

Designing and Analyzing three-Blade Vertical Axis Wind Turbine Stress under Dynamic Loading

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ABSTRACT

Clean and renewable energies have encouraged the engineers to try to meet the needs and problems of today's world, among which wind energy is the most important one. In this course, innovation in designing and updating and improving the function of wind turbines as the best known energy convertor has been the subject of many industrial and academic studies in recent decades. The wind turbine designed in this article is of vertical axis type which has less been addressed in literature in which the moving shaft is perpendicular to the ground. As the demands of the designing, this turbine rotates with the constant rotation speed of 165 rpm and its nominal power is 3kw. Three blades with constant profile are considered for this wind turbine and two holding strut connectors are designed for each blade. Among the most important parts of the design are tubular shaft connected to the strut connectors besides to the main shaft to keep the turbine between the bearing, sprocket wheel to convert the speed ratio and finally the mechanical brake to control the speed. The turbine's tower is designed, according to the geographical conditions of the area, and installed and started in the given height and the dynamic analysis is conducted according to the obtained forces. In this paper, different stages of designing the turbine parts referred here are presented based on the above analyses. At the end, fatigue analysis and determining the stress exerted on some of this wind turbine parts are presented.

KEYWORDS: Dynamic Stress Analysis, Fatigue Damages, Vertical Axis Wind Turbine Designing.

1. INTRODUCTION

Wind energy is one of the most important types of renewable energy using which is inevitable in today's world. Using this energy has been taken into consideration from the past and first it was used as windmills for daily use and now, in developed countries, it is utilized in different kinds of wind turbines with multi-megawatt power of energy generation. In our country, extreme reliance to nonrenewable resources and production of pollutions in metropolises has encouraged the researchers and officials to find a renewable replacement, which is ecosystem friendly. Undoubtedly, wind energy is the best option using which is dependent on the construction and designing of wind turbines through the available technologies.

Currently, two kinds of wind turbines, among different designs considered by the designers, are horizontal axis wind turbine (HAWT) and vertical axis wind turbine (VAWT), used mainly to generate power. In comparison, each one has its own advantages and disadvantages. Some advantages of vertical axis turbine are easy designing and construction, lower cost, no need to rotor yaw mechanism (Yaw) to find the wind direction and sound pollution and ecosystem damage reduction. Among its disadvantages are less efficiency, power production with higher fluctuation, lower speed of the blades and lower energy yield.

With regard to the fact that in most literatures, horizontal axis turbines are studied and mostly aerodynamic analyses are presented, in this paper the mechanical designing process for parts of vertical axis wind turbine is explained with the nominal power of 3 kilowatt of Darius type (H-type) using Abaqus 6.11 analysis software, besides a brief introduction to vertical axis turbines, and a critical case of fatigue analysis is reported because of the dynamic forces exerted on the structure.

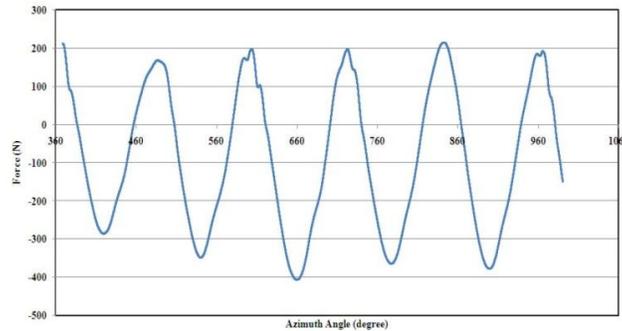
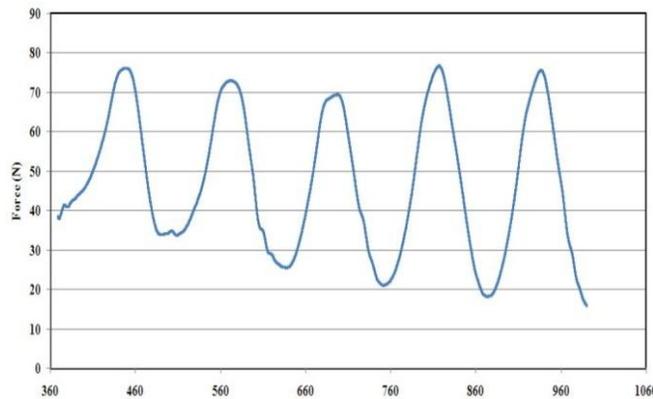
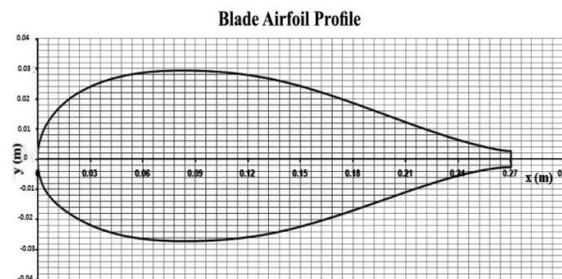
2. Vertical axis wind turbine

