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Numerical Modeling and Analysis of a Horizontal Axis RM1 NACA-4415 Wind Turbine

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ABSTRACT

Wind turbines are widely used for conversion of the wind power into mechanical energy. The failure of the blade during operation is a common phenomenon which can lead to the degradation of the power output. Modeling and analysis of wind turbine blade is critical for the design and safe and efficient operation. In this study, a one-way coupled Finite Element (FE) scale model of RM1 SAFL turbine is developed to simulate structural integrity and deformations in the blades. The study is primarily focusses on the strength and deformation of the blades under varying wind speeds ranging from 5 m/s to 30 m/s. The wind turbine blades were modelled from aluminum alloy and unidirectional carbon reinforced composite (epoxy carbon). The results obtained from numerical simulation demonstrated higher stresses and blade tip deformation in blades from composite compared to aluminum AL 6061 alloy. Maximum displacements were calculated at the tip of blades and were well under the threshold level. The maximum stress intensity was found in the center of the blades. On the basis of the current geometry, modal analysis of turbine blades was performed and benchmark cases for the dynamic response were investigated. The natural frequency for aluminum alloy was calculated to be almost three time higher than of composite material structure. The modal in case of composite material was approximately 35% of that obtained using aluminum alloy. This study suggests further analysis to predict surface integrity of the turbine blades under more volatile wind conditions.

1. Introduction

Carbon emissions are major contribution to the environmental pollution in the world. According to the latest statistics on world energy published by British Petroleum (BP) [1], power gained from renewable energy sources grew by 17% in the year 2017. Among other sources of renewable energy, wind provided more than half of renewables growth. Unfortunately, carbon emissions are estimated to have increased by 1.6% in 2017 [1]. It is anticipated that at least 20% of the United States energy

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requirements will be obtained from onshore and offshore wind farms. A complete data on expected amount of electrical energy from renewable sources in the Gulf Cooperation Council (GCC) countries is provided in Ref. [2]. Wind energy has emerged as one of the cleanest and sustainable sources of energy. A comprehensive review on the testing of wind turbine blades can be found in recent research studies [3, 4]. One of the most popular design of a wind turbine used in several studies is the horizontal axis wind turbine (HAWT) [5]. Modern wind turbine blades used for commercial applications have large structures with complex aerodynamic profile of the blade and fabricated from composite materials in sandwich configurations.

Tremendous advancement has been done in developing high performance computing systems which have facilitated strength tests of structures and loadings of complex nature [6, 7]. Majority of published research on the aerodynamic performance of wind turbine was performed using finite element (FE) modeling of the interaction of the air and the blade. Among the published studies, majority were focused on the structural integrity using static structural analysis. With the advancement of high performance computational systems have led to the modeling and analysis of wind turbine using dynamic analysis or fatigue life estimation under various loading and environmental conditions [8-10]. One of the major concern in published studies was the vibration control of wind turbines during service and harsh loading conditions [11, 12]. Modeling dynamic characteristics of blades using nonlinear geometric and material properties were studied in Ref. [13, 14].

Wind turbines are widely used as a source of green power replacing other expensive and hazardous sources of energy such as obtained from nuclear and oil and gas power plants. Modeling and analysis of wind turbine blades of different types of materials are widely discussed in the published literature. A number of commercially available FE codes such as ANSYS and ABAQUS are widely used for the static and dynamic behaviour of wind turbines. Recent studies have used advanced features available in the commercially available Finite Element (FE) software for coupling CFD and structural analysis of wind and turbines [15-17]. Composite materials have been the major choice of several industries involved in designing and manufacturing of wind turbine blades as well as research groups [18-22]. Several studies have reported analysis of composite blade with multiple design and performance objectives. A procedure based structural optimization design of Horizontal-Axis Wind Turbine (HAWT) blades was presented in Ref. [18, 19]. The deformation of the blades of wind turbine is one of the most important parameter with regard to the performance of the turbines [23, 24].

