FATIGUE LIFE OPTIMIZATION OF WIND TURBINE BLADE

Satishkumar V Tawade[1], Sachin B Todkar[2], Ashwinikumar S Hade[3]

[1]*Asst. Professor, Mechanical Engineering, NESGOI, Faculty of Engineering, Maharashtra, India.*
[2]*Asst. Professor, Mechanical Engineering, NESGOI, Faculty of Engineering, Maharashtra, India.*
[3]*Asst. Professor, Mechanical Engineering, NESGOI, Faculty of Engineering, Maharashtra, India.*

Abstract

Wind Turbine is one of the most useful non-conventional energy sources in today's energy crisis scenario. But the initial cost of the Wind Turbine plant is very high. The manufacturing cost of the Wind Turbine blade is about 15-20% of the Wind Turbine plant cost. So it is likely to reduce the investment cost of the Wind Turbine blade by maximizing the service life of the Wind Turbine blades. Different types of loads acting on the Wind Turbine blade and consequential stresses developed in blade are studied. The Finite Element model of Wind Turbine blade is analyzed by using ANSYS software. Fatigue stresses are developed on the Wind Turbine blade due to change in wind speed. The maximum wind speed range (from cut-in to cut-out wind speed) is considered for design of blade as well as predicting the fatigue life of the blade. Morrow's equation is used for calculating the fatigue life of wind turbine blade. The parameters which govern the fatigue life of the blade are the chord length; blade length and the twist angle. For optimizing the fatigue life of the Wing Turbine blade, the length of blade, the chord length and the twist angle, these parameters are varied. Constrained Gradient (Steepest ascent method) method is used for fatigue life optimization of the blade. The twist angle is very sensitive to the fatigue life of the blade than the chord length and the blade length. The fatigue life increases exponentially with the increase in twist angle, while there is parabolic relation between the fatigue life of the blade and the chord length. The fatigue life decreases with increase in the blade length linearly. Due to increase in fatigue life of the blade, the cost of the wind turbine plant gets reduced with more reliability.

Keywords: *Fatigue life, Optimization, Wind turbine blade*

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1. INTRODUCTION

Modern wind turbines are fatigue critical machines that are typically used to produce electrical power from the wind. These large rotating machines indicate that their rotating components (primarily blades and blade joints) were failing at unexpected high rates, which led the wind turbine community to develop fatigue analysis capabilities for wind turbines. Hence the prediction of service lifetime is becoming an essential part of the design process. Wind is a form of solar energy. Winds are caused by the uneven heating of the atmosphere by the sun, the irregularities of the earth's surface, and rotation of the earth. Wind flow patterns are modified by the earth's terrain, bodies of water, and vegetation. Humans use this wind flow, or motion energy, for many purposes: sailing, flying a kite, and even generating electricity. The terms wind energy or wind power describes the process by which the wind is used to generate mechanical power or electricity. Wind turbines convert the kinetic energy in the wind into mechanical power. This mechanical power can be used for specific tasks (such as grinding grain or pumping water) or a generator can convert this mechanical power into electricity. So how do wind turbines make electricity? Simply stated, a wind turbine works the opposite of a fan. Instead of using electricity to make wind, like a fan, wind turbines use wind to make electricity. The wind turns the blades, which spin a shaft, which connects to a generator and makes electricity. This aerial view of a wind power plant shows how a group of wind turbines can make electricity for the utility grid. The electricity is sent through transmission and distribution lines to homes, businesses, schools, and so on. The work is divided into two major parts: The stress analysis of the wind turbine blade & the optimization of the wind turbine blade for maximum fatigue life.

2. DESIGN OF WIND TURBINE BLADE

Literature survey for structural analysis for wind turbine blade is carried out. It is found that wind turbine blade is treated as cantilever to find out various stresses acting on it. Blades are subjected to various stresses developed due to various static forces and moments. Stresses acting on the wind turbine blade are varying in nature as turbine blade rotates. Design of wind turbine blades involves static, dynamic as well as fatigue analysis. The static forces are thrust, tangential forces and gravity force. Due to these static forces mentioned above, moments are generated. Aerodynamic moments are also acting on the wind turbine blade. The fatigue stresses are developed due to variation in wind speed and wind properties. The fatigue analysis causes of the fatigue stresses, the relation of these fatigue stresses with the fatigue life of the blade. The dynamic analysis of wind turbine involves the effect of the gyroscopic forces on the wind turbine blade and the study of the modal analysis of the wind turbine blade.

