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Modelling and Analysis of Deformation and Stresses in Horizontal Axis Wind Turbine

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ABSTRACT

This study compares the strength and deformation in blades of a horizontal axis wind turbine made of composite and aluminium alloy. A 3D geometric model was generated and imported into a Finite Element code for the purpose of analysis. The Computational Fluid Dynamic (CFD) analysis was coupled with structural analysis using one-way fluid structure interaction. The deformation and stresses produced in the two types of blades (aluminium alloy and composite) were analysed and compared. The tip deflection and stress on the blades were related to the wind speed and Yaw angles. The obtained results are compared and discussed in the context of similar studies available in the published literature.

1. Introduction

Wind turbines are widely used for conversion of the wind power into mechanical or electrical energy. Vertical axis wind turbines (VAWT) and horizontal axis wind turbines (HAWT) are the two main types used for obtaining power. The complicated structure of the rotor and material of the turbine blades make the design, analysis, fabrication and testing of the wind turbine a complicated task. Current research on the topic is largely focused on the design and development structure made of lightweight and high strength composite material based on carbon fiber reinforced polymer (CFRP) capable of sustaining volatile and harsh environmental conditions. Besides structural integrity, the aerodynamic performance at a lower cost is another parameter for evaluating the efficiency of wind turbines, designs and the examination of economical and durable materials. Analytical modelling and numerical simulations are replacing complex and costly experimental set ups for evaluating the performance of large wind turbines. Recent studies have used advanced features available in the Finite Element (FE) codes for coupling CFD and FE analysis of wind and tidal turbines rather than analyzing flow and structural analysis separately [1-6]. One of the advantages of modelling and

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simulations of wind turbines is the optimization of the turbine for maximum output [7-10]. A comprehensive review of the testing of wind turbine blades can be found in recent research studies [11, 12]. The large structure of wind turbine blades made of composites with complex aerodynamic profiles are used for commercial applications.

Conducting experiments for evaluating the performance of wind turbines is costly and time consuming. However, simulating wind turbine through Computational Fluid Dynamics (CFD) software offers inexpensive solutions for efficiently analysing it. The deformation of the blades and the resulting stresses produced in the turbine blades are the most important parameter predicting the strength of the blades to withstand harsh wind conditions and the aerodynamic performance of the turbines [13, 14]. The main aim of the current study was to compare the strength and analyse the deformation behaviour of wind Horizontal Axis Wind Turbine blades made of composite and aluminium alloy. A full geometric model was analysed in FE code ANSYS Fluent (version 2020 R1) by coupling CFD analysis with structural analysis. The level of deformation and stresses generated in the two types of blades are compared with the data available in the published literature. The details of the geometric and computational models and results are presented in the proceeding sections. The results obtained from the study are discussed in the context of available studies in the literature.

2. Materials and Methods

2.1 Geometry, Mesh and Boundary Conditions

The geometric modelling of the wind turbine blade is based on the parameters and technical specifications as reported in Ref. [15]. Unlike the symmetrical model presented in Ref. [16], a full geometric model was considered in this study. A full scale turbine blades were attached to a hub and a column was added to complete the geometry. The solid body was imported to ANSYS for simulating flow pattern over blades and calculating stresses and deformation in the blades. The analysis of the wind turbine was divided into four parts: geometric modelling and importing to analysis platform, CFD modelling, Finite Element Analysis (FEA) and coupling CFD analysis with FEA. The geometry of the turbine, fluid domain and rotating domain are shown in Figure 1.

The mesh sensitivity analysis was performed to determine the mesh size suitable for analysis. The face sizing option was applied to the rotor surface with an element size of 0.07 m. The total number of elements used in the analysis was 8,136,238. This mesh size was sufficient for obtaining a smooth profile of velocity, pressure in CFD analysis and deformations and stresses on the blades in FEA. The fluid domain was kept large enough to keep the blades away from the effects caused by the walls on geometry. The finite Element mesh of the turbine blades is shown in Figure 2. In this study, the k–ω shear stress transport (SST k–omega) model was applied to study the effect of turbulence [16, 17]. This model has widely been used for simulating wind turbines using FE codes [18, 19]. The velocity was assigned to the inlet section of the fluid domain while pressure condition was imposed at the outlet.

