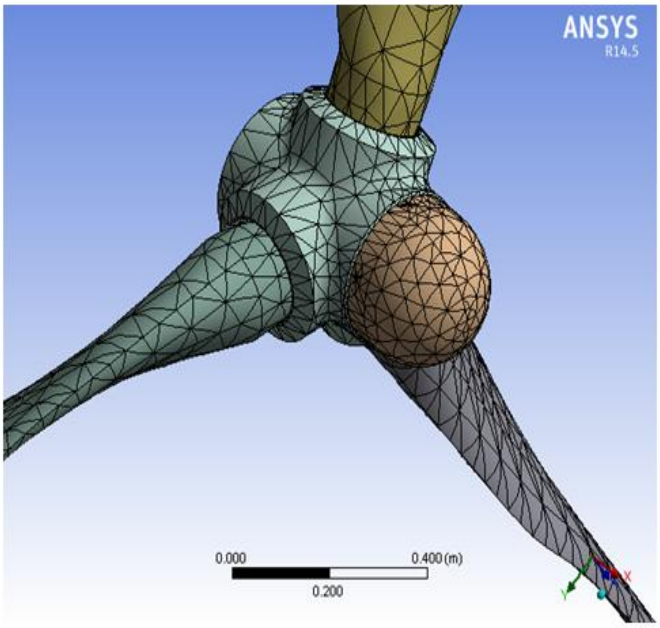

Fig. 11 mesh modal

0~9999Hz. The connections of blades and hub could be regarded as fixed, so it is only need to restrict all DOFs of the root, for modal analysis does not require applying loads.Fig. 11 shows mesh modal.

IX. RESULTS AND DISCUSSION

Hub is the structural part of the assembly. Hub structure supports the three blades of assembly, so structural analysis is done to find out the total deformation of the blade and stress produced in hub. Minimum edge length is $3.583e^{-3}$ in the mesh which gives great accuracy with 49806 elements.Wind turbine blade experiences the wind on the front face of the blade, so a pressure of 382.18 Pa is applied on the blade then a maximum of $9.576e^{-5}$ mm deformation has occurred at the blade section. Fig. 12 shows the deflection of the assembly. Mmaximum stress produced is 101.04 KPa. From the fig. 13 the maximum stress produced at the hub of the assembly.

Figures 14 shows the total deformation of mode 4. The maximum frequency in mode 4 is 15.533 Hz. The red colour in those figures shows max deformation and blue indicates minimum deformation. The deformation at the tip of the blade is maximum and at the root of the blade it is minimum. The material used in model analysis is glass fibre. For the blade E-glass fibre material is used and for hub structural steel is used. E-glass fibre is one of the composite material and it has good material properties and less weight. Six vibration modes of the assembly is tabulated below.

Fig. 11 mesh modal

Mode	Frequency
1	4.0291
2	4.0309
3	4.0476
4	10.637
5	10.858
6	10.875

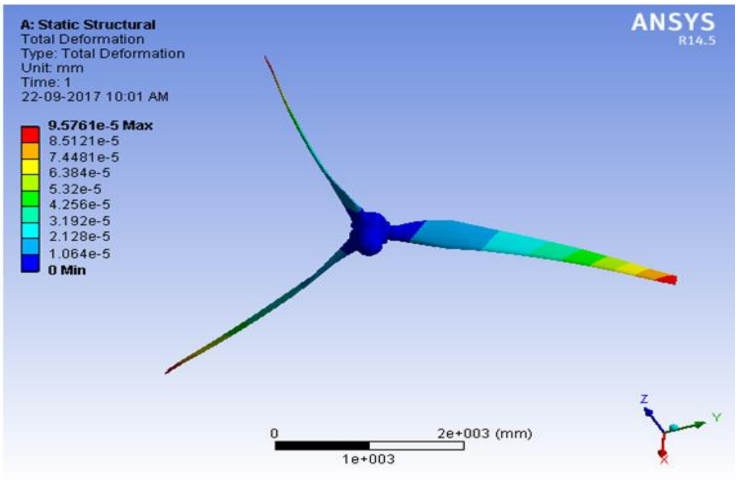

Fig. 13 total deformation due to pressure applied

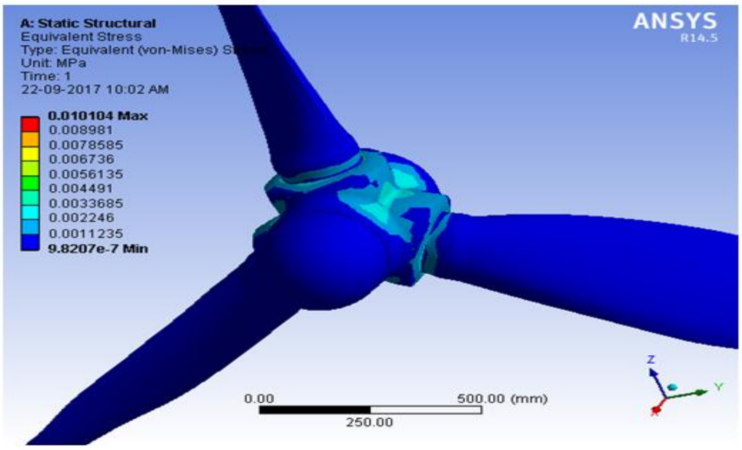

Fig. 13 von-mises stress

Table.1 six modes of frequency

From the above table maximum frequency of the blade and hub coupled system is found to be 10.
The excited frequency of rotating rotor or hub with 3 blades will be

$$f = \frac{3\omega}{2\pi} = 1.1057 \text{ Hz}$$

Wind turbine blade is designed successfully Static structural analysis is carried out and the maximum of 101. 04 KPa

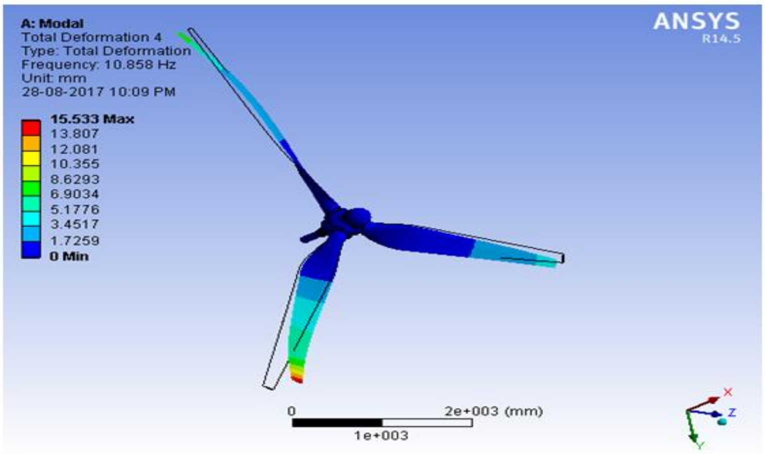

Fig.14 total deformation mode4

stress is produced which is very less.From modal analysis the excited frequency is less than the first order frequency of the wind turbine hub and blade. Therefore no resonance will happen when the blades run at rated wind speed.

X. CONCLUSION

MATLAB programming is applied to realize the aerodynamic contour optimization design of wind turbine blade. The way of combining CATIA and ANSYS was adopted to establish the blade model so as to describe actual shape and layer structure of the composite blade precisely. The dynamic performance of the blade was checked by modal analysis.

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