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Research Article

Meta Heuristic Method for the Design Optimization of a Wind Turbine Blade

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Abstract

The cost of wind turbine is the important criteria to make the wind energy competitive. The manufacturing cost of wind turbine blade is about 15-20% of wind turbine production cost. The expenses of innovations in the design of turbine blades represent the small amount of overall cost of wind turbine production. Small changes in the structural model or the use of suitable composite materials or better techniques of manufacturing will lead to greater profits. When designing a wind turbine, the goal is to attain the highest possible power output under specified atmospheric conditions. From the technical point of view, these depend on the shape of the blade. The change in the shape of the blade changes dynamic and mechanical properties of wind turbine. This paper presents the design, selection and optimization of a turbine blade among four different materials. The blade is modeled by using Pro/E and analyzed by standard FEA software ANSYS for different materials. In order to continuing the efforts for innovation, optimization is performed by using a meta heuristic method Ant Colony Optimization (ACO) and the results are satisfactory.

Keywords: *Ant Colony Optimization (ACO), Energy Cost, Meta heuristic methods, Wind Turbine, Blade Design, Blade Energy Momentum (BEM).*

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1. Introduction

For wind energy to become competitive with respect to other sources of energy, the initial consideration must be to reduce the cost of energy from wind power. In modern wind power researches, how to minimize the cost of a wind turbine per unit of energy is an important task. The shape of the rotor blades plays a decisive role in determining the overall aerodynamic performance of a horizontal axis wind turbine. The aerodynamic profiles of wind turbine blades have crucial influence on aerodynamic efficiency of wind turbine.

G.B. Eke1, J. Onyewudiala (2010), studied optimization of Wind Turbine Blades. They consider, optimizing the blade of wind turbines with respect to maximizing the energy yield of wind turbine using Genetic Algorithm approach. The analysis of aerodynamic loads in our cases is based on the Blade Element Momentum method (BEM) (Sunith Fernando,2001 and Grant Ingram, 2011). Nitin Tenguria et.al (2010) has designed by glauert's optimal rotor theory of horizontal axis wind turbine. In this analysis of designed blade is done in flapwise loading. Henrik Broen Pedersen et.al (2003) has studied rotation rates and power coefficients of miniature wind turbine rotor models manufactured using NACA profiles were investigated. Ali Vardar, Ilknur Alibas (2008) have identified design requirements for the rotor is severe because the blade will be highly loaded. Analyses of the design show that both the strength and dynamic requirements can be met and the blades are manufactured.

Juan M´endez and David Greiner (2007) showed a method to obtain optimal chord and twist distributions in wind turbine blades by using genetic algorithms. K. Turgut Gürsel et.al (2012) this paper presents vibrations are taken into consideration in design phases in order to avoid resonance. Gunner C. Larsen et.al (2002) have identify natural frequencies, damping characteristics and mode shapes of wind turbine blades of modal analysis. Different experimental procedures have been considered and the most appropriate of these has been selected. Nitin Tenguria, N.D. Mittal, Siraj Ahmed (2010) studied over all aerodynamic performance of horizontal axis wind turbine. For designing blade, Blade Element Momentum Theory (BEMT) is used and a computer program is developed to automate the complete procedure.

2. Blade Materials

Small turbine blades are made of steel or aluminium. These materials have heavier weight. Less weight materials requirement for wind turbine components making overall cost to be lower. The blade is made of composite materials containing more than one bonded material, each material with different properties. One of the materials, called the reinforcing phase is embedded in the other material of the matrix phase.

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If the composite is designed and fabricated correctly, it combines the strength of the reinforcement with the toughness of the matrix to achieve a combination of desirable properties not available in any single conventional material.

The main advantage of composite materials is the potential for a high ratio of stiffness to weight. Composites used for typical engineering applications are advanced fibre or laminated composites, such as fibreglass, glass epoxy, graphite epoxy and boron epoxy.

Longer blades require another materials to be applied, usually carbon-based composites. Carbon fibre composites allow to lower blade’s mass (from 20 to 18 T at 61.5m long blade). A carbon-based composite also allows to reconstruct older blades made of fibre glass reducing mass and increasing its stiffness. However, use of carbon materials requires increased accuracy and makes manufacturing costs to be higher.