The three core components of a wind turbine are the towers, the nacelles and the turbine blades. The tower of a wind turbine should be strong enough to withstand the dynamic loads of the blade rotations and nacelles. Therefore, not only the static structural analysis but also the vibrational analysis of a wind turbine is considered to be of extreme importance when designing a wind turbine structure. Composite laminates are widely used in the wind energy field for the reason of high strength, high stiffness to weigh ratio, higher resistance to fatigue, high temperature resistance and easy to design properties. A wind turbine blade can be considered an elastic beam subjected to stress alterations and random vibrations. That vibrational loads in a wind turbine structure are inevitable and often leads to malignant structural failure. The understanding of the dynamic behavior of a wind turbine blade is very important in order to maximize the blade useful life operational efficiency. Studies comparing strength of blade turbine made of the aforementioned materials under normal loading condition are limited. The current study compares the strength of wind turbine made of two different materials namely aluminum alloy and unidirectional carbon reinforced composite (epoxy carbon). In addition, we performed the modal analysis of the considered NACA-4415 wind turbine blade by computing its natural frequencies and mode shapes.

One of the reasons for analyzing the deformation process and the resulting stresses in a wind turbine blade is to performed numerical simulations, which is the prime focus of this study. Factors contributing to performance of the wind turbine are wind speed and direction, blade design, wind condition (sandy, moist) etc.

2. Materials and Methods

2.1 Geometry, Mesh and Boundary Conditions

The geometry of the turbine and domain of the fluid (air) are show in Figure 1. The turbine model used in this study is produced at 1:40 scale of RM1 SAFL model turbine with a rotor diameter of 20 meters. The blade profile is NACA 4415 with the dimensions of the fluid domain (air) was selected based on the dimensions of the wind turbine. The solid body was imported for simulating flow patter as well as stresses and deformation in the blades. The wind speed was varied from 5 m/s to 30 m/s. The computational domain of fluid was large enough to minimize the effect of the walls on the geometry of the blades.

The numerical domain was divided into 52000 elements for obtaining a smooth profile of velocity, pressure, deformations and stresses on the blades. The turbine and tower were modeled using tetrahedron element. The Finite Element mesh of the whole turbine is shown in Figure 2. A preliminary study was performed with different mesh densities to obtain an optimized mesh for the solution. The fluid domain was given velocity from the front sides of the blades leaving the tail of the hub from the backside of the turbine. The flow field was modeled of both stationary and rotating domains. The fluid was given a velocity at the inlet of the fluid domain whereas and opening condition was for considered for at the outlet. A turbulence model that involves the dissection of the unsteady flow field around the airfoil was analyzed using the κω shear stress transport (SST) model.

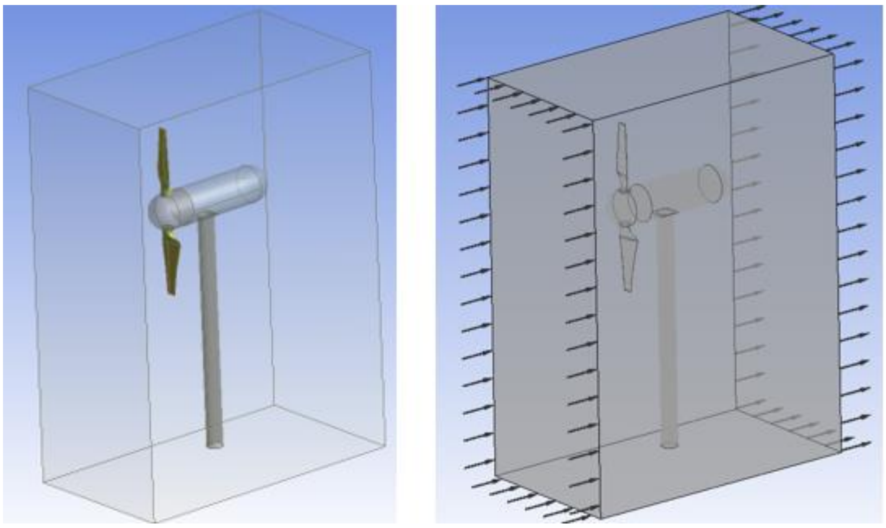

Fig. 1. Geometry of the fluid and structure domains. Arrows showing the direction of the wind at the inlet and outlet of the fluid domain