These turbines are of two types: Savonius and Darius and in this paper, we refer to designing the H-shape rotor model of wind turbine, which is one of the subtypes of the second group. During the design stages of this wind turbine parts, an aerodynamic engineering group[6]; analyzed the aerodynamic impacts, performed the force calculations, and obtained the optimal speed of the blade tip and power of these wind turbines. The results of the researches and theoretical calculations are used as a base to design the parts and construct this vertical axis wind turbine[2]. The information used here includes some general specifications of this turbine presented in *table 1* and the forces exerted on each blade and the rotor, which are referred to in figure 1,2. The blades airfoil is of constant profile type proportionate to the structure of this wind turbine, which is presented in figure 1.

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Table 1: General specifications of wind turbine

| Turbine Specifications | Definitions |
|---|---------------------------|
| $P = 3000 \text{ W}$ | Desired output Power |
| $\sigma = 0.44$ | Solidity: $\sigma = Bc/R$ |
| $AR = 12.2$ | Aspect Ratio: $AR = H/c$ |
| $B = 3$ | Number of Blades |
| $U = 10 \text{ m/s}$ | Free Stream Velocity |
| $C = 0.27 \text{ m}$ | Chord Length |
| $H = 3.3 \text{ m}$ | Rotor Height |
| $R = 1.85 \text{ m}$ | Rotor Radius |
| $\rho = 1.224 \text{ Kg/m}^3$ | Air Density |
| Viscosity = $1.82 \times 10^{-5} \text{ Pa.s}$ | Air Dynamic Viscosity |
| $\lambda = 3.2$ | Design Tip Speed Ratio |
| $\omega = 165.13 \text{ rpm} = 17.29 \text{ rad/s}$ | Design Rotor Speed |

**Fig. 1:** The force exerted on the rotor set in terms of blade rotation angle in the direction of rotor radius**Fig. 2:** The force exerted on the rotor set in terms of blade rotation angle perpendicular to rotor radius**Fig. 3:** Airfoil profile (ML-VAWT) constant in the length of the blade

3. Detailed explanation of designing and modeling vertical axis wind turbine

VAWT consists of three blades each 3300mm, which are made of three discrete parts of composite with polymeric background linked together in binding site of the strut connectors. The static analysis of blade structure is based on composite fracture factor and material selection and designing the number of layers, fabric angles and layers' order is done in finite elements software in such a way that the structure could bear the exerted loads such as aerodynamic forces, centrifuge and gravity. This structure analysis is studied separately in another paper. Each blade is kept through two strut connectors with special profile made of aluminum (Aluminum6063-TS) to form an arm to create the required torque. The

tubular shaft of rotor which transfers the power to the sprocket wheel is designed with the length of 1610mm, 110mm diameter and 6mm thickness made of steel (St37). To make the blades more rigid and prevent their bending against centrifugal forces, some cables are used to adjust the length that is shown in figure 4.