In this work four materials Kelvar 149, Technora, Glass E and Glass S are taken as blade materials. The properties of these materials are listed in Table 1. Turbine blade is modelled and analysed for these material and best material is selected for the blades.

Table. 1. Investigated composite material

Material	Elastic modulus (Gpa)	Density (kg/m^3)
Kevlar 149	179	1470
Technora	70	1390
Glass E	76	2540
Glass S	88	2540

3. Modeling of Wind Turbine Blade

The model of wind turbine blade with a NACA 4412 airfoil where the chord length and blade angle are varied with the coordinates and is created using pro/E Fig 1. The blade is divided to 15 cross sections, nodal coordinates and other parameters are from (DNV/Risø Second Edition and XFoil-copyright, 1995-2009).

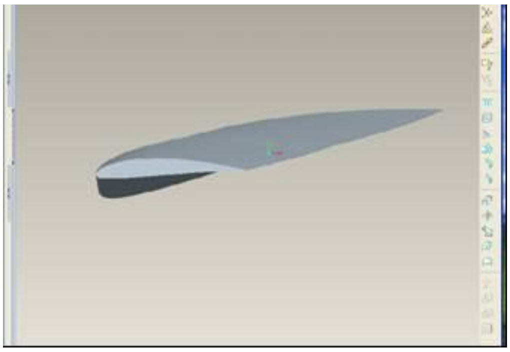

Fig 1. Modelling of wind turbine blade

Analysis of wind turbine was done in by using a standard FEA package ANSYS Fig 2. The natural frequencies of the blade made of different composite materials are calculated as shown in Table 2.

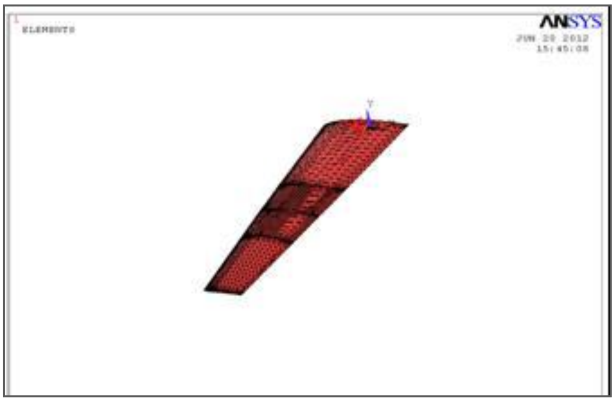

Fig.2 Meshing Model of wind turbine blade.

Table. 2. Natural frequencies of blade for different materials

No mode shape	Frequency[Hz]			
	Glass S	Glass E	Technora	Kevlar 149
1	1.6728	1.5546	2.0168	3.1361
2	6.4494	5.9936	7.7756	12.091
3	12.723	11.824	15.339	23.853
4	15.679	14.571	18.903	29.394
5	20.042	18.626	24.164	37.574
6	29.031	26.979	35	54.425
7	39.25	36.476	47.321	73.583
8	45.656	42.429	55.644	85.593
9	47.036	43.712	56.708	88.181
10	60.773	56.478	73.27	113.93

4. Stress Analysis of Wind Turbine Blade

A static analysis calculates the effects of steady loading conditions on a structure, while ignoring inertia and damping effects, such as those caused by time-varying loads.In this analysis stresses and deflections are estimated of different composite materials.

4.1 Methodology

The analysis of aerodynamic loads in this case is based on the blade element momentum method. The input data are the free stream velocities, geometry of aerodynamic profiles used in blade with C_l and C_d as the aerodynamic lift and drag coefficients unique for each of them. In literature they are represented as $C_l(\alpha)$ and $C_d(\alpha)$ which means they depend on the angle of attack alpha.

Blade element momentum method is an iterative method, at the beginning the value of axial retardation coefficient also is assumed to be zero, the results of simulation calculated are compared with the initial value. If their values differ the calculation is repeated with the received axial retardation coefficient as initial value. If they agree calculation is finished. Below equations 1, 2, 3, 4and 5 are used in BEM method (Sunith Fernando et.al, 2001 and Grant Ingram ,2011).