2.2 Material Properties

Developed a one way coupled Finite Element (FE) scale model of RM1 SAFL turbine from composite and aluminium alloy to simulate structural integrity and deformations in the blades. Table 1 and Table 2 show the properties of both types of materials used in the current study.

Table 1
Material properties of composite turbine blades

Property	Value
Density [kg/m^3]	1550
Young's Modulus-X [Pa]	1.1375E+11
Young's Modulus-Y [Pa]	7.583E+09
Young's Modulus-Z [Pa]	7.583E+09
Poisson's Ratio-XY	0.32
Poisson's Ratio-YZ	0.37
Poisson's Ratio-XZ	0.35
Shear Modulus-XY [Pa]	5.446E+09
Shear Modulus-YZ [Pa]	2.964E+09
Shear Modulus-XZ [Pa]	2.964E+09

Table 2
Material properties of aluminium alloy blades

Material Property	Value
Density [kg/m^3]	2770
Young's Modulus [Pa]	7.1E+10
Poisson's Ratio	0.33
Shear Modulus [Pa]	2.669E+10
Density [kg/m^3]	2770

3. Results

Simulations were run using a fixed wind speed of 12 m/s. The velocity and pressure around the blades in the rotating and stationary domain are shown in Figure 3. The flow separation surrounding the blades can be seen both in CFD and structural analysis. The distribution of velocity and pressure are shown in Figure 4. A maximum velocity of 98 m/s was found at the outer periphery of the blades. Similarly, the maximum pressure of 2.65 kPa was calculated at the tips of the blades. The distribution of pressure on the surface of the blade and the near surrounding region largely depends on the velocity of the wind, angle of attack, and the geometric profile of the blade.