2.1 Static Forces acting on wt Blade

It is found that wind turbine blade is treated as a cantilever to find out various forces acting on it. Blades are subjected to various static forces and moments. Forces acting on the turbine blade are varying in nature as turbine blade rotates. The aerodynamic forces are of varying in nature, as the wind speed is not constant in lateral as well as in longitudinal direction. Design of wind turbine blade involves static, dynamic as well as fatigue analysis. The static forces are, Thrust or Normal force (FN), Tangential force (FT), Gravitational force. (FG), Centrifugal force. (FC), Reaction forces. ® Thrust force and the gravitational forces create bending stresses in the wind turbine blade in edge wise direction while the tangential forces create the bending stresses in the wind turbine blade in flap wise direction. Centrifugal forces create direct stresses in the wind turbine blade [6].

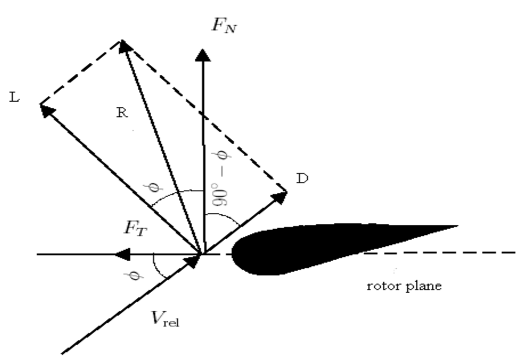

Fig-1: Resolved forces acting on wind turbine blade

3. FATIGUE ANALYSIS OF THE WIND TURBINE BLADE

The fatigue phenomenon occurs on the wind turbine blade due to number of factors. These factors are divided into major and minor parameters [1]. The primary parameters of the wind property affect the fatigue life dominantly while there is not such affect of the secondary parameter on the fatigue life. Therefore here only the mean wind speed and the turbulence of the wind speed are considered while studying the fatigue of the wind turbine blade [5].

3.1 Fatigue

If the loading is of varying nature in terms of mean as well as the amplitude then there is progressive damage to the mechanical components which results in much more earlier failure of component well before its ultimate or yield strength. Such mode of loading is called fatigue loading and the failure is termed as fatigue failure. Machine parts can withstand static stresses of high magnitude but will fail if these stresses fluctuate. Fatigue limit is used for analysis of machine parts under fluctuating loads. Fatigue strength is well below the yield point and the ultimate strength of metal. The lower the magnitude of the load cycle, the greater will be the number of cycles that the material can withstand.

3.2 Causes of Fatigue in Wind Turbines

Cyclic loadings produce progressive damage [7] that can ultimately results in Wind Turbine structural failure. Wind turbines are subject to fluctuating wind and hence fluctuating forces are acting on the blades. Components, which are subject to repeated bending, such as rotor blades, may eventually develop cracks, which ultimately may make the component, break. Thus Wind Turbine is a Fatigue critical machine. Components, which are subject to repeated bending, such as rotor blades, may eventually develop cracks, which ultimately may make the component, break. A historical example is the huge German Growian machine (100 m rotor diameter), which had to be taken out of service after less than three weeks of operation.

3.3 Sources of Wind Turbine Fatigue Loads:

The actual loads that, contribute to fatigue of a wind turbine originate from a variety of sources. These include steady loads from high winds, periodic loads from rotations and gravity, fatigue loads from variations in wind speed, transient loads from such events as gusts, starts and stops etc; and the resonance induced loads from vibrations of the structure. As the wind turbine blade is rotating in vertical plane, the steady and periodic fatigue loads are acting on the wind turbine blade due to gravity effect. The fatigue load is the function of the azimuth angle (ψ). The exercise is carried out for finding out the gravity effect on the stress amplitude of the wind turbine blade. The stress amplitude is very less around 0.324mpa with respect to the mean stress value of 141.025mpa. Thus the effect of the gravity on the fatigue life of the blade is very negligible. As the wind speed is varying from time to time, the loads acting on the wind turbine blade are also varying and ultimately the stresses acting on the wind turbine blade are also changing, this lead to the fatigue of the wind turbine blade. The stresses developed in the wind turbine blade are minimum when the wind speed is cut-in wind speed, while the stresses developed in the wind turbine blade are maximum when the wind speed is cut-out wind speed. So for safer design purpose, the maximum stress amplitude is considered.

