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This work studies the fatigue behavior of an optimized composite wind turbine blade of a previous research. It employs methodologies using classical theory, as well as probabilistic and numerical techniques for the study of the blade. Modal Analysis showed that the blade is safe from resonance phenomenon. Fatigue analysis showed that the service lifetime of the blade until failure is about 17 years for the turbine operating speed of 36 rpm, and about 15.8 years for the operating speed of 47 rpm, which are less than the expected life of 20 years by 14.7% and 20.9% respectively.

Keywords: Wind Energy, Composite Materials, Blade Design, Modal Analysis, Fatigue.

1. Introduction

Wind power is an alternative to fossil fuels. Its environmental effect is much less problematic than that of nonrenewable sources of energy. For that reason, wind energy is one of the dominant topics of research nowadays. Research in this field is based on improvement of the efficiency of energy extraction from the wind, reducing the stresses on the rotor blades, and reducing the weight of the blade itself.

2. Problem statement and methodology

The wind turbine blade subject to study in this work is a result of a previous study[1,2)]. The composite material Horizontal Axis Wind Turbine (HAWT) blade was optimized using genetic algorithm to determine the number of layers of the composite laminate, fibers orientation in each layer, fiber volume fractions, and layer thickness. The optimized laminated material resulted in 21-35% stresses reduction, 10-28% blade deformations reduction, and about 25% blade weight reduction, compared to the equivalent aluminum blade for the same wind turbine. The design was based on a static loading only. A specific position for the blade and a wind speed of 10 m/s was used to predict the pressure distribution over the blade. Then this pressure distribution was used for design and analysis. The real situation is that the rotor blade is subject to dynamic loads, due to the variation of wind speeds, directions, intensities, and for the centrifugal effect of the blade rotation. These dynamic loads must be considered because they affect the lifetime of the wind turbine, and that is the point of research in this work; a fatigue analysis for the optimized composite blade following the work made in another research[3)].

Many theories describe the physics of studying the wind turbines. For aerodynamics, there are theory with high fidelity like computational fluid dynamics (CFD), and vortex-wake methods, and lower fidelities like generalized dynamic wake (GDW) and blade element momentum (BEM) theory. Application for CFD technique for example, is very costly. Computational time and cost can be a drawback for using this technique despite its highly accurate results. Special techniques like decreasing the model order can be used to reduce the computational time[4)]. However, CFD results are accurate enough to sacrifice the computational cost for the quality of the simulations. Specially for simulations for a complex topography[5)], dynamic (floating) foundations [6)], or study the effect of any obstacles on the aerodynamics of the turbine[7)]. Also for the structural study, high fidelity method is by using finite element analysis (FEA). It follows the same trend as the CFD, from discretizing the structure into millions of elements, solving for each element using the suitable governing equations, and then assembling the results. Like the CFD, the computational cost for the FEA is very high, however accurate[8,9,10)].

However, the industry requires iterative process for the design, considering all the possible environmental conditions and operating scenarios. With the computational cost of the numerical solutions like CFD or FEA, it is impossible to consider all the cases for this iterative process. The National Renewable Energy Laboratory (NREL) created a Computer-Aided

Engineering (CAE) tool named FAST[11] (Fatigue, Aerodynamics, Structure and Turbulence) which is based on advanced models, derived from the fundamental theory, but with suitable assumptions and simplifications[12]. FAST is a very sophisticated software tool which is used currently in many academic researches and for industry. It has been proven to be accurate and give satisfactory results. In addition to the capability to model very specific cases. For example, it can model the soil-structure interaction for offshore wind turbines[13], undergo coupled simulations for different analyses[14], study the effect of operating scenarios or environmental conditions on the wind turbine like ice-crushing[15], or study the blades and the support structure[16].

For the merits of using the FAST tool, in this work analysis is made using QBlade[17], an open source turbine calculation software with a FAST simulation tool seamlessly integrated into it. The aerodynamic loads are calculated using BEM for a variety of wind conditions, and then a structure analysis is made on an equivalent isotropic model for the wind turbine blade. FAST simulation results in time series for different loads and wind velocities over the wind turbine blade. These time series are used for post-processing on MLife[18], a MATLAB® based tool to estimate the fatigue lifetime of the turbine blade.