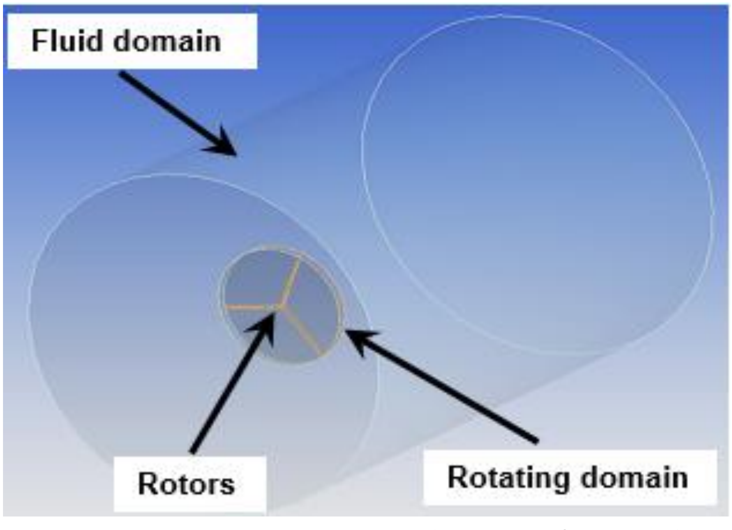
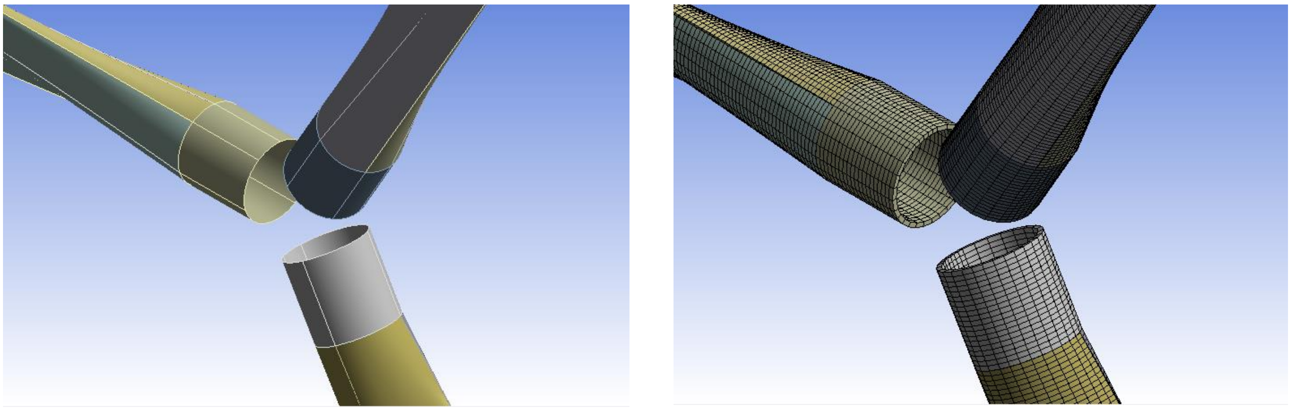
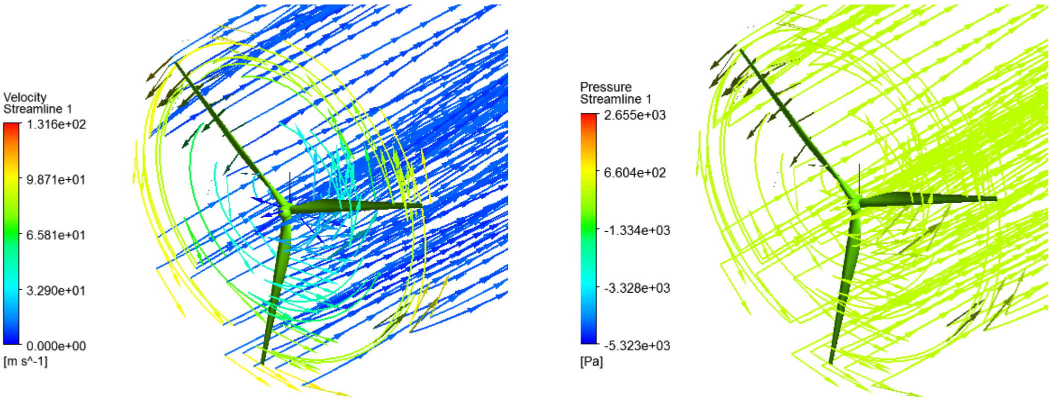


Fig. 1. Geometric and computational domain of wind turbine showing rotors, fluid domain and rotating domain



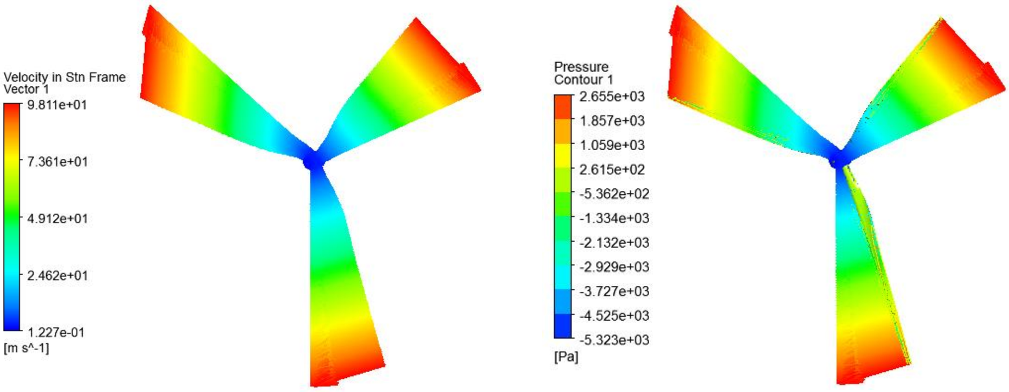
(a) (b)

