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Structural Design and Stress Analysis of a Helical Vertical Axis Wind Turbine Blade

Özer ÖĞÜÇLÜ*[1]

Abstract

In this study, a Computational Fluid Dynamics (CFD) model is designed to investigate the structural analysis of a helical Vertical Axis Wind Turbine (VAWT) blade which is using National Advisory Committee for Aeronautics (NACA) 0018 airfoil and numerical calculations are conducted by using Comsol Multiphysics. The main objective of this study is to determine that the strength of the turbine blade against bending caused by increased wind speeds is sufficient for the selected turbine blade material. This paper presents also an investigation of the effects of different wind speeds on the structure of a helical VAWT blade that is fixed to the support arm which is attached to the VAWT's main shaft. In this study, a turbine blade which is placed in an air flow field is subjected to approaching strong wind with different velocities. The model solves for the flow around the blade and the structural displacement due to the fluid load. This investigation consists of two main parts: Solving for the fluid flow around the turbine blade with a free stream velocities of 1, 3, 5, 7, and 9 m/s, and Studying the deformation of the turbine blade caused by the fluid load. The risk of failure according to the von Mises criterion for the ductile materials such as aluminum is also investigated.

Keywords: CFD model, airfoil, helical, Vertical Axis Wind Turbine, turbine blade, von Mises

1. INTRODUCTION

Wind turbine is one of the renewable energy sources whose importance is increasing. Therefore, the analysis, design and production of wind turbines is very important for the world's power generation industry. The most critical components of a wind turbine are turbine blades. The turbine blade, the first link in the energy conversion chain, is an important issue in wind turbine design.

The kinetic energy in the wind should be transferred to the turbine blades without any loss. This significantly affects the yield to be achieved. For this reason, the turbine blades must be designed in such a way that they can capture the maximum energy from the wind. In the production of wind turbine rotors, the strength of the turbine blades at high wind speeds is an important consideration. If this issue is not taken into account sufficiently, the results can be very harmful. If no action is taken, resistance problems may arise in the turbine tower and especially the blades at high wind speeds.

As a result, the turbine elements may be deformed or even broken. The load that forces the tower is due to the wind force acting on the tower and especially the turbine blades. Turbine blades have to withstand wind, gravity and centrifugal loads, because they produce electricity by rotation. The blades are affected by the tangential and normal

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components of the inertia forces resulting from both the wind force and the rotation of the blades. These forces cause bending stresses and normal stresses in towers and blades. If these stresses exceed the safe stress limit specific to the material used, they cause damage to the turbine tower and blades. Thus the structure of a turbine blade requires it to be made of strong materials.

Turbine rotor blades are exposed to different cyclic loads such as aerodynamics, centrifugal and gravitational forces during life of a wind turbine. Then the fatigue life of the wind turbine blades becomes the first step in design procedure to estimate the effectiveness of a wind turbine. The turbine blades must be strength and stiff. When the strength and stiffness of blades is considered, the weight of turbine blades becomes very important to determine the cost and to avoid the fatigue failure. In order to minimize total weight of a wind turbine system, a stiff and light material is generally required. The key of design a reliable wind turbine blade under complicated loading conditions is the correct fatigue life prediction. Sutherland presented a long record of the researches about wind turbine rotor blade material fatigue [1]. Winterstein and Veers defined the fatigue stress in terms of the root mean square of the instantaneous stress, which was regarded as an exponential function of wind speed [2]. Cox and Echtermeyer has designed a Horizontal Axis Wind Turbine (HAWT) with the 70 meter long blade were to use in a location where wind speeds are high [3]. They designed a blade which was made of a hybrid composite structure was subjected to Finite Element Analysis (FEA) researches to show its capability to resist excessive loading conditions according to the international open sea wind standards. Furthermore their results verified that the design to have sufficient capacity in point of tip deflection, maximum and minimum strains, and critical buckling load. In their paper, they presented detailed definitions of the turbine structural components with the results of maximum and minimum strains and deflections. Yeh and Wang evaluated the stress and deformation analyses of the National Renewable Energy Laboratory (NREL) turbine composite blade with FEA [4]. The stress distribution and deformation of the wind turbine blades under various loads was analyzed, and the effect of changing the stacking angle in composites and the thickness variation of the blade structure on the simulation results was discussed in their study. The increases in the size and flexibility of large wind turbine blades produces remarkable aeroelastic impacts which are produced by Fluid Structure Interaction (FSI). Correct FSI modeling of wind turbine blades is very important in the improving of large wind turbines. Wang et al. [5] established a wind turbine blade FSI model at full scale. They calculated the aerodynamic loads with a CFD model performed in ANSYS FLUENT and determined the blade structural responses with a FEA model applied in ANSYS Static Structural module. Wind turbine blades are tested for new structural improvements. Fagan et al. [6] developed and tested a special turbine blade. In their study, experimental tests on a wind turbine with long composite blades were presented. They used the results of the tests to calibrate FEA models. At last of this study, they implemented a design optimisation work with a genetic algorithm. To reduce the wind turbine blade's weight is an important subject for engineers. To improve the efficiency of power generating, wind turbines changed bigger in size. Turbine blades have also extended to capture more wind energy. A wind turbine blade made of fabric-based material can reduce the blade weight. To verify structural capability, Choi et al. [7] developed a 10 kW wind turbine with small fabric-covered turbine blades. They designed the cross section of turbine blades by using Variational Asymptotic Beam Sectional analysis (VABS), then they implemented structural analysis. Static structural tests and modal tests were completed. At last, they compared the analysis results with the test results in their study.