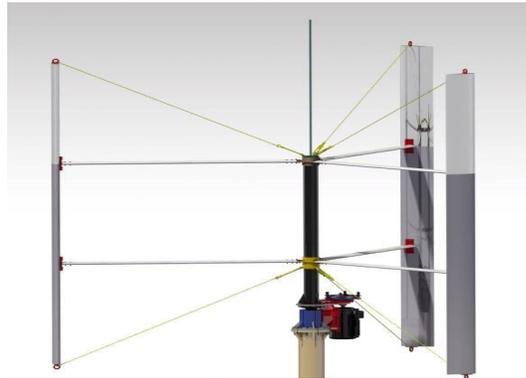


Fig. 4: Blades, strut connectors, cables and tubular shaft's profile

The tubular shaft of rotor is connected to the large sprocket wheel and the main shaft flange through a flange and six M18 screws. The lower shaft, which is made of steel VCN 200, is kept in housing through two roller bearings of [DIN 720-33212] type. A steel holder connects generator and mechanical brake as two layers with the thickness of 20mm made of iron through four iron rectangular profiles (50×60mm) to the housing body. This wind turbine's brake is mechanical which uses centrifugal force and is able to brake and control the wind turbine speed even in undesirable atmospheric conditions when the rotor rotation speed is high. This brake's design is similar to the mechanism of fishing hook self-locking shown in figure 5. With regard to the nominal spinning speed of the generator, the speed should be raised from 165 to 375 rpm, which is performed using double-row sprocket wheel system among the advantages of which are lower cost and smaller space, relative to the gear-box system [4,5]. The tower of this turbine is designed according to the information related to the wind speed in the area to be installed and consists of two or three tubes connected through internal flanges and their strength is increased using a rib that is shown in figure 6 [7].

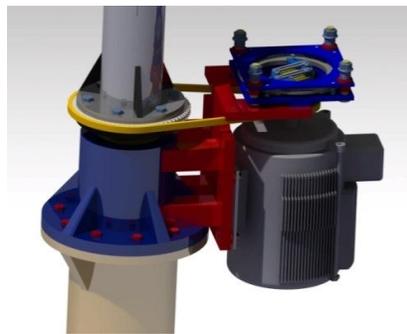


Fig. 5: Housing, generator, mechanical brake and sprocket wheel profile

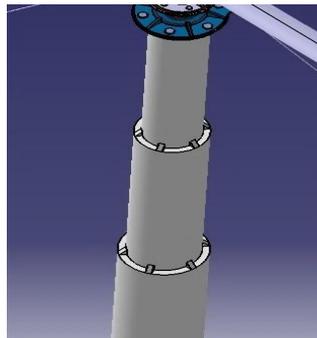


Fig. 6: Wind turbine tower

4. Dynamic stress analysis of the turbine in full-scale condition

To analyze the resistance of the system parts of this wind turbine, fatigue analyses are required because of the fluctuation of the forces exerted to the system. This fact is used for fatigue analysis for high rotation based on the stress. The approaches related to the stress are divided into four types: equivalent experimental stress, invariable stress mean stress and critical stress plate. In this article, we analyzed the wind turbine tower stress and wind turbine strut connector stress under dynamic loading using multi-axial fatigue analysis approach. A review of multi-axial fatigue analysis approach can be found in other literature [8, 9, 10, 11]. Liou and Mahadowan [12] suggested a model based on critical plate to model the multi-axial fatigue damage and made it reliable using experimental data o torsional bending fatigue. It is supposed that the fatigue crack plate is α which is different according to the material properties [13]. The formulas and explanations with more details are presented in the suggested literature. Here we just show the results. The general fatigue state is worked out as (Equ. 1 , 2) in which $\sigma_{a,c}, t_{a,c}, \sigma_{a,c}^H$ are respectively the vertical stress range, shear stress range and hydrostatic stress range exerted on critical plate. $\sigma_{m,c}$ is the mean vertical stress exerted on the critical plate and N_f is the number of bearable rotation of the part up to fracture and η_{N_f} is the correction factor of the mean stress. We can use (Equ,1) if the fatigue test with mean stress is not available.

$$\frac{1}{\beta} \sqrt{[\sigma_{a,c}(1 + \eta_{N_f} \frac{\sigma_{m,c}}{f_{N_f}})]^2 + (\frac{f_{N_f}}{t_{N_f}})^2 (\tau_{a,c})^2 + k(\sigma_{a,c}^H)^2} \quad (1)$$

$$\eta_{N_f} = \frac{3}{4} + \frac{1}{4} \left(\frac{\sqrt{3} - \frac{f_{N_f}}{t_{N_f}}}{\sqrt{3}-1} \right) \left(\frac{f_{N_f}}{t_{N_f}} > 1 \right), \eta_{N_f} = 1 \quad \left(\frac{f_{N_f}}{t_{N_f}} > 1 \right) \quad (2)$$

f_{N_f} and t_{N_f} are fatigue strength coefficient in finite age of N_f for uniaxial loading and torsional load respectively. k and β are the material parameters which can be determined using f_{N_f} and t_{N_f} values. The material parameters of α , k and β are listed in table 2 [13].