Fig. 2. Geometry and FE mesh of wind turbine blades



(a) (b)

Fig. 3. Velocity and pressure variation across the wind turbine



(a) Velocity distribution (b) Pressure contour

Fig. 4. Velocity and pressure distribution over rotating turbine blades from CFD analysis (wind speed – 12 m/s)

The pressure exerted on the wind blade was calculated in CFD simulation and was imported as pressure load in structural analysis. A one-way fluid-structure interaction (FSI) scheme was implemented in ANSYS programme for the interaction between the wind domain and structural domains with profile preserving for mapping the imported pressure. The deformation and stresses of turbine blades occur due to the wind forces the blade encounters during rotation. The pressure distribution on the rotating blade surface depends on the inflow velocity, angle of attack, and the profile of the surface of the blade. The total deformation calculated on the tip of the aluminium blade

(876 mm) was more than the deformation found at the same location of the composite blade (635 mm). Similarly, the maximum stress of 43.7 MPa calculated on the front side of the composite blade facing the wind was higher than the maximum stress calculated at the same location of aluminium blade (39 MPa). The location of maximum deformation and stresses at both sides of the blades were the same. The deformation and Von-Mises stresses in blades for both types of materials are shown in Figure 5, Figure 6 and Figure 7.

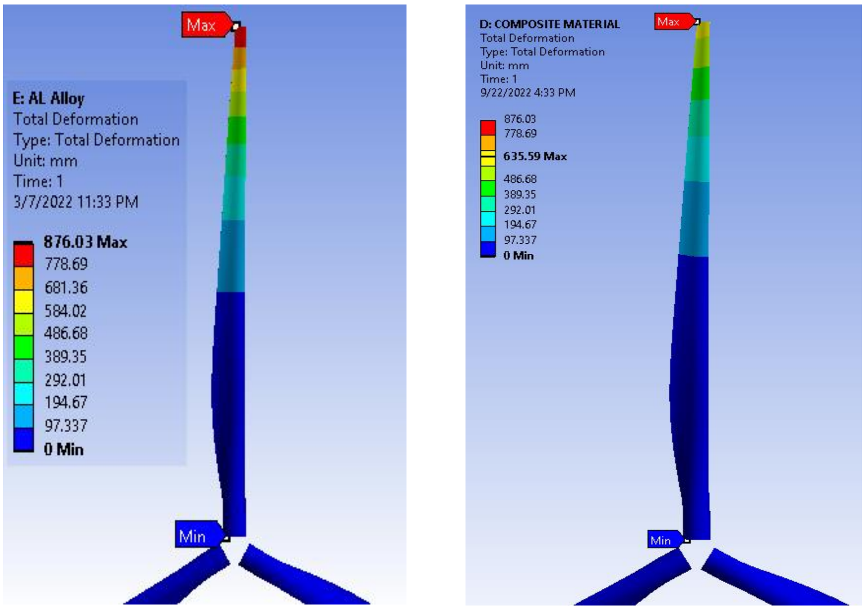