3.4 Fatigue Life Calculator

The stresses acting on the wind turbine blade are obtained from the Finite Element Analysis software (ANSYS). The maximum stress is obtained when the blade is rotating at cut-out wind speed while the minimum stress is obtained when the turbine is rotating at the cut-in wind speed. These obtained stresses are used to calculate the stress amplitude (σa). The stress based fatigue analysis criteria is used for determining the fatigue life of the wind turbine blade. The fatigue life of the wind turbine blade is obtained by using the Morrow's equation. Morrow suggested that the monotonic yield and ultimate strength are not appropriate for describing the fatigue behavior of a material. Morrow suggested that the stress amplitude plus mean stress could never exceed the fatigue strength coefficient Sf'. The fatigue strength coefficient is the fatigue strength of the material at one reversal. The b is the slop of the line joining the endurance strength on amplitude axis to fatigue strength coefficient on the mean stress axis. The value of b varies from -0.04 to -0.15 for metals [3].

$$\sigma_a = (\sigma_f^{'} - \sigma_m) \times (2N_f)^b$$

3.5 Mechanical Power Extracted from wt Blade

As the basic criteria of the optimization in this project work is that there should not be the compromise between the fatigue life of the wind turbine blade and the power extracted from the wind turbine blade, the power factor plays important role in the constraint of optimization program. The power obtained from the wind turbine blade is due to the torque developed along the blade. The elemental torque produced due to the normal forces is given by The total power extracted from the wind turbine blade from length zero to the length of blade is given by the integration of the above equation

$$P = \int_0^R dP = \int_0^R (1/2).\rho.B.(U_{rel})^2[Cl \sin\Phi - Cd \cos\Phi](c.r.dr)$$

3.6 Dynamic Analysis of the Wind Turbine Blade

Dynamic analysis of the wind turbine deals with the study of the gyroscopic effect on the wind turbine blade and the modal analysis of the wind turbine blade. Other than static and fatigue analysis, the study has been done on the dynamic analysis of the wt blade. In the dynamic analysis, the gyroscopic force is considered along with the fatigue forces. When the turbine turns to face the wind, the rotating blades acts like a gyroscope. As it is pivot, gyroscopic precession tries to twist the turbine into a forward or backward somersault. This places a limit on how fast the rotor may be pivoted about a vertical axis. . This yaw rate is limited by the strength of materials; therefore, the blades, shafts, and bearings must be designed with this requirement in mind. When the rotor is spinning, on the other hand, as this same pivoting is started from east–west to north–south, the bearings of the vertical axis have to exert a strong torque about the north–south direction. This torque must be transmitted through the horizontal axle and its bearings, the blades, and also by the roots of the blades near the hub to the main mass of the blades. This cyclic twisting can quickly fatigue and crack the blade roots, hub and axel of the wind turbine. For this and other reasons, all those members must be strong. It is helpful to have the blades made of a light yet sturdy material. The lighter the gyroscope spinning at a certain speed, the easier it is to pivot it. The detail study of the gyroscopic effect is out of the scope of this project work. Dynamic analysis deals with the study of the natural frequency of the material and to take the corrective actions to avoid to matching of this natural frequency with the frequency of the excitation forces. This is because as these two frequencies match, the material vibrates with large amplitude resulting in catastrophic failure of the material.

The excitation force come from the wind speed, change in the wind speed and wind direction, gravitational force as well as gyroscopic force. The natural frequency of the blade is kept as low as possible. The twisting of the blade tip affects the free vibration of the blade in such a way to decrease Eigen values. This means that twisting decreases the probability of reaching the resonant frequency.