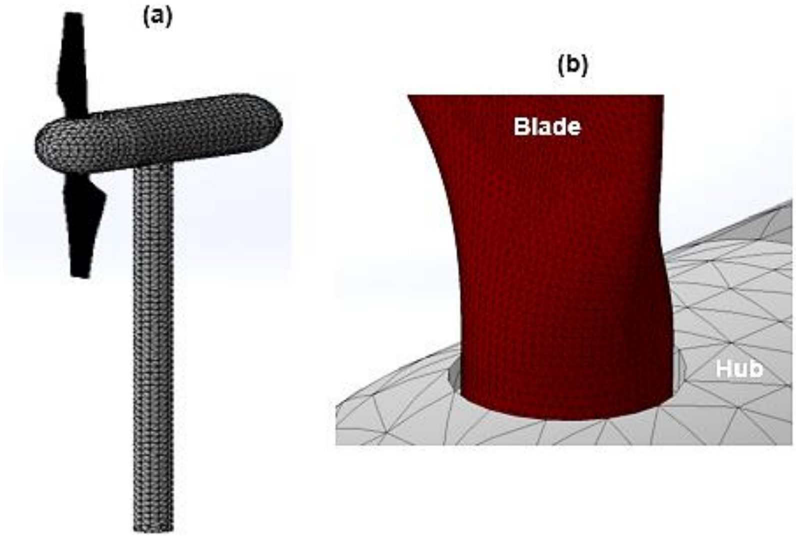

Fig. 2. (a) FE mesh of the whole turbine (b) Closed view of mesh of turbine blade and hub

2.2 Modeling Fluid Structure Interaction

In fluid structure interaction (FSI) module available in commercial FE codes, a fluid dynamics and structure mechanics disciplines are coupled to obtain flow pattern and resulting deformation in the structure simultaneously. In FSI simulations, hydrodynamic forces from fluid flow are applied on a solid structure which either deform or translate them in the direction of the applied forces. The velocity to the fluid domain changes its shape and thus changes as a result of the deformation of rigid body translation of a solid structure. In one-way FSI simulations, small deformations in the structure are assumed where no update and recalculation of flow is considered. Contrary to one-way FSI, large deformations as well as recalculations of the parameters of fluid flow are considered. A schematic of the flow diagram in one-way FSI simulation is shown in Figure 3. In one-way FSI of available in ANSYS Workbench, fluid pressure data is mapped on finite element method (FEM) solid model to evaluate the structural stability. The flow for one-way FSI analysis with the ANSYS software is demonstrated in Figure 4.

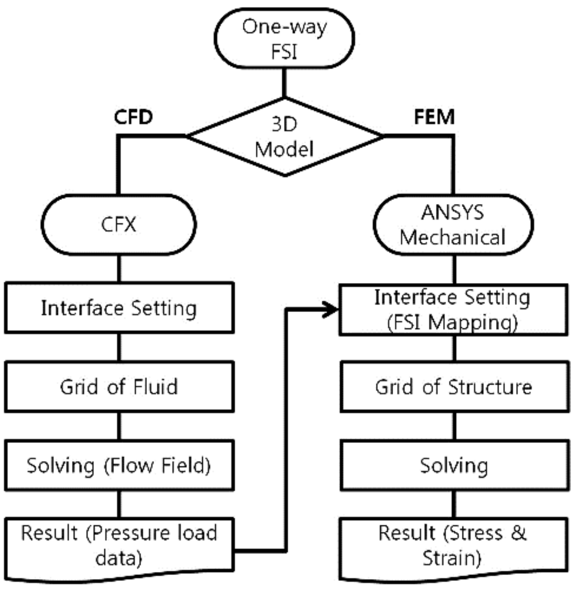

Fig. 3. Flowchart for one-way FSI analysis [25]

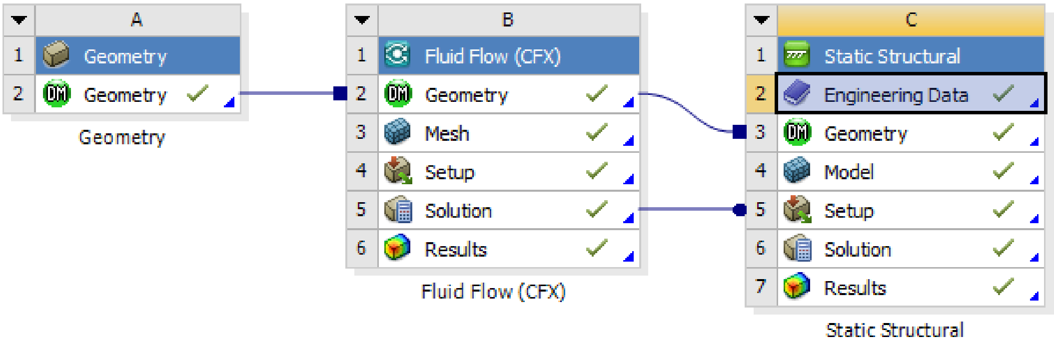

Fig. 4. Schematic of the flow diagram in one-way FSI simulation

2.3 Material Properties

Two different types of materials *i.e.,* aluminum 1060 Alloy and carbon reinforced composite were defined for blades of the turbine. Table 1 and Table 2 show volumetric and the material property of both materials used in the current study.