Firstly, wind turbines were used as windmills whose blades convert the kinetic energy they obtain from the wind into mechanical energy. These windmills have shafts that are spinning and moving the lever of pocket. Wind turbines are rotated by the movement of air that propels the blades or rotors of the turbine, which are generally named as airfoils. The airfoils are designed to react with wind and take the rotational power that is converted to energy. The shape of the airfoils has a great effect because it causes the pressure on one surface higher than the pressure on the other surface of the blade. These uneven pressure values make the blade rotate.

Small wind turbines are manufactured with a horizontal or vertical axis. Especially vertical axis wind turbines are interesting for building applications. Usual horizontal axis wind turbines must always be oriented to the wind destination. In contrast, the vertical axis wind turbines can catch incoming wind from any direction via the helical blade profile or the arms. Therefore, vertical axis wind turbines do not need to be steered, they can also benefit from turbulences [8].

The HAWT's axis is parallel to the wind flow whereas the VAWT's rotor is positioned vertically. The HAWTs are mounted on a large tower and has generally two or three blades. The difference in wind speeds on the top and bottom surfaces of the blade results a pressure difference between the blade surfaces. This pressure difference produces an aerodynamic lift and the rotation of the blade starts. On the other hand, there is a drag force perpendicular to the lift force which opposes the rotation of the blade. VAWTs has advantages when they operate at low wind speeds.

VAWTs are wind turbines that rotate about a vertical axis that is perpendicular to the wind direction. In modern designs, VAWT's center axis is a vertical shaft that is connected to a gearbox which increases turbine speed. The gearbox's output shaft drives a generator that converts the mechanical torque of the turbine rotor to electrical power [9]. Fig.1 shows typical designs of basic VAWT Configurations. The two main types of VAWTs are the Savonius and the Darrieus turbines.

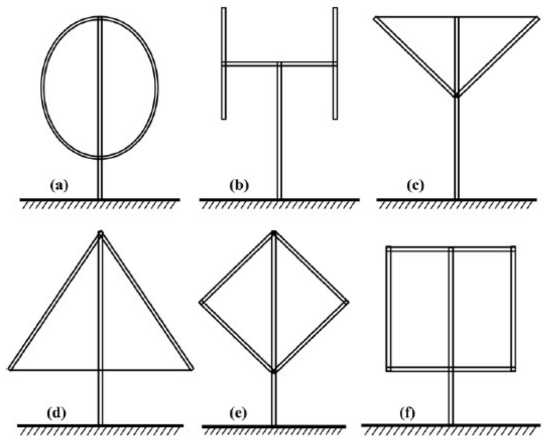

Figure 1 Basic VAWT Configurations: (a) Darrieus, (b) H, (c) V, (d) Delta, (e) Diamond and (f) Gyromill [9]