3.7 Environmental Factors Affecting the Blade Life

Dust circulation in open fields such as those found in the project area comes from airflow over loose dust particles on open ground. Wind turbines extract energy from the wind through the aerodynamics of the blades. The rotors would be located between 65 feet to 115 feet (under the lower end scenario) above ground level and ground level airflow disturbance would be negligible. Furthermore, the wind speed downwind of the rotor is slower than wind speed upwind of the rotor, meaning that dust circulation in the area would possibly even decrease. Hence it is assumed that the wind is clean and clear in this project work. In case of gust or disturbed air flow, the wind turbine blade faces the impact of dust particles, results in damage of the blade surface. This would ultimately results in decrease in fatigue life of the blade and decrease in power extracted from the wind turbine. But, Today's wind turbine blades have sufficient surface strength to withstand the effect of dust particles. The moisture content in the environment reacts with the metal and corrodes metal, resulting in decrease in the strength of material. The aluminum is a good corrosion resistant material. The large wind turbine blades are made up of composite material. The stresses developed in the composite materials due to moisture and the temperature, are very negligible. Hence the effect of the moisture in the wind does not affect on the fatigue life of the wind turbine blade. Studying these environmental parameters, the standard properties of the clean wind are considered in this project work.

4. FINITE ELEMENT ANALYSIS

The finite element method is used for calculating the structural analysis, modal analysis, thermal analysis of the engineering component. ANSYS is a Finite Element Tool (software), which is used in this project to calculate the stresses. The wind turbine blade is considered as a cantilever. As the thickness of the wind turbine blade is very less than the length and the cross section of the blade the plane stress condition is assumed. For that, the shell-63 which is a 4-noded element is used. The centrifugal forces, the gravity force, the aerodynamic normal force and tangential forces are applied to the blade. The displacement of all the nodes at the root of the blade is fixed. The total number of nodes generated is 8686, while the total number of elements generated is 8600.The structural error is 5.4875% while up to 15% structural error is allowable for better results. The equivalent stresses are considered for design considerations as the material used for the blade is Aluminum. The material properties are Modulus of elasticity is 71000 N/mm² & Poisson's ratio is 0.33. The element used for meshing of the FE model is SHELL 63. It is the 4-noded 2-D element. The finite element model is parametrically defined in terms of the chord length (C), the length of the blade (L) and the twist angle (Φ). The loading of the aerodynamic loads are also applied to the model parametrically depending upon the chord length (C), the length of blade (L), the twist angle (Φ), and the wind velocity (V). As the material is ductile material, the equivalent stress is considered for design purpose. In my project work, the stresses obtained from the Beam Element Method (BEM theory) are applied to the Finite Element model instead of the pressure coefficient method. The geometrical model is examined for the same wind speed of 50m/s. The number of nodes generated 8686. The number of the elements generated 8600. The structural error generated 5.4875%.