3. Simulations

3.1 Case study

As mentioned before, the studied blade is a result of a previous research. The blade main geometrical properties are as follows;

Table 1. Blade baseline design properties[2]

Rotor Diameter, m	19
Hub Radius, m	2.7
Airfoils	NACA 63-2XX Series
Maximum Twist Angle, deg	15^0 at hub section
Minimum Twist Angle, deg	0^0 at rotor tip
Operating Speeds, rpm	35.6 and 47.5

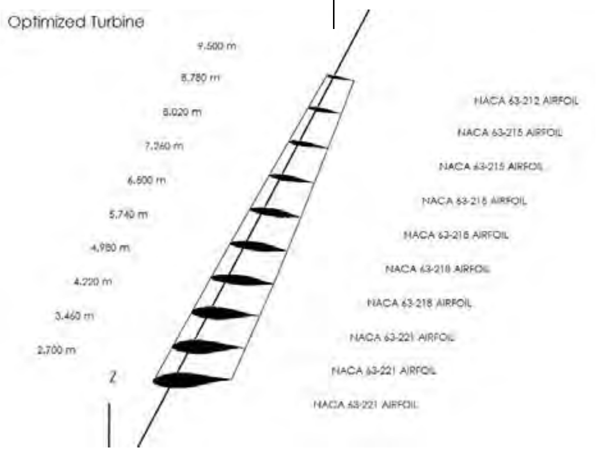

Fig. 1. Effective Part of the Blade

Table 1 gives the baseline design properties of the blade. The effective part of the blade under study is shown in Figure 1.

3.2 Wind field simulation

To compute the dynamic loads on the wind turbine structure, it is necessary to have an environment like that the wind turbine faces. The wind turbine is subject to turbulence, wind shear, and turbine tower effect, so we must create a similar environment by generating a wind field with spatial and tentative variation. A turbulent wind field is generated by the module embedded in the software using the Sandia Method[19] (Also known as Veers Method). Turbulent wind field simulation parameters are defined for the rotor radius, hub height, a mean turbulence intensity of 10%, and mean wind speed of 12 m/s. Simulation is defined for a simulation time of 60s with 0.5s time step. A sample of the simulation results is shown graphically in Figure 2.

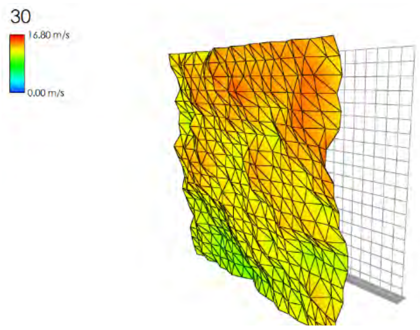

Fig. 2. Turbulent Wind Field Simulation at Time t=30s

The maximum wind speed is 16.8 m/s for the wind field simulation at the shown time step of t = 30s.

The highest wind spectrum frequency in this generated wind field is 0.8333 Hz, and the minimum frequency is 0.0167 Hz. The turbulent wind field is applied over the wind turbine blades; the trailing vortices over the blade tip, and the velocity distribution over the blade length are presented as a color diagram in Figure 3. The results of the simulation are stored in the software for further processing in the structural analysis module.

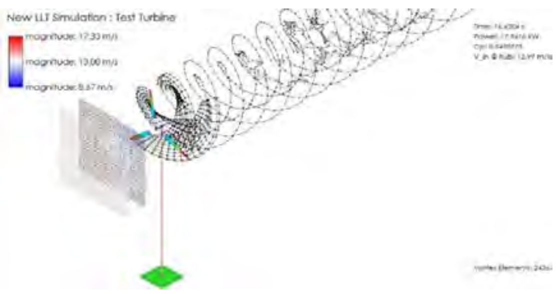

Fig. 3. Wind Field Simulation over the Rotor

3.3 Modal analysis

Before studying the fatigue behavior of the wind turbine blade, a modal analysis must be made to ensure that the blade is safe from the threat of resonance phenomenon. Dynamic analysis has been performed for an equivalent isotropic model to the composite model of the wind turbine blade[20]. Dynamic beam equation[21] (Known as Euler-Lagrange Equation) is used to calculate the natural frequencies of vibration of the blade for the first four modes in all directions, but the most important directions are the edge-wise (In-plane) and flap-wise (Out-of-plane) directions. Table 2 shows the natural frequencies for the wind turbine blade. For illustration, the first and second mode shapes for the flap-wise and edge-wise directions are shown in Figure 4.