Though vertical axis wind turbines are manufactured in various shapes, they are classified into two basic categories as Savonius and Darrieus turbines. The Savonius turbines mainly work on the drag principle. These vertical axis turbines generally have low efficiency but they are very suitable for areas with turbulent winds. On the other hand, Darrieus turbines work on the lifting principle. The Darrieus vertical axis wind turbines require a motor to start their motion. They are also well suited for places with turbulent winds where they can have high efficiencies. Now, there are innovative models on the market that take advantage of the features of both Savonius and Darrieus turbines. A Savonius turbine is widely used in many places that require high reliability, such as ventilation and anemometers. They are less efficient than general HAWT since they are drag type turbines. Savonius turbines are perfect for turbulent wind fields and they have the feature of self-start at low wind speeds. Nowadays Darrieus wind turbines are manufactured with great efficiency. However they can cause much torque fluctuations and cyclical stress on the shaft. This results in bad reliability [8]. There is a helical bladed design, which is a more efficient development and called Gorlov turbine after its inventor. Fig.2 shows different types of Vertical Axis Wind Turbines.

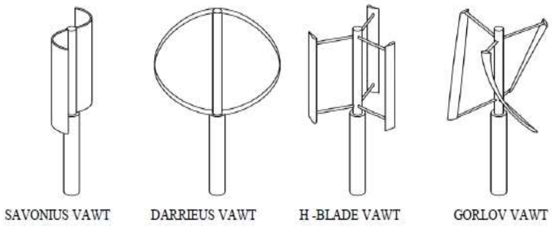

Figure 2 Different types of VAWTs [8]

Many research institutions and universities achieved wide research activities and improved a plenty of designs about many aerodynamic CFD vertical axis wind turbine models. Engineers used these important models for searching the performance of vertical axis wind turbine and achieving the best design parameters before manufacturing vertical axis wind turbine models [10]. Blade design aim is finding the right blade geometry that generates the most rotary action. Thus, blade design considers the wind turbine parameters which are: angle of attack, power coefficient, lift coefficient, drag coefficient, tip speed ratio, blade chord length, and number of blades.

2. TURBINE DESIGN

In this study, the helical VAWT turbine, also known as the Gorlov turbine, with three blades is investigated [11]. VAWTs with helical blades can yield a less noise emission and better aerodynamic performance compared with VAWTs which have straight blades [12]. Recently CFD models are often applied to VAWT turbines and give results that can express real flow events. In this study, the dimensions of the turbine as 0.3 m height and 0.3 m diameter are chosen, because they are convenient for a small-scale wind turbine.

Solidworks design software is used for drawing of three dimensional vertical axis wind turbine blade. Then blade drawing is imported into Comsol Multiphysics from Solidworks using Import command in the Comsol Model Builder.

In this study, due to its symmetrical structure, NACA 0018 airfoil profile is used [13]. The NACA 0018 airfoil profile coordinates required for drawing the three-dimensional blade geometry are taken from airfoiltools.com website. This site retrieves wing profile coordinate values from the University of Illinois at Urbana–Champaign (UIUC) – Airfoil Coordinates Database, which contains approximately 1600 aircraft airfoil coordinates [14].

For the improving of wind turbine blades, a great deal of airfoil types are designed in wind energy systems technology. The small wind turbine blade airfoils could be used already at the low attack angles where drag coefficient must be lower than lift coefficient. NACA series airfoils are generally used to design the turbine blade geometry. A significant part of the NACA airfoils, originally designed for aircraft, were later used in wind turbines. Early NACA airfoil series were composed with analytical equations that define camber of geometric center line of airfoil cross section with the cross section thickness distribution over the length of airfoil. NACA airfoil cross section is shaped from a camber line and a thickness distribution which is plotted vertical to camber line. A camber line equation is separated into sections both side of the point of maximum camber position. The gradient of camber line is also needed to calculate the position of final airfoil envelope. The first family of airfoils is known as NACA four digit series which were designed using this approach. NACA four digit airfoil series specification is defined by four numbers which describe camber, position of maximum camber and thickness. The first number states the maximum camber in percentage of airfoil chord length. The second number shows the position of maximum camber in tenths of chord length. And the last two numbers express maximum thickness of airfoil in percentage of chord length [14]. If the first two numbers of an airfoil of NACA four digit series are 00, it means that this airfoil is in symmetrical structure and has not a camber geometry [13]. Fig.3 shows a normal NACA airfoil's profile geometry.