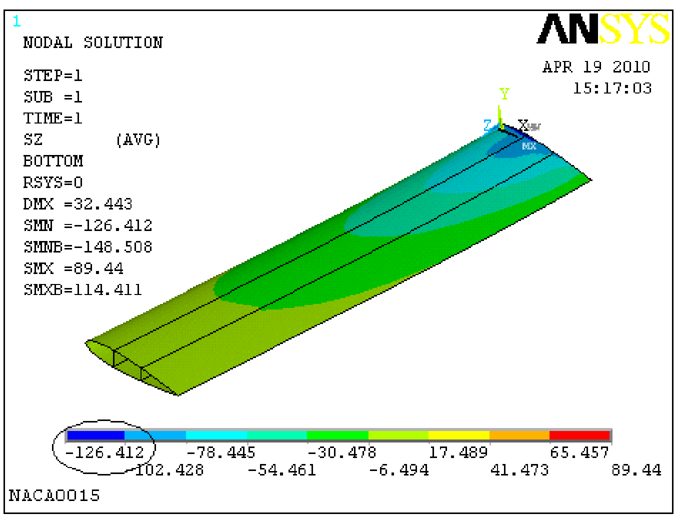

Fig-2: Compressive stress pattern on upper surface of wind turbine

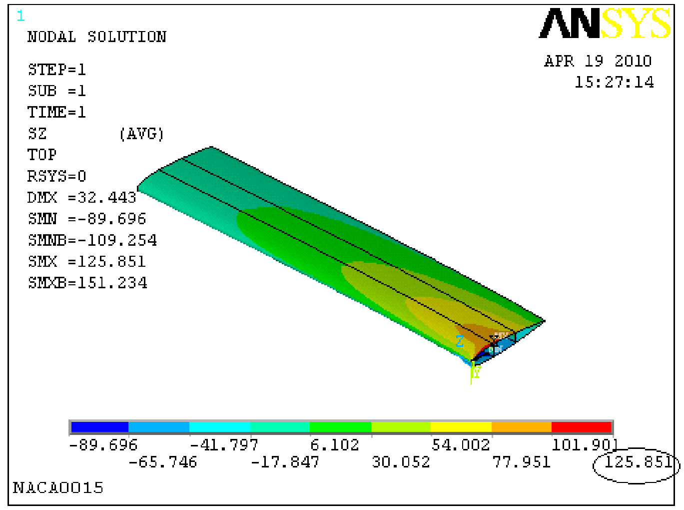

Fig-3: Tensile stress pattern on lower surface of wind turbine

5. FATIGUE LIFE OPTIMIZATION OF WIND TURBINE BLADE.

Maximize the fatigue life (N) of the wind turbine blade which is under the fatigue stresses due to change in wind speed. Create a model of wind turbine blade such that the fatigue life of the wind turbine blade is optimum without affecting the power (P) extracted from the wind turbine plant. Before we precede for fatigue life optimization of the wind turbine blade by varying the three parameters simultaneously, the effect of individual parameter on the fatigue life of the wind turbine blade is studied

5.1 Effect of Variation of Chord Length on Fatigue Life of Wind Turbine Blade:

The length of blade is 8000 mm, the twist angle is 15 º, Blade material: aluminum, Cut-in wind speed is 5 m/s, Cut-out wind speed is 25 m/s

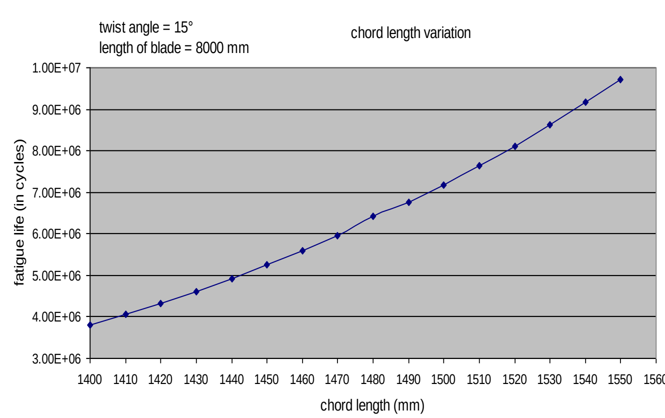

Fig-4: Graph of chord length variation

The fatigue life increases with increase in chord length parabolic ally. There is a second order relationship between the fatigue life and the chord length.

5.2 Effect of Variation of Blade Length on Fatigue Life of Wind Turbine Blade:

The chord length is 1400 mm, the twist angle is 15º, Blade material is aluminum, Cut-in wind speed is 5 m/s, Cut-out wind speed is 25 m/s

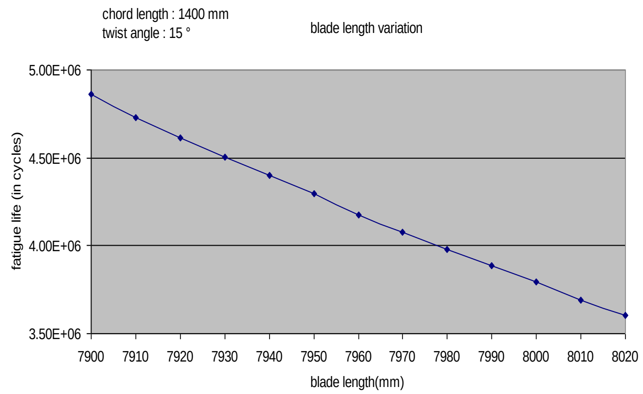

Fig-5: Graph of blade length variation

The fatigue life of blade is inversely proportional to the blade length. There is a linear relationship between the fatigue life of the blade and the blade length.