Table 2. Material parameters in the measure of fatigue damage

| Material property | $s = \frac{t_{N_f}}{f_{N_f}} \leq 1$ | $s = \frac{t_{N_f}}{f_{N_f}} > 1$ |
|-------------------|--|-----------------------------------|
| α | | $\alpha=0$ |
| K | | $K = 9(s^2 - 1)$ |
| β | $\beta = 0$ | $\beta = 0$ |
| | $\cos(2\alpha) = \frac{-2 + \sqrt{4 - 4(\frac{1}{s^2} - 3)(5 - \frac{1}{s^2} - 4s^2)}}{2(5 - \frac{1}{s^2} - 4s^2)}$ | |
| | $\beta = [\cos^2(2\alpha) s^2 + \sin^2(2\alpha)]^2$ | |

In this paper, the analysis is performed for strut connectors holding blades and wind turbine tower because of the criticality of the related part, but complete designing of the turbine is dependent on the analysis of all of the members affected by dynamic loads. With regard to the force diagram in terms of rotation angle of the blades obtained from aerodynamic analyses, we first calculate the recurrence interval and then force changes in time are drawn which is shown in figures 7,8. According to the drawn diagrams, the obtained results are entered in finite elements analysis software as force range changes format to calculate and study the stresses and structure displacement.

$$f = 165 \frac{rev}{min} \times \frac{min}{60 s} = 2.75 \text{ HZ} \quad (3)$$

$$T = \frac{1}{f} = \frac{1}{2.75} = 0.36 \text{ s} \quad (4)$$

In which f is frequency and T is recurrence interval in seconds.

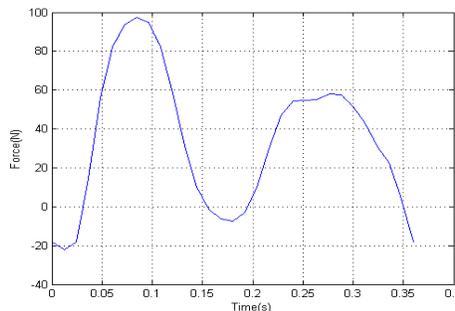


Fig. 7: Force changes exerted to a blade perpendicular to the rotor radius in terms of time.

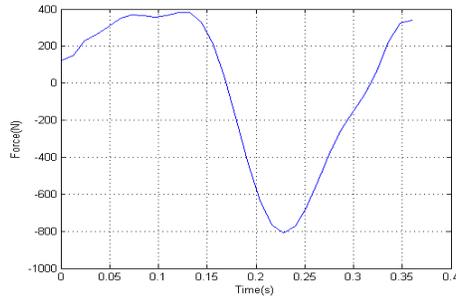


Fig. 8: force changes exerted to a blade in the direction of rotor radius in terms of time.

As can be seen in figure 9, related to the wind turbine tower designing and figure 10, related to the wind turbine strut connectors designing, it experiences some stresses and strains, that using Abaqus 6.11 stress analysis software we modeled the stress span [1] and this dynamic stress analysis helps the redder to study the main parts of wind turbine [3].