Table 2. Natural Frequencies of the First Four Modes in the Flap-Wise and Edge-Wise Directions

Direction	Mode Number	Natural Frequency (Hz)
Flap-Wise	First	3.37
	Second	10.03
	Third	23.13
	Fourth	41.92
Edge-Wise	First	15.30
	Second	51.65
	Third	117.32
	Fourth	213.67

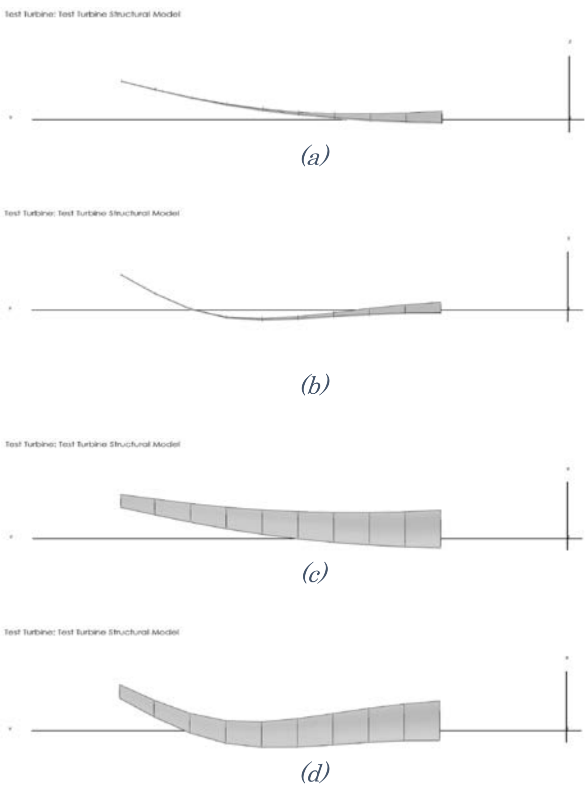

Fig. 4. Mode Shapes of the Wind Turbine Blade (a) First Mode in Flap-wise Direction (b) Second Mode in Flap-wise Direction (c) First Mode in Edge-wise direction (d) Second Mode in Edge-wise direction

Recall that the generated turbulent wind field spectrum maximum frequency is 0.8333 Hz, while the natural frequencies of the blade's first mode in both flap and edge wise directions are 3.37 Hz and 15.30 Hz respectively. These frequencies are far away from the exciting frequency of the wind. So, the blades of the wind turbine are safe from the danger of resonance when the turbine operate at the rated wind speed.

3.4 Fatigue Analysis

Typically, wind turbines are designed to last for at least twenty years of operation. Although structure analysis to the wind turbine can show that the blades are safe under static loads per von-Misses stress, but due to fluctuating loads, the blades are subject to cyclic loading that leads to fatigue in the blades causing failure. Fluctuation of the loads is a result of different wind flow velocities and directions, also due to the centrifugal effects of rotating the blades. That's why fatigue analysis is very important in the process of wind turbines design.