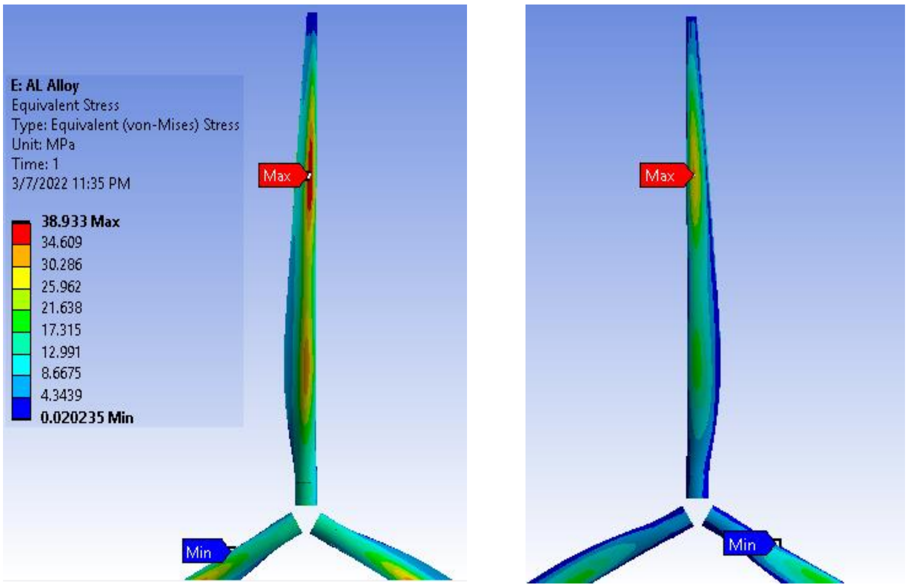
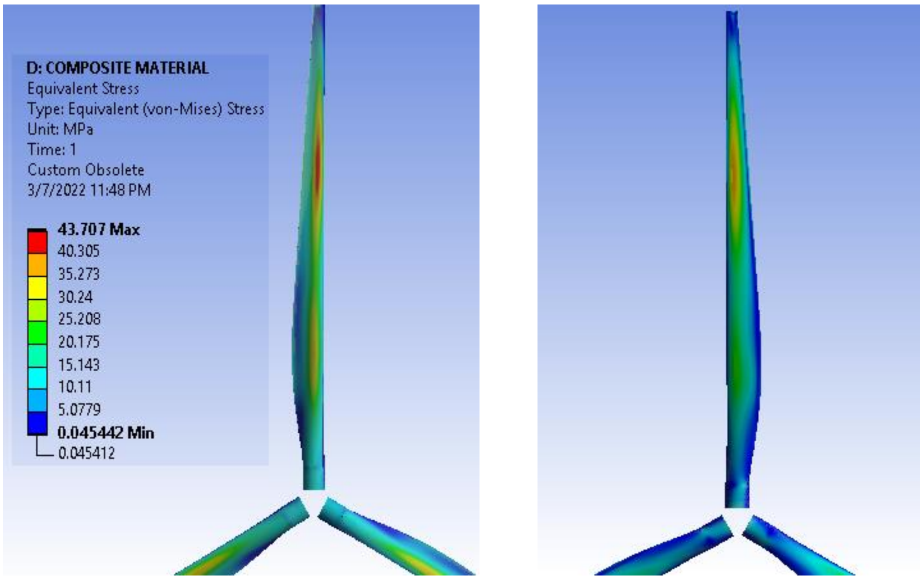


Fig. 5. Deformation of aluminium alloy and composite turbine blades obtained from structural analysis (wind speed – 12 m/s)



(a) Stresses on pressure side (b) Stresses on suction side

Fig. 6. Plots of effective stress of aluminium turbine blades (wind speed – 12 m/s)



(a) Stresses on pressure side (b) Stresses on suction side

Fig. 7. Plots of effective stress of composite turbine blades (wind speed – 12 m/s)

In addition, malfunction of the Yaw mechanism in wind turbines could happen. Therefore, a CFD case of Yaw angle effect has been investigated. Figure 8 and Figure 9 show the tip deflection and equivalent stress at different cross wind speed components applied on composite blade. A component of 1, 2 and 3 m/s of wind speed applied in CFD which correspond as Yaw angle of 4.8°, 9.6° and 14.6° ,respectively at 12 m/s wind speed and to Yaw angles of 2.9°, 5.7° and 8.7° at 20 m/s wind speed respectively. Tip deflection increased from 635 mm at 0 Yaw angle to 680 mm at 14.6° Yaw angle for 12 m/s wind speed. Also, for 20 m/s wind speed, the tip deflection is increased from 896 mm at 0 Yaw angle to 924 mm at 8.7° Yaw angle which corresponds to an increase of 3.1% in tip deflection. Similarly, equivalent stress increased from 43.7 MPa to 46.8 MPa due to the increase of Yaw angle to 14.6° at 12 m/s wind speed and from 59.3 MPa at 20 m/s to 60.9 MPa at Yaw angle of 8.7°. This increase is due to the increase in the drag component across wind turbine.