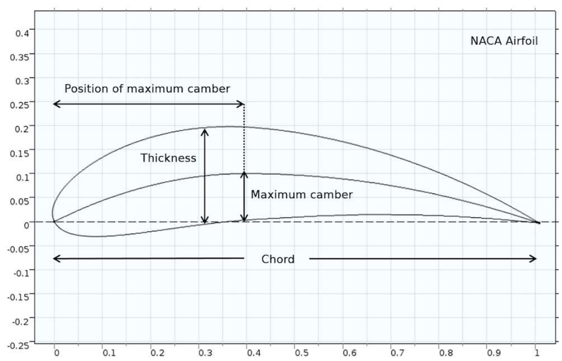

Figure 3 NACA airfoil profile geometry

NACA0018 airfoil has maximum thickness 18% at 30% chord length and maximum camber 0% at 0% chord length [14]. In this study, the chord length is chosen as 0.05 m.

First, airfoil profile is drawn using the NACA 0018 airfoil profile coordinates which are taken airfoiltools.com website. For this purpose, Solidworks design software uses the Curves Through XYZ Points command on the Curves Toolbar, which is used to generate three-dimensional curves from solid or surface forms. This command is used to create a curve according to the coordinate values entered in the table. Since only two dimensional drawing will be made, Z coordinates are given as zero in this table. Fig.4 shows the NACA 0018 airfoil profile drawing in design software.

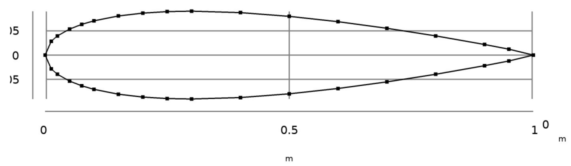
Figure 4 Blade airfoil drawing

The coordinates of point M(x, y, z) on the Gorlov turbine blade helical curve at height L and radius R are calculated by the following geometric correlation formulas [11];

$$x = R\cos\varphi \quad (1)$$

$$y = R\sin\varphi \quad (2)$$

$$z = R\varphi\tan\delta \quad (3)$$

where φ; is the helical rotation angle and δ; is the helix angle of rise. Using these geometric correlation formulas in Microsoft Excel or LibreOffice Calc, we can multiply the coordinates of the helical curve of the airfoil profile, which we have previously drawn in Solidworks, to form the three-dimensional turbine blade drawing. By using these helix curve coordinates, the helix curve that we will use to draw the three-dimensional turbine blade drawing from the airfoil profile, we have previously drawn in Solidworks design software, is drawn using the Helix/Spiral draw command of the Solidworks design software. With the Variable Step Helix draw option in the menu, the coordinates of the helix curve we want to draw are entered into the Solidworks as a table and the curve is drawn. This plotting process is shown in Fig.5.

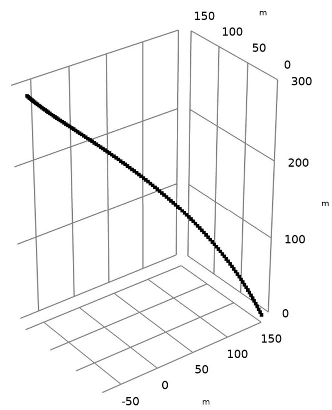
Figure 5 Blade Helix curve drawing

After completing the airfoil profile and helix curve drawings in the Solidworks design software, a three-dimensional blade model is drawn using the Sweep command in the Solidworks. For this, in the Profile and Path selection boxes in the command menu, the airfoil profile curve we have drawn as Profile and the helix curve that we have previously drawn as Path are selected. After setting the other start and end states, our solid blade model is completed by running the Sweep command. Since our vertical axis wind turbine model, which we designed, has three blades, the other blades are copied from our first drawing and two solid bottom and upper cylindrical blade connection elements are drawn and our solid model is finalized [15]. Fig.6 shows the final version of the Gorlov Turbine design.