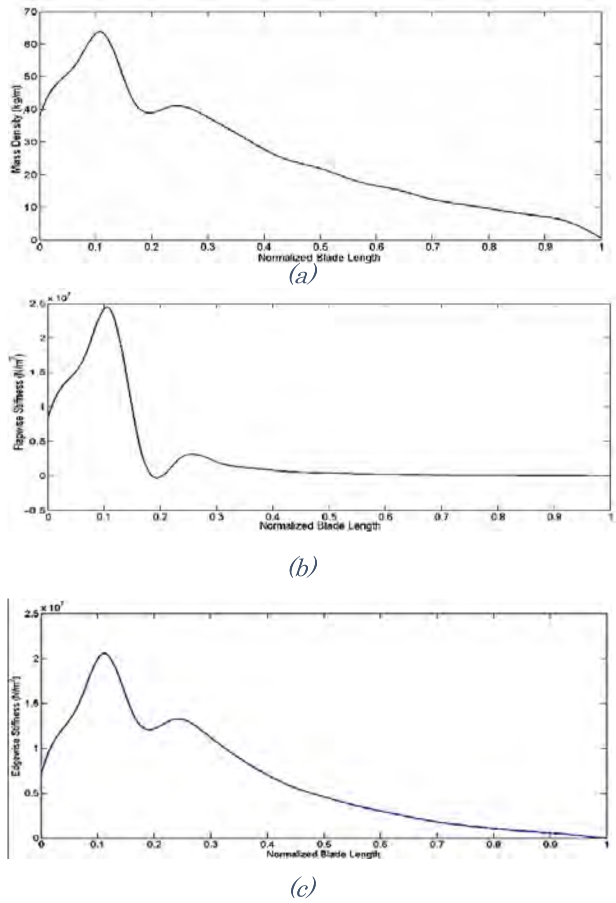

Fig. 5. Mass Properties per Blade Length: (a) Mass (b) Flap-wise Stiffness (c) Edge-wise Stiffness

It is observed that there is a drop in the mass at about 20% of the blade length; this indicates the end of the hub section and the beginning of the effective part of the blade. The change in the cross-section shape from circular part of the hub to airfoil shape of the effective part of the blade results in a change in mass properties.

This also applies for the stiffness distributions.

Fatigue simulation is made for the wind turbine subject to study. It has a 19-m diameter, 100 kW nominal power, and two operating speeds; 36 and 47 rpm[1]. Study was made for both operating speeds to estimate the lifetime for each one. The mass and stiffness distributions are calculated per unit length of the blade. Mass properties of the blade are shown in Figure 5.

FAST simulation parameters are set for a simulation time of 60 s with time step 0.05 s for the operating speed of 36 rpm. The objective of FAST simulation is to obtain time series for wind velocities, loads, and blade deflections over the blade length to be used for further analyses. Then a Fast Fourier Transform (FFT) analysis is performed for each time series to observe the dominant frequencies. Sample time series and their FFT analyses are shown in Figures 6-9.

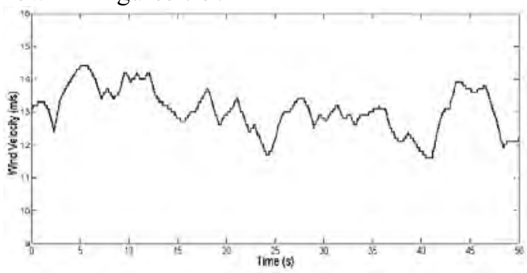

Fig. 6. Total Wind Velocity at Hub Height Time Series

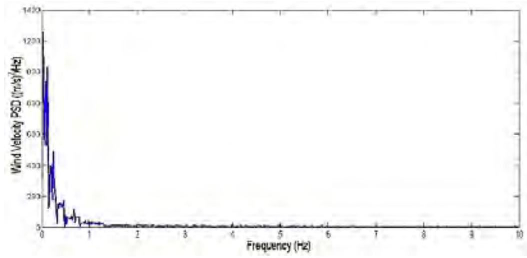

Fig. 7. FFT Analysis for Wind Velocity at Hub Height

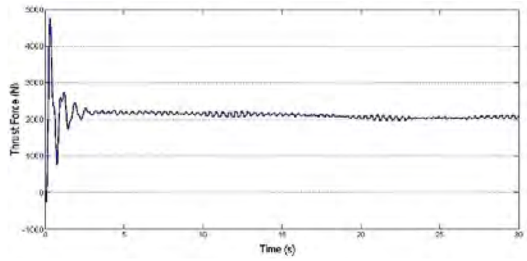

Fig. 8. Rotor Thrust Force Time Series

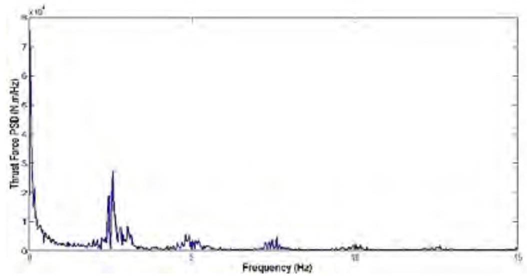

Fig. 9. FFT Analysis for the Thrust Force

From Figure 8, we can observe that the thrust force fluctuates severely for the first 5 seconds before damping; this indicates the effect of the operation start, which has a great effect on the blade dynamics. Severe fluctuations in the aerodynamic loads over the wind turbine blade affect the fatigue behavior of the blade in a big way. This also applies for all aerodynamic loads acting on the blade including shear forces – in-plane and out-of-plane – and bending and torsional moments; fluctuations for the first 5 to 15 seconds occur then their values settle around a certain value. In this study, operating scenarios were not considered for fatigue behavior, only the steady state of the turbine rotation.