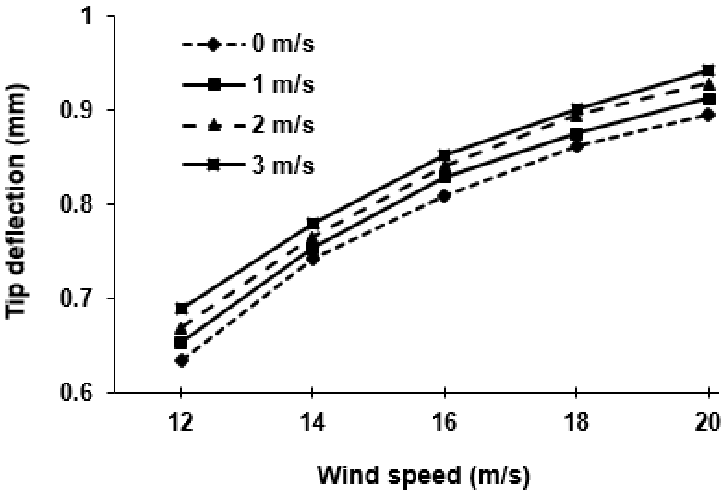


Fig. 8. Plots of tip deflection of composite turbine blades at different Yaw angles

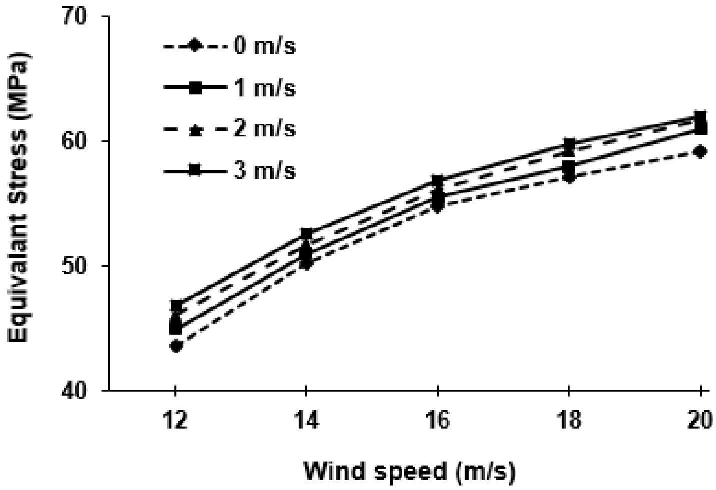


Fig. 9. Plots of equivalent stress of composite turbine blades at different Yaw angles

A complex geometry of a turbine blade and loading and boundary conditions associated with modelling of a wind turbine requires experience in both CFD and mechanics of structures. At the same time, the previous research mainly demonstrates how the geometry of the wind turbine blade influence the power output under varying wind speeds. Since deformation and the resulting stresses are important for the life and efficiency of the wind turbine under extreme loading conditions, this study is mainly focused on the prescribed parameters by considering two types of materials (aluminium and composite). The majority of studies on wind turbine are based on two approaches for the structural part of the FSI modelling namely the Beam model and the Finite Element Analysis (FEA) [20, 21]. This study analysis wind turbine blades made of two materials (aluminium alloy and composite) by coupling two different types of analysis (CFD and structural analysis). One-way FSI coupling, which is primarily the interaction between the fluid flow over a deformed structure, is implemented as the expected maximum deformation at blade tip should not impact significantly on the overall pressure profile on the blade surface. However, it will impact the wake behaviour significantly which is not the focus of this study. The pressure loading obtained from CFD analysis is directly applied to the structure of the blades and the resulting deformation and stresses are measured.