5.3 Effect of Variation of Twist Angle on Fatigue Life of Wind Turbine Blade

The chord length is 1400 mm, the blade length is 8000 mm, Blade material is aluminum, Cut-in wind speed is 5 m/s, Cut-out wind speed is 25 m/s

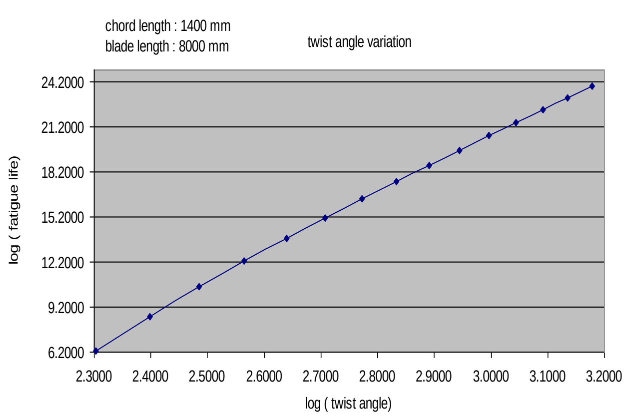

Fig-6: Graph of twist angle variation

The graph of log (twist angle) verses log (fatigue life) gives a straight line indicates that the fatigue life varies exponentially with the twist angle. The twist angle plays an important role in design of fatigue life as well as the power extracted from the wind. There is an optimum value of twist angle at which both the fatigue life and the power extracted satisfies the design.

5.4 Effect of Variation in RPM on the Fatigue Life of the Wind Turbine Blade

The rotation of the wind turbine blade generates the centrifugal forces which act racially outward. The axial stresses are developed due to this force. The effect of change in the RPM of the wind turbine blade on fatigue life of the blade is studied.

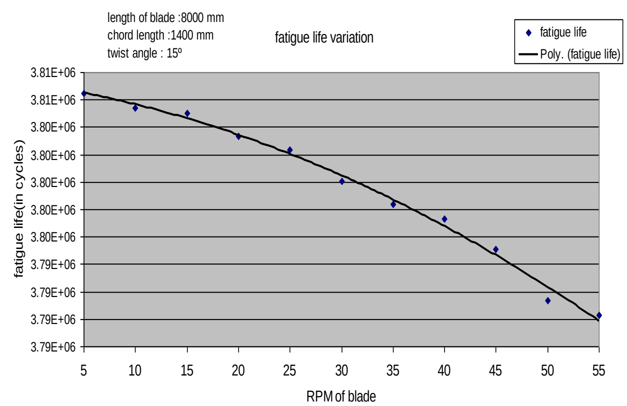

Fig-7: Graph of RPM variation

The graph shows the fatigue life decreases with increase in the RPM of the blade parabolic ally.

5.5 Results and Discussion

The twist angle is an important parameter which governs the fatigue life of the blade as well as the power extracted from the wind turbine. The fatigue life increases with increase in chord length linearly while the fatigue life decreases with increase in the blade length parabolic ally. The effect of change in RPM of blade on fatigue life is negligible. The fatigue life decreases from 3.81e6 to 3.79e6 with wide change (from 55 RPM to 5 RPM) in RPM of blade.

5.6 Optimization of Fatigue Life of Wind Turbine Blade

The main constraint of this optimization is the power output obtained from the modified blade dimensions should not be less than the specified power output P*. The ANSYS software is used for calculating the stresses on the blade while fatigue life calculator is used for calculating the fatigue life of the blade. The Gradient based (steepest ascent) optimization program is used for redesigning the parameters of the blade such that the fatigue life of the blade goes to maximum [10]. The initial dimensions of the blade are The blade length (L):8000mm,The chord length (C):1500mm,The twist angle (Φ):12° The wind properties are Cut-in wind velocity: 5 m/s, Cut-out wind velocity: 25m/s, Rated wind velocity: 22m/s, Density of clean air: 1.2 kg/m3 , RPM of the wind turbine blade: 45 rpm. The batch program is run up to 19 iterations. The fatigue life is maximized from 3.21472*105 cycles to 4.0458436* 10 7 cycles. The variations of the blade length (L); chord length (C); and the twist angle (Φ) are plotted on the following graphs. The fatigue life and power extracted variation are also plotted on the graph. As the Gradient based optimization has a drawback of finding out local optimum, the initial values of the parameters must be defined with lot of care. So, the basic design or the rough design is necessary before going for the optimum design of any component. The local maxima obtained by this Gradient method is not necessary be the global maxima. The solution obtained from this method is maximum or minimum within the local domain near the initial guess values.