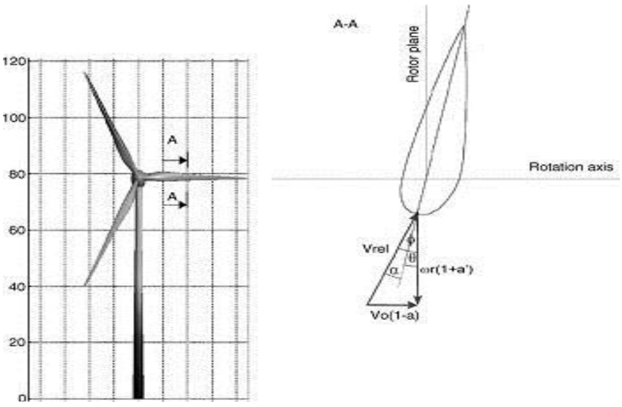

Fig.3. Wind Velocity Components

Relative velocity of wind is calculated from the equation:

$$V_{rel} = \frac{w \times r \times (1 + a')}{\cos\phi} \tag{1}$$

Where ω is angular velocity, a` is tangential interface factor, Ø is angle of relative wind to plane rotation.

The aerodynamic loads are expressed in the following forms:

Lift: $$L = \frac{1}{2} \times \rho \times V_{rel}^{2} \times A \times C_l \tag{2}$$

Drag: $$D = \frac{1}{2} \times \rho \times V_{rel}^{2} \times A \times C_d \tag{3}$$

Thrust: $$F_N = L\cos\phi + D\sin\phi \tag{4}$$

Torque: $$F_T = L\sin\phi - D\cos\phi \tag{5}$$

Where V_{rel} is relative velocity, ρ the density of the air, A is frontal area of blade and c is is the chord of aerodynamic profile.

The aerodynamic loads as shown in table 3 are applied on the aerodynamic centre of the each stations and the modal of ANSYS is in Fig 4. The corresponding stresses and deflections are calculated and shown in table 4.

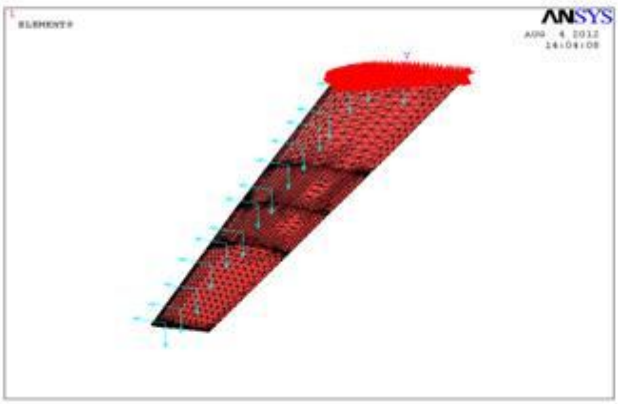

Fig.4. Loads on the Blade

Table. 3. Thrust and Torques of all Stations

Blade Station	Radius	C_l	C_D	F_N(N)	F_T(N)
1	0.15	1.4	0.039	27.54	29.43
2	0.2	1.4	0.039	40.44	32.27
3	0.25	1.38	0.039	54.66	34.6
4	0.3	1.38	0.029	70.72	37.96
5	0.35	1.37	0.024	87.6	40.51
6	0.4	1.31	0.022	101.45	40.73
7	0.45	1.28	0.019	116.6	41.5
8	0.5	1.22	0.016	127.81	40.92
9	0.55	1.2	0.013	141.54	41.1
10	0.6	1.12	0.0093	146.06	38.77
11	0.65	1.04	0.01	147.48	35.44
12	0.7	0.95	0.009	144.24	31.64
13	0.75	0.87	0.008	139.19	27.9
14	0.8	0.78	0.007	129.45	23.75
15	0.85	0.68	0.0065	115.18	19.22

Table. 4. Stresses and Deflections of blade for different materials

Material	Stress (Mπα)	Deflection (μμ)
Kevlar 149	268.411	5.69
Technora	268.46	14.56
Glass E	267.69	13.38
Glass S	267.69	11.55

5. Selection of Composite materials of Wind Turbine Blade

The study yields the estimation of the influence of composite materials, which the blade is made, on dynamical properties of wind turbine blades. The composite materials of investigation are presented in Table 1. From the Tables 4 and 2 it is observed that the natural frequency high in Kevlar 149 material and deflections are less in Kevlar 149 material.