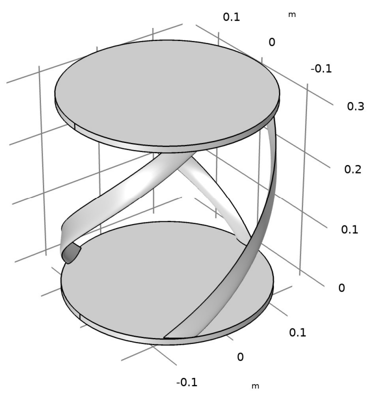

Figure 6 Gorlov Turbine design drawing

In this study, wind is considered a homogeneous mass without dust, steam or other particles. Therefore, the model is based on single-phase flow at low wind velocities. In Comsol Multiphysics, single-phase flow is modeled by Navier-Stokes fluid flow equations. The Re number is calculated as 16.7×10^3, at the conditions which are air density ρ =1.2 kg/m^3, wind speed U = 5 m/s, airfoil chord length c = 0.05 m, and air dynamic viscosity $\mu = 1.8\times10^{-5}$ kg/(m.s) for NACA0018 airfoil used in this model.

$$\mathrm{Re} = \frac{\rho U c}{\mu} = \frac{1.2x5x0.05}{1.8x10^{-5}} = 16.7x10^{3}$$

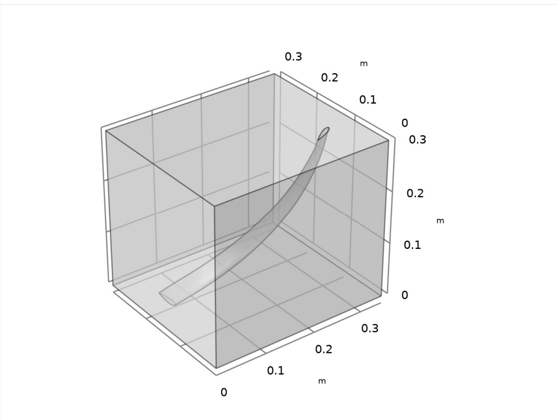

Figure 7 Model geometry

For simplicity, model geometry is reduced to a single blade as shown in Fig.7. The blade is free to move along all axis and is subjected to only the fluid forces. In Comsol, the fluid forces are automatically applied when using the Fluid-Structure Interaction multiphysics coupling. The blade is attached to the turbine body which is assumed to be rigid. The rigidity is enforced by applying a Fixed Constraint to the both blade ends. The turbine blade is then placed in a cubic volume of 0.3 m long, 0.3 m wide and 0.3 m high, which represents a part of a wind tunnel. The lateral, upper and lower walls of this cube and the surface of the turbine blades are determined as the wall boundary condition. At the same time, the right and left walls of this cube are set as the inlet and outlet where the wind flows evenly along the horizontal direction.

Fluid-Structure Interaction is a common class of multiphysics problems in which structural response and surrounding fluid flow are coupled. The interaction between the fluid flow and structural deformation is in general bidirectional. The fluid exerts an external load on the structure, leading to deformation of structural components. Conversely, the motion or deformation of structural components changes the direction of fluid flow. Depending upon the type of interaction between fluid and solid objects, Fluid-Structure Interaction problems can be categorized into either one-way coupled or two-way coupled problems [16].

In the general design of the Fluid-Structure interaction problem, the elastic solid object is immersed in a channel where the fluid flows [17]. The interaction between the fluid and the structural mechanism is specified through the interface boundaries between the two domains. The two identity pairs between the fluid and solid domains are selected in the Fluid-Structure Interaction to incorporate the multiphysics coupling between the two physics. Thus, in the Multiphysics section, Coupling Type is selected as Fluid loading on structure in Comsol Multiphysics [16].

In this study, mesh independency is conducted to assure that the number of the mesh is adequate for estimating the maximum velocity around blade for wind speed U = 1 m/s. Four different number of mesh is generated for model as shown in Fig.8. The number of domain elements is varied from 94.2 thousands to 5.35 millions.