Table -1: Optimization iterations

Iterations	C (mm)	L(mm)	Theta(in degree)	Fatigue life(cycles)	Power(kw)
1	1500	8000	12	321472.2188	996.517151
2	1500.105713	7999.962402	12.415361	667450.1875	993.715149
3	1500.273682	7999.878418	12.812836	1253021.75	989.546387
4	1500.674072	7999.734863	13.191434	2272259.5	984.597778
5	1501.394043	7999.477539	13.5481	3909090.75	979.312012
6	1502.62146	7999.037598	13.878074	6374928.5	974.153442
7	1504.604492	7998.326172	14.174754	9833538	969.603577
8	1507.590698	7997.235352	14.43028	14266020	966.125732
9	1511.876099	7995.663086	14.637288	19412650	964.172058
10	1517.549683	7993.53125	14.791011	24702468	963.981689
11	1524.735962	7990.836914	14.891914	29527282	965.6922
12	1533.223022	7987.626465	14.945732	33420016	969.097961
13	1542.811523	7984.010742	14.962053	36270856	973.911987
14	1553.149414	7980.08252	14.951068	38186660	979.719788
15	1563.924438	7975.94043	14.921722	39318212	986.153381
16	1574.974854	7971.689941	14.881458	39981284	992.972229
17	1586.056152	7967.358887	14.834703	40280800	999.929077
18	1597.246582	7963.153809	14.78491	40422800	1007.047852
*19	1608.401978	7958.930176	14.733573	40458436	1014.167236
20	1619.491577	7954.700195	14.681711	40441460	1021.24762
21	1630.406372	7950.455078	14.629831	40344080	1028.206299

*The iteration no. 19 gives the optimum value of fatigue cycles.