6. Optimization of Wind Turbine Blade

The cost of energy of wind turbine rotor depends upon the cost of rotor and annual energy production. Cost of rotor depends upon the weight of the rotor and a well designed wind turbine with a low cost of energy always has an aerodynamically efficient rotor. Therefore, the rotor design plays an important role for the whole design procedure of a wind turbine. Hence the objective function is restricted to the cost from the rotor. Thus the objective function is given in equation 6.

$$Minimize..Z = \frac{C_{rotor}}{AEP} \tag{6}$$

Where Z is the cost of energy of a wind turbine rotor;
C_{rotor} is the total cost for producing, transporting and erecting a wind turbine rotor
AEP is Annual Energy Production.
Therefore the total cost of a rotor, Crotor, is a relative value defined in eq 7.

$$C_{rotor} = b_{rotor} + (1 - b_{rotor})W_{rotor} \tag{7}$$

Where Wrotor is the weight parameter of the rotor, b_{rotor} is chosen to be 0.1 (G.B.Eke and J.I.Onyewudiyala, 2010).

The fixed part of the cost for a wind turbine rotor $b$rotor is chosen to be 0.1. In this work, the weight parameter is calculated from the chord and mass distributions of the blades. Supposing that a blade can be divided into n cross-sections, Wrotor is estimated as

$$W_{rotor} = \sum \frac{M_i \times C_{i,opt}}{M_{tot} \times C_{i,or}} \tag{8}$$

Where M_i is the mass of the $i-th$ cross – section of the blade; $C_{i,\text{opt}}$ is the averaged chord of the $i-th$ cross section of the optimized blade; $C_{i,\text{or}}$ is the averaged chord of the $i-th$ cross section of the original blade; M_{total} is the total mass of the blade.

The power curve is determined from the Blade Element Momentum (BEM) method. In order to compute the Annual Energy Production (AEP), it is necessary to combine the power curve with the probability density of a wind (i.e. the Weibull distribution)[1]. The function defining the probability density can be written in the following form [(G.B.Eke and J.I.Onyewudiyala, 2010):

$$f(V_i < V < V_{i+1}) = \exp\left(-\left(\frac{V_i}{A}\right)^K\right) - \exp\left(-\left(\frac{V_{i+1}}{A}\right)^K\right) \tag{9}$$

Where A is the scale parameter, K is the shape factor and $[m/s]$ is the wind speed.

Hence the shape factor is chosen to be $K = 2$ corresponding to the Rayleigh distribution. If a wind turbine operates about 8760 hours per year, its AEP can be evaluated as (G.B.Eke and J.I.Onyewudiyala, 2010):

$$AEP = \sum_{i=1}^{n-1} 1/2 \times P(V_{i+1}) \times P(V_i) \times f(V_i < V < V_{i+1}) \times 8760 \tag{10}$$

Where (Vi) is the power at the wind speed of Vi.
The expression for power P is given by

$$P = 0.5\dot{m}V_o = 0.5\rho A_o V_o^3 \tag{11}$$

Where $\dot{m}$ $[m^3/s]$ is the mass flow rate; $V_0[m/s]$ is the wind speed ; $\rho[kg/m^3]$ is the density of the air; and $A_0[mm^2]$ is the area of the wind speed

To obtain a reliable optimization of a wind turbine blade, the geometry of the blade needs to be represented as much as possible. This requires a great number of design variables. On the other hand, the selection of more design variables in the optimization procedure requires more complex solution algorithm and computational time. The rotor shape is controlled by the rotor diameter, chord, twist, relative thickness. The airfoil characteristics are the lift and drag dependency on the angle of attack. Based on a general chord distribution, a cubic polynomial is used to control the chord distribution. Because of the multiple distribution characteristics, a spline function is used to control the distributions of twist angle and relative thickness. The constraints of the design variables are

$$C_{\min} \le C \le C_{\max}; \beta_{\min} \le \beta \le \beta_{\max}$$

Where $C_{\min}$ is the lower limit and $C_{\max}$ is the upper limit of chord, and $\beta_{\min}$ is the lower limit and $\beta_{\max}$ is the upper limit of twist angle and of the blade respectively.