Mesh Refinement	Number of Mesh Elements		Maximum Velocity
Coarser	Domain Elements	94.203	1.60 m/s
	Boundary Elements	6.403	
	Edge Elements	369	
Coarse	Domain Elements	301.269	1.67 m/s
	Boundary Elements	13.714	
	Edge Elements	596	
Normal	Domain Elements	1.472.800	1.69 m/s
	Boundary Elements	43.223	
	Edge Elements	1.193	
Fine	Domain Elements	5.353.997	1.69 m/s
	Boundary Elements	130.646	
	Edge Elements	2.458	

Figure 8 The number of elements for the three-dimensional mesh

Thus, Physics-controlled mesh with Fine element size is selected and the final model meshing is shown in Fig.9. The mesh used to discretize the fluid domain and the turbine blade is characterized by tetrahedral elements. The maximum element size for the entire domain is set to 0.0276 m, whereas the minimum element size is 0.00345 m. The mesh is configured to be tightest around the blade, in order to resolve the stress within the bending blade.

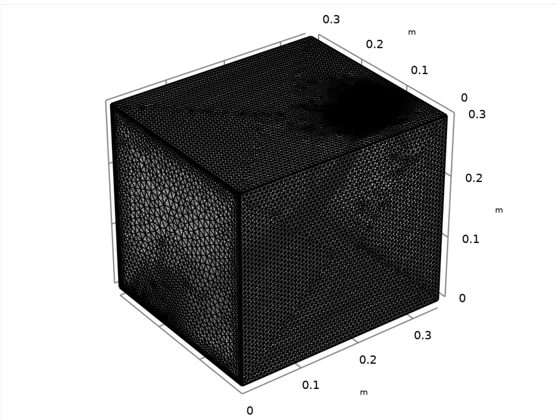

Figure 9 Model geometry meshing

Low number mesh distribution may produce computation with large error but high number mesh may increase computational time. Therefore high concentrated mesh distribution is applied close to the blade surface. The maximum element size for the blade surface is set to 0.00692 m, whereas the minimum element size is 0.00045 m. Mesh distribution around NACA 0018 airfoil is presented in Fig.10.

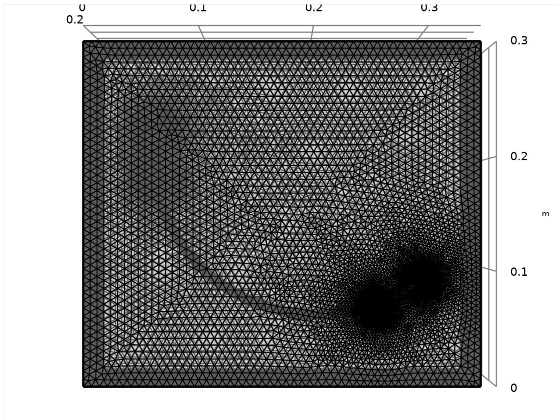

Figure 10 Model airfoil meshing

In this study, the turbine blades and body are made of Aluminum ASTM 5083 alloy which is used in marine, auto and aircraft applications [18]. The material properties of Aluminum ASTM 5083 alloy are Density; ρ = 2.66 g/cm^3 at 20 ºC, Tensile Strength; 290 MPa, Yield Strength; 145 MPa, Young's modulus; E = 70.3 GPa, and Poisson's ratio; μ = 0.33.

In this study, the simulation is set up by using a Turbulent Flow, k-ω interface with a stationary study type to analyze the interaction of the blade and the fluid. Turbulence is modeled with the k-ω model instead the k-ε turbulence model. The k-ω turbulence model is a widely used model for CFD simulations in the near-wall region with good performance for swirling flows. Although the k-ω model is better suited for these types of flows, it takes longer to converge than the k-ε model due to the strong non-linearity in the turbulence coefficients [16]. The model solves for the flow around the blade and the structural displacement due to the fluid load for flow inlet velocities of 1, 3, 5, 7, and 9 m/s. Then model investigates the deformation of the turbine blade caused by the fluid load. The outlet is set as a pressure outlet, keeping the pressure constant equal to 101325 Pa.

The lateral, upper and lower walls and the surface of the blade are set as No-slip wall boundary condition.