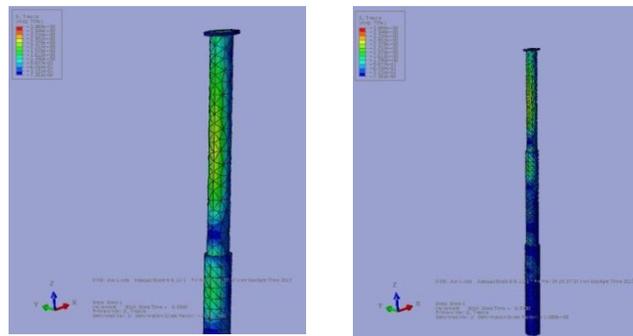


Fig. 9: The meshed profile of the tower under dynamic load

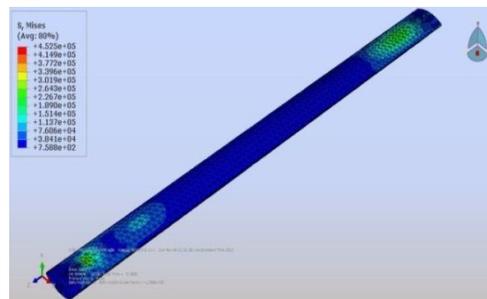


Fig. 10: The meshed profile of the strut connector under dynamic load

Then we have tried to determine figure 11 for better understanding of the highest value of stress along the force recurrence span and this diagram is selected for the Struts. Based on these results, we can calculate the confidence coefficient of the structure and redesign the dimensions or connections according to the design requirements considering the complementary information of the work conditions in each project.

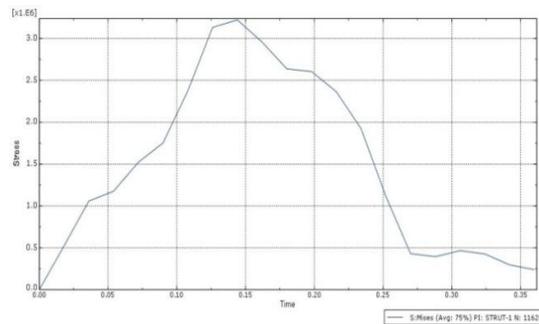


Fig.11: Stress changes in terms of time

5. Conclusions

In this paper, it is tried to briefly introduce vertical axis wind turbine, which are less known compared to horizontal axis wind turbines. In addition, we first studied the results of a real analysis based on theoretic and experimental aerodynamic analyses and then we introduced the basics of designing and analysis of mechanical parts of the turbine based on the general protocols of wind turbines designing after determining the general specifications of them. The fatigue analysis of two of the critical parts of this turbine is also presented, which is an integrated part of mechanical analyses of these turbines because of the fluctuation of the loads exerted to the wind turbines.

REFERENCES

- [1] Documents of Abaqus 6.11-1 software
- [2] Wood,D, "Small Wind turbines,analysis,design and application" university of Calgary,department of mechanical,Canada,Springer London Dordrecht Heidelberg New York,2011
- [3] Thomas G. Carrie, Donald W. Lobitz "Finite Element Analysis and Modall Testing of a Rotating Wind Turbine", prepared by sandia national laboratories, new mexico,1982
- [4] Bhatta ,P,"Individual Blade Pitch and Camber Control for Vertical Axis Wind Turbines",Princeton Satellite Systems, Inc., 33 Witherspoon Street, Princeton, NJ 08542, USA
- [5] Isaac M. Asher, "A Low Order Model for Vertical Axis Wind Turbines", *Massachusetts Institute of Technology, Cambridge, MA 02139, U.S.A.*
- [6] Maghrebi,M,G. "Design and aerodynamic analysis vertical axis wind turbine strath blade with 3 KW power",havakhorshid institute, Ferdowsi university,mashhad,iran,2012
- [7] Fischer, Ulrich, "Machine Design tables and standards", valinejadTranslated, 2009, Sixteenth Edition, designer, Tehran, 2011
- [8] Papadopoulos IV, Davoli P, Gorla C, Filippini M, Bernasconi A. Acomparative study of multiaxial high-cycle fatigue criteria for metals. *IntJ Fatigue* 1997;19(3):219–35.
- [9] Garud YS. Multiaxial fatigue: a survey of the state-of-the-art. *JTest Eval*1981;9(3):165–78.
- [10] You BR, Lee SB. A critical review on multiaxial fatigueassessments ofmetals. *Int J Fatigue* 1996;18(4):235–44.
- [11] Wang YY, Yao WX. Evaluation and comparison of severalmultiaxialfatigue criteria. *Int J Fatigue* 2004;26(1):17–25.
- [12]Liu Y, Mahadevan S. Multiaxial high-cycle fatigue criterion and life prediction for metals. *Int J Fatigue* 2005;7(7):790–800.
- [13]Liu Y,StratmanB,Mahadevan S. Fatigue crack initiation life prediction of railroad wheels. *Int J Fatigue* 2006: 747–756.