As a usual procedure for optimization problems, we have one objective function and multiple constraints. To achieve the optimization, the ACO code in C-Program is written for the objective function of the wind turbine.

7. Ant Colony Optimization

ACO algorithms are approximate algorithms used to obtain good enough solutions to hard Combinatorial Optimization problems in a reasonable amount of time. Ant Colony Algorithms are typically used to solve minimum cost problems. We may usually have N nodes and A undirected arcs. The two points in which we want to establish a minimum cost path are called the source and destination nodes. In the Ant Algorithms, the source and destination nodes are deemed the nest and food source. A detailed explanation on ACO can be found in any of literature (D. Sameer Kumar et.al, 2007&2011)

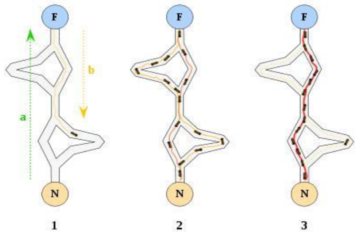

Fig. 5. Ants Forgoing Behaviour

The ants evaluate the cost of the paths they have traversed, thus modulated the deposited pheromones. The shorter paths will receive a greater deposit of pheromones. An evaporation rule will be tied with the pheromones, which will reduce the chance for poor quality solutions. In General, the ACO approach attempts to solve the optimization problems by repeating the following two steps.

- Candidate solutions are constructed using a pheromone model that is a parameterized probability distribution over the solution space.

- The candidate solutions are used to modify the pheromone values in a way that is deemed to bias future sampling toward high quality solutions.

7.1 Steps for solving a problem by ACO

a) Represent the problem in the form of sets of components or graphs on which ants can build solutions.
b) Define the meaning of the pheromone trails and also define the heuristic preference for the ant while constructing a solution
c) If possible implement a efficient local search algorithm for the problem to be solved.
d) Choose a specific ACO algorithm and apply to problem being solved
e) Tune the parameter of the ACO algorithm.
f) Update the solution till the required criterion is met.

8. Results and Discussion

Based on ACO the program written in C-language, the optimum values are observed for different iterations as given in table 5. Figure 6 depicts that the cost of energy of turbine rotor is converged.

Table. 5. Optimum values of the cost of Energy

Iteration no	Chord length	Blade angle
1	0.1679	0.254
5	0.1	0. 219
30	0.1409	0.297
80	0.11358	0.245
140	0.12716	0.271
500	0.12716	0.271

From the execution of the C-program of ACO technique, it is observed that the cost of energy of wind turbine rotor is reduced by 7.5% and Annual Energy Production increased by 5% and the corresponding global optimum values of chord length 0.12716m and blade angle 0.271 radians ie. 15.52^0.

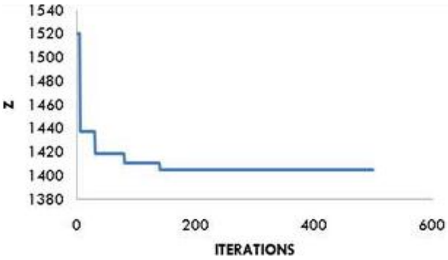

Fig. 6. Graph between no of iterations Vs Cost of Energy of turbine rotor

Conclusions

In this work, Optimization of wind turbine blade of NACA 4412 is carried out. To optimize, the turbine blade various composite materials are modelled and analysed for best material to use for the blade. From the analysis, it is observed that the natural frequencies are high and deflection is less for Kevlar 149 material when compared with other composite materials. For Turbine blade using Kevlar 149 material the blade parameters are optimised to minimise the cost of energy of wind turbine rotor using Ant Colony Optimization approach. From the execution of the C-programme of ACO technique, it is observed that the cost of energy of wind turbine rotor is reduced by 7.5% and Annual Energy Production increased by 5% and the corresponding global optimum values of chord length 0.12716m and blade angle 0.271 radians ie. 15.52^0.

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