3. RESULTS

Fig.11 shows the fluid velocity magnitude around the blade of the turbine for inlet velocity 5 m/s. The maximum velocity is about 8.49 m/s and the main flow path and the recirculation flow around blade are clearly visible.

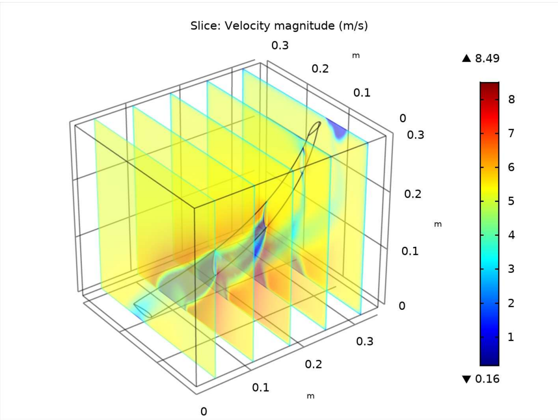

Figure 11 Velocity magnitude around blade

Fig.12 presents fluid pressure around blade due to the surrounding flow. The maximum relative pressure, about 33.3 Pa, occurs on the nearest point to the bottom rigid blade end.

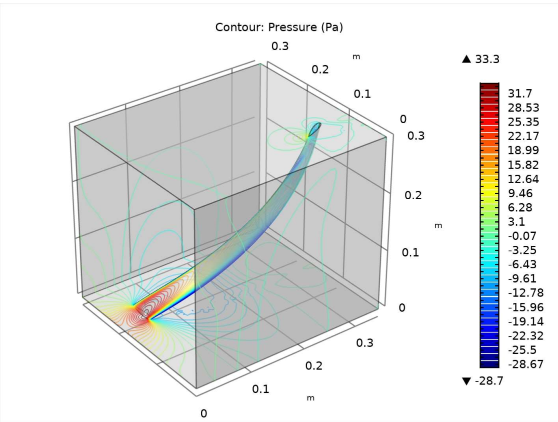

Figure 12 Fluid pressure around blade

Fig.13 shows the von Mises stress in the solid blade. Because of fluid pressure, the original structure of turbine blade bends. The deformed shape of the blade due to fluid load is seen clearly from Fig.13.

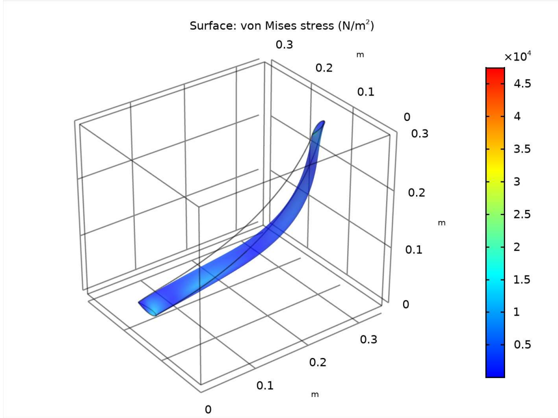

Figure 13 von Mises stress in blade

The largest displacement occurs in the middle part of the blade between both rigid ends. It is seen in Fig.14. However, the maximum displacement is small, about $1.05x10^{-7}$ m. This indicates that the strength of the blade effectively protect the blade from wind flow. The fluid load on the structure at the current flow velocity is not significant enough to affect the design of the blade. The yield strength for the Aliminum 5083 Alloy is large enough to consider that the blade is far from failure.

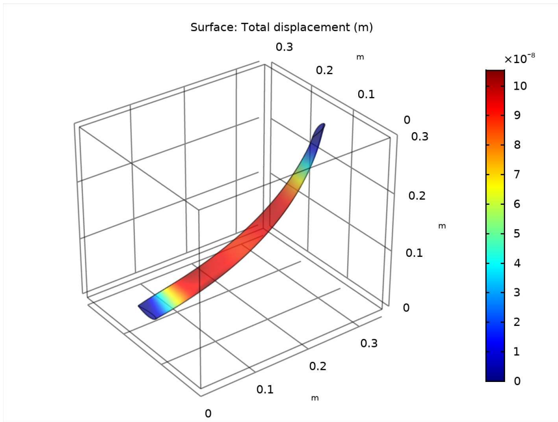

Figure 14 Total displacement of blade

The maximum von Mises stress in the blade is formed on the nearest point to the rigid blade end. It is seen clearly in Fig.15.