Unfortunately, no experimental data on the blade deformation and stresses were found in the available literature. The deformation was found to be maximum near the tip of the blades which is consistent with the results published earlier. In recent study [16], a one-way coupling analysis of 1500 kW rated power, rotor diameter of 86.5 meters with three blades was performed to investigate the deformation and effective stresses in four types of composite blades. The maximum deformations and stresses found under a wind speed of 12 m/s for four types of composite blades were in good agreement with the current study. In that study, all blades showed increasing trend in stress for a pitch angle of 4◦ regardless of the wind speed which was changed from 8 m/s to 24 m/s in simulations.

4. Conclusions

The current study predicts deformation and stresses of blades on one hand and can be utilized to find the amount of lift on the blade (which is the difference between the pressure on the suction surface and the pressure surface) on the other. The tip deflection and equivalent stress were found to increase with increase in the wind speed. In addition, increase in the Yaw angle also causes increase in the tip deflection and the equivalent stress on the blades. The discrepancies found between the current study and those published earlier are due to the size and geometry of the blade, materials, boundary conditions and loading conditions used in the analysis.

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References

[1] Shkara, Yasir, Martin Cardaun, Ralf Schelenz, and Georg Jacobs. "Aeroelastic response of a multi-megawatt upwind horizontal axis wind turbine (HAWT) based on fluid–structure interaction simulation." *Wind Energy Science* 5, no. 1 (2020): 141-154. https://doi.org/10.5194/wes-5-141-2020

[2] Zhu, Rui, Da-duo Chen, and Shi-wei Wu. "Unsteady flow and vibration analysis of the horizontal-axis wind turbine blade under the fluid-structure interaction." *Shock and Vibration* 2019 (2019). https://doi.org/10.1155/2019/3050694

[3] Borouji, Ehsan, and Takafumi Nishino. "Fluid Structure Interaction Simulations of the NREL 5 MW Wind Turbine—Part I: Aerodynamics and Blockage Effect." *Journal of Offshore Mechanics and Arctic Engineering* 141, no. 2 (2019). https://doi.org/10.1115/1.4040980

[4] Halawa, Amr M., Basman Elhadidi, and Shigeo Yoshida. "Aerodynamic performance enhancement using active flow control on du96-w-180 wind turbine airfoil." (2018): 16-24. https://doi.org/10.5109/1929723

[5] Wang, Lin, Robin Quant, and Athanasios Kolios. "Fluid structure interaction modelling of horizontal-axis wind turbine blades based on CFD and FEA." *Journal of Wind Engineering and Industrial Aerodynamics* 158 (2016): 11-25. https://doi.org/10.1016/j.jweia.2016.09.006

[6] Badshah, Mujahid, Saeed Badshah, James VanZwieten, Sakhi Jan, Muhammad Amir, and Suheel Abdullah Malik. "Coupled fluid-structure interaction modelling of loads variation and fatigue life of a full-scale tidal turbine under the effect of velocity profile." *Energies* 12, no. 11 (2019): 2217. https://doi.org/10.3390/en12112217

[7] Borg, Mitchell G., Qing Xiao, Steven Allsop, Atilla Incecik, and Christophe Peyrard. "A numerical structural analysis of ducted, high-solidity, fibre-composite tidal turbine rotor configurations in real flow conditions." *Ocean Engineering* 233 (2021): 109087. https://doi.org/10.1016/j.oceaneng.2021.109087

[8] Lee, Hak Min, and Oh Joon Kwon. "Performance improvement of horizontal axis wind turbines by aerodynamic shape optimization including aeroealstic deformation." *Renewable Energy* 147 (2020): 2128-2140. https://doi.org/10.1016/j.renene.2019.09.125