The importance of FFT analysis is to figure the dominant frequencies for each load, deflection or wind property. As observed from Figure 9, the Power Spectral Density (PSD) overshoots at about 3 Hz, which is the same exciting frequency for the first mode of vibration of the flap-wise direction. The thing that emphasizes the results of the modal analysis, since the thrust force is one of the most important factors affecting the flap-wise bending motion of the rotor blade.

4. Post Processing

FAST simulation time series are post processed using MLife to estimate the fatigue lifetime of the blade. MLife computes statistical information and fatigue estimates for one or more time-series. The input file to MLife is a Design Load Case (DLC) file, including the time series in a certain template provided by the software developers. The fatigue analysis tool uses the Palmgren Miner's sum. The probability density function used to represent the wind speed distribution properties is a Weibull distribution. According to a study for the wind field in AL-Zaafarana Region in Egypt, the Weibull distribution factors are A= 10.4 and k= 3.42[22].

Using results of the FAST simulation, post processing using MLife creates summary statistics for the time series file including the maximum, minimum, mean, standard deviation, skewness, and range values.

MLife then applies the Rainflow counting technique. MLife uses the one-pass cycle counting method. With this approach, unclosed partial cycles can be generated anywhere in the time-series, if certain criteria are met. The method attaches an unclosed cycle count to these cycles. Complete cycles are assigned a cycle count of one. For typical wind turbine loads data, only a small percentage of cycles tend to be counted as partial cycles. MLife analysis follows this general outline;

i) Processing all input data files,

ii) computing aggregate statistics across all data files,

iii) determining the fatigue cycles for each time-series using Rainflow counting,

iv) computing the short-term damage rates and damage equivalent loads (DEL),

v) summing the damage contribution of each time series,
vi) extrapolating the damage contribution of each time series to determine the lifetime damage, and finally
vii) computing the time until failure.

Fatigue damage due to load variation is accumulated over the lifetime of the wind turbine. MLife assumes that the damage accumulates in a linear manner with the load cycles which are characterized by a load-mean and range. Short term damage rates and Damage Equivalent Loads (DELs) are calculated for two DLCs; DLC_1, and DLC_2 corresponding to the two operating speeds of 36 and 47 rpm respectively.

5. Results and Discussion

The results of the total service time estimation and the deviation percentage from the design service time of 20 years are presented in Table 3.

Table 3. Service Lifetime Until Failure for Two Load Cases

Load Case	Service Lifetime (Seconds)	Service Lifetime (Years)	Deviation %
DLC_1 36 rpm	530720000	17	14.7
DLC_2 47 rpm	491608936	15.8	20.9

MLife post processing results show that the equivalent isotropic model for the composite wind turbine blades' service lifetime until failure for the first operating speed of 36 rpm, is 530720000 seconds, equal to about 204.75 months, or in years, 17 years of operation. And for the second operating speed of 47 rpm, the time until failure is 491608936 seconds, equal to 189.67 months, or 15.8 years. If a wind turbine is designed to last for 20 years, equal to 240 months, this means that the blade service lifetime is 14.7% away from the design point of the turbine at the first operating speed, and 20.9% away for the second operating speed. Three years difference from the design lifetime of the blade, compared to the new technologies in wind turbines emerging every year, is somehow acceptable as it is not too large deviation from the design point. However, for less deviation, few modifications to the blade design like changing the composite laminate structure, change the type of the fibers, or the matrix; would result in improving the lifetime of the blade.

6. Conclusions

Modal analysis of the wind turbine blades showed that the blade is safe from the danger of resonance. Fatigue analysis of the wind turbine blades showed that the service lifetime of the blades until failure is about 17 years for rotational speed of 36 rpm and about 15.8 years for the rotational speed of 47 rpm. Further optimization for the blade design taking into consideration the dynamic behavior of the blades would improve the service lifetime. Also, environmental effects and operating scenarios such as braking and idling of the rotor should be considered to study their effect on the fatigue behavior of the blades. Other optimization parameters in the geometry of the blade can be considered, like twist angles and chord length distributions, for improving the structure behavior with dynamic loads.

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