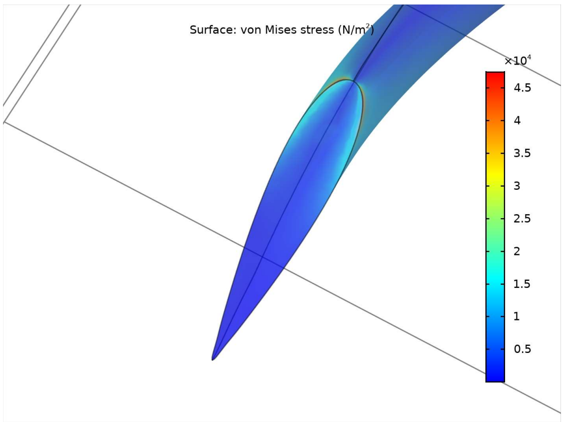

Figure 15 Maximum von Mises stress in blade

The von Mises yield criterion is formulated in terms of von Mises stress in material science and engineering. The von Mises stress is a value which is used to determine whether a ductile material will yield or fracture. A given ductile material starts to yield when its von Mises stress exceeds a critical value named the yield strength.

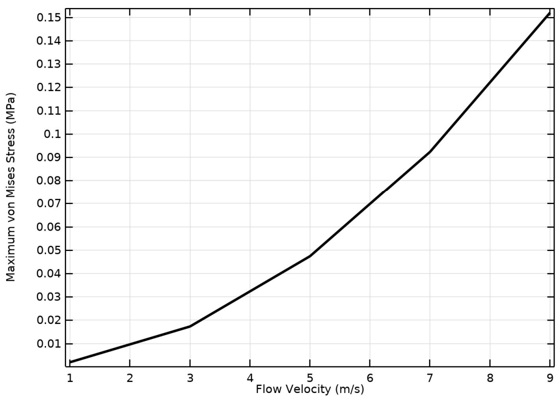

Figure 16 Relationship between flow velocity and maximum von Mises stress of blade

Fig.16 shows the relation with the maximum von Mises stresses and different air flow velocities. Obviously, with increase of flow velocity, the maximum von Mises stress value of the blade increases. Additionally the maximum von Mises stress rapidly increases from the velocity 5 m/s to the velocity 9 m/s. A ductile structural material is safe as long as the maximum value of the von Mises stress in that material remains smaller than the yield strength of the same material.

4. CONCLUSION

This model presents the structural analysis of a helical vertical axis wind turbine blade made of Aluminum 5083 Alloy which is placed in an air flow field. First, a CFD analysis is solved for the fluid flow around the turbine blade to calculate the velocity magnitude and the pressure distribution around the blade.

Second, a stress analysis is carried out in which the blade is exposed to a strong wind at different velocities. At all points on the blade, the total displacement and maximum von Mises stress values are calculated for different wind velocities. At last, the relation with the maximum von Mises stresses and different air flow velocities is calculated and represented.

Because of fluid pressure, the original structure of turbine blade bends. The largest displacement occurs in the middle part of the blade between both rigid ends.

The maximum displacement is small, this indicates that the strength of the blade effectively protect the blade from wind flow.

The maximum stress in the blade occurs on the nearest point to the rigid blade end. The yield strength for the blade's material is large enough to consider that the blade is far from failure.

With increase of flow velocity, von Mises stress in the blade increases. The fluid load on the structure at the current flow velocities are not significant enough to affect the design of the blade.

The model developed in this study can be used to decide the best material for the wind turbine blades among different materials under different loading conditions. Also it can be used to examine the strength and stiffness of the turbine blades made of selected materials for different wind velocities. In future works, turbine design parameters such as turbine height and diameter, blade chord length, and number of blades can be changed and this model can be used easily.

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The Declaration of Conflict of Interest/ Common Interest

No conflict of interest or common interest has been declared by the author.

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