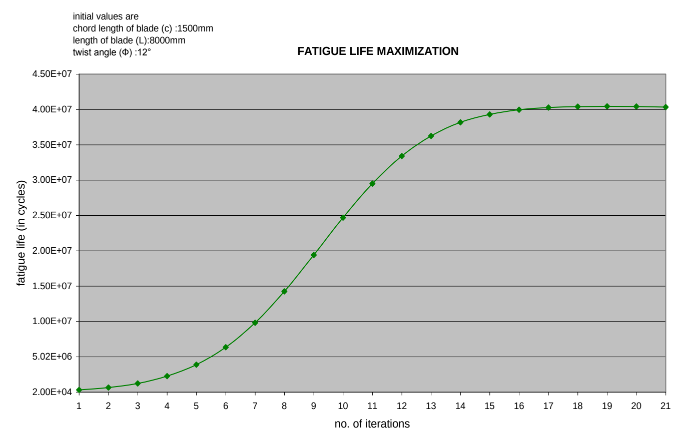

Fig-8: Graph of fatigue life variation

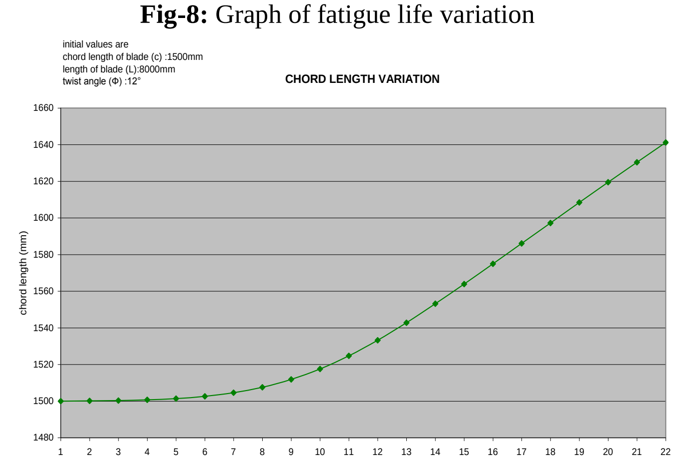

Fig-9: Graph of chord length variation 1

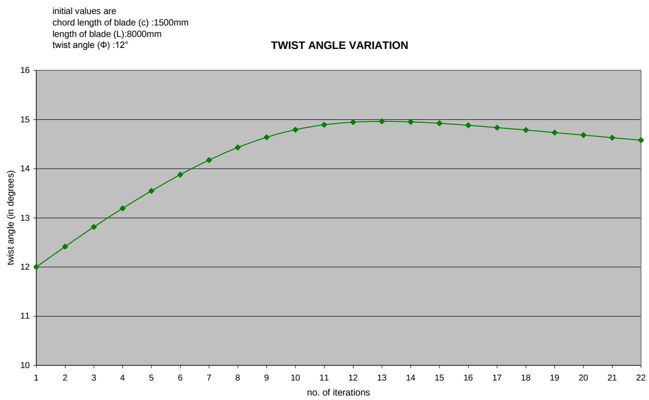

Fig-10: Graph of twist angle variation1

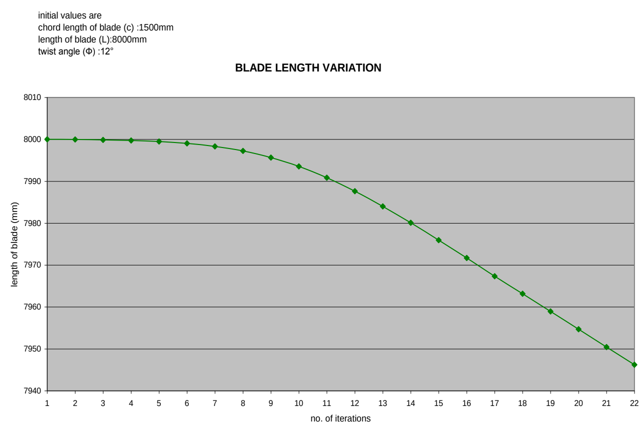

Fig-11: Graph of blade length variation1

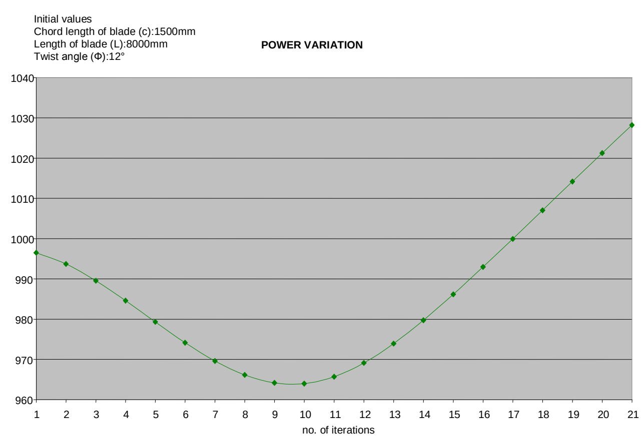

Fig-12: Graph of power output variation 1

6. CONCLUSIONS

The 4-noded SHELL 63 element proved to be a successful finite element in the analysis of the three-dimensional structures, as it takes into accounts six degrees of freedom at each element node. For the blade configurations, the maximum stress occurs at the blade root, fixed to the rotor hub, so it is the most critical section which must be taken into consideration when designing a rotor-blade fixation. The effect of self weight on the fatigue life of the blade is very less as compared to the effect of change in wind speed on the fatigue life of the blade. The stresses are seemed to be static than fatigue. Figure no 4 shows variation of fatigue life of wind turbine blade due to exclusive change in chord length of the blade. The fatigue life increases with increase in the chord length of the blade. There is a second order relationship between the fatigue life of the blade and the chord length of the blade. Figure no 5 depicts the effect of change in fatigue due to exclusive change in the blade length. The fatigue life of the blade is inversely proportional to the blade length. There is an exponential relationship between the fatigue life of the blade and the twist angle of the blade. This is shown in figure no 6. Figure no.10 shows the variation of twist angle, first increases from 12º to 14.7335º then decreases to 14.6298º. Thus there is an optimum value of the twist angle at which the stresses are minimum which gives the maximum fatigue life. For this particular case, the fatigue life increases from 3.21472e5 to 4.0458436e7 with 7.2% increases in chord length, 0.51% decrease in length of the blade and 22.75% increase in twist angle. The figure no. 7 shows the variation of the fatigue life of wind turbine blade due to exclusive variation of the RPM of the wind turbine blade. The graph shows that the increase in RPM of the blade from 5 rpm to 55 rpm results in decrease in fatigue life of the blade from 3.81e6 fatigue cycles to 3.79e6 fatigue cycles. Thus there is very negligible effect of the change in RPM of the rotation of the blade on the fatigue life of the wind turbine blade. As the Gradient Optimization Technique gives the local optimum solution, the rough design of WT blade is necessary for initial guess of the governing parameters such as initial values of chord length (C), length of blade (L) and the twist angle (Φ).

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