[9] Polat, Ozge, and Ismail H. Tuncer. "Aerodynamic shape optimization of wind turbine blades using a parallel genetic algorithm." *Procedia engineering* 61 (2013): 28-31. https://doi.org/10.1016/j.proeng.2013.07.088

[10] Jureczko, M. E. Z. Y. K., M. Pawlak, and A. Mężyk. "Optimisation of wind turbine blades." *Journal of materials processing technology* 167, no. 2-3 (2005): 463-471. https://doi.org/10.1016/j.jmatprotec.2005.06.055

[11] Bin, Yang, and Sun Dongbai. "Testing, inspecting and monitoring technologies for wind turbine blades: A survey [J]." *Renewable and Sustainable Energy Reviews* 22 (2013): 515-526. https://doi.org/10.1016/j.rser.2012.12.056

[12] Hossain, Md Liton, Ahmed Abu-Siada, and S. M. Muyeen. "Methods for advanced wind turbine condition monitoring and early diagnosis: A literature review." *Energies* 11, no. 5 (2018): 1309. https://doi.org/10.3390/en11051309

[13] Hren, Gorazd. "Numerical Analysis of a Wind Turbine Blade with Different Software." *Tehnički vjesnik* 26, no. 4 (2019): 1017-1022. https://doi.org/10.17559/TV-20180615151600

[14] Wang, Hao, Bing Ma, Jiaojiao Ding, and Shuaibin Li. "The modeling and stress analysis of wind turbine blade." *TELKOMNIKA Indonesian Journal of Electrical Engineering* 12, no. 6 (2014): 4178-4183. https://doi.org/10.11591/telkomnika.v12i6.5536

[15] Mezaal, Naji Abdullah, K. V. Osintsev, and S. V. Alyukov. "The computational fluid dynamics performance analysis of horizontal axis wind turbine." *International Journal of Power Electronics and Drive Systems* 10, no. 2 (2019): 1072. https://doi.org/10.11591/ijpeds.v10.i2.pp1072-1080

[16] Roul, Rajendra, and Awadhesh Kumar. "Fluid-structure interaction of wind turbine blade using four different materials: numerical investigation." *Symmetry* 12, no. 9 (2020): 1467. https://doi.org/10.3390/sym12091467

[17] Abobaker, Mostafa, Sogair Addeep, Lukmon O. Afolabi, and Abdulhafid M. Elfaghi. "Effect of Mesh Type on Numerical Computation of Aerodynamic Coefficients of NACA 0012 Airfoil." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 87, no. 3 (2021): 31-39. https://doi.org/10.37934/arfmts.87.3.3139

[18] Sørensen, Niels N., J. A. Michelsen, and Scott Schreck. "Navier–Stokes predictions of the NREL phase VI rotor in the NASA Ames 80 ft× 120 ft wind tunnel." *Wind Energy: An International Journal for Progress and Applications in Wind Power Conversion Technology* 5, no. 2-3 (2002): 151-169. https://doi.org/10.1002/we.64

[19] Mo, Jang-Oh, and Young-Ho Lee. "CFD Investigation on the aerodynamic characteristics of a small-sized wind turbine of NREL PHASE VI operating with a stall-regulated method." *Journal of mechanical science and technology* 26, no. 1 (2012): 81-92. https://doi.org/10.1007/s12206-011-1014-7

[20] Hansen, Martin Otto Laver, Jens Nørkær Sørensen, S. Voutsinas, Niels Sørensen, and H. Aa Madsen. "State of the art in wind turbine aerodynamics and aeroelasticity." *Progress in aerospace sciences* 42, no. 4 (2006): 285-330. https://doi.org/10.1016/j.paerosci.2006.10.002

[21] Zhang, Pinting, and Shuhong Huang. "Review of aeroelasticity for wind turbine: Current status, research focus and future perspectives." *Frontiers in Energy* 5, no. 4 (2011): 419-434. https://doi.org/10.1007/s11708-011-0166-6