Table 1
Material properties of wind Aluminium turbine blades

Material Property	Value
Elastic Modulus (MPa)	69000
Poisson's ratio	0.33
Shear Modulus (MPa)	27000
Mass Density (Kg/m3)	2700
Yield Strength (MPa)	27.5

Table 2
Material properties of composite (epoxy carbon) 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

3. Results & Discussion
3.1 CFD Analysis

The simulations were performed by changing the blade materials under a fixed wind load. The velocity and pressure distributions around the blades are shown in Figure 5. The flow separation at blades can be seen near the trailing edge and this variation can also be in the result obtained from the structural analysis. There is a significant flow chaos and formation of vortex can be seen at the downstream flow. A low pressure and low velocity zone is observed at downstream flow. The maximum pressure was found near the middle of the blade. The maximum pressure was in the portion of the blades attached to the hub due to the flow stagnation.

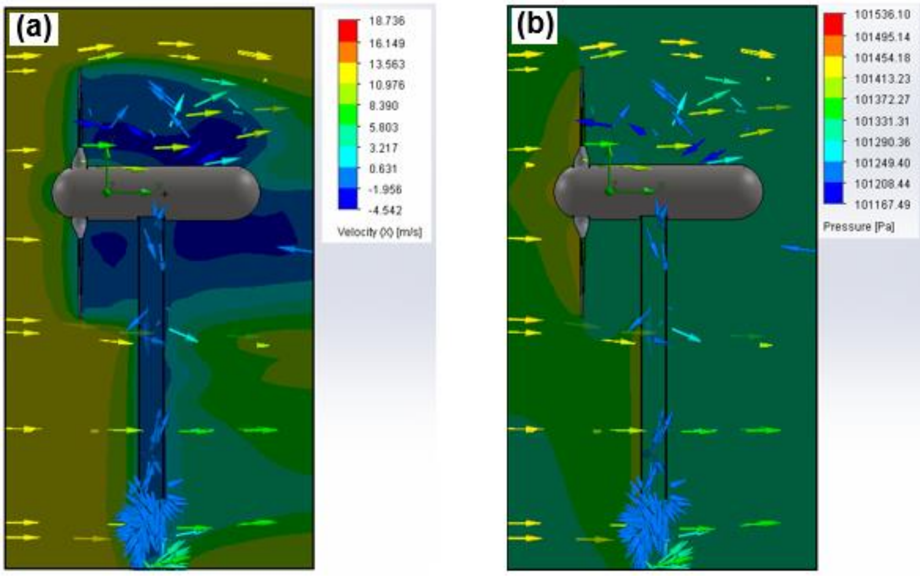

Fig. 5. Velocity and pressure variations across the wind turbine, (a) velocity distribution, (b) pressure distribution

3.2 Structural Analysis

The available FE codes have the capability to provide this interaction where the pressure of the fluid from CFD simulation is applied on structure to predict deformation and stresses. The deformation of blades occurs due to the forces and pressures the blade encountered during wind striking of wind at different speeds. Since small deformations were expected, a one-way fluid-structure interaction (FSI) scheme was implemented for the interaction between the fluid and structural domains. 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 amount of lift on the blade strongly depends on the difference between the pressure on the upper surface (suction surface) and the lower surface (pressure surface).

Computational fluid dynamics (CFD) simulation was performed in ANSYS CFX platform. After performing CFD simulation, the wind pressure on structural domain were imported to the structural analysis and was applied on the whole turbine. Importing wind pressure from CFD simulation was more realistic than applying simply static mechanical pressure on wind turbine as practiced in several published studies. The deformation and Von-Mises stresses in blades for both types of blade using a constant wind speed of 15 m/s are shown in Figure 6 and Figure 7. The equivalent stress on the structure was caused by the hydro-forces developed in CFD analysis. The maximum stress was calculated in the blades near the location closed to the hub. This is because the blades acted as a cantilever beams. In addition, the stress concentration has arisen between blade and hub because of blade deformation. This is due to the fact that the middle part of the blade is the most sensitive part with regard to the damaged. Also, the maximum stress at the portion of the blade attached to the hub was due to the maximum fluid pressure at that region. This was due to the flow stagnation at that region. The deformation was found to be maximum near the tip of the blades which is consistent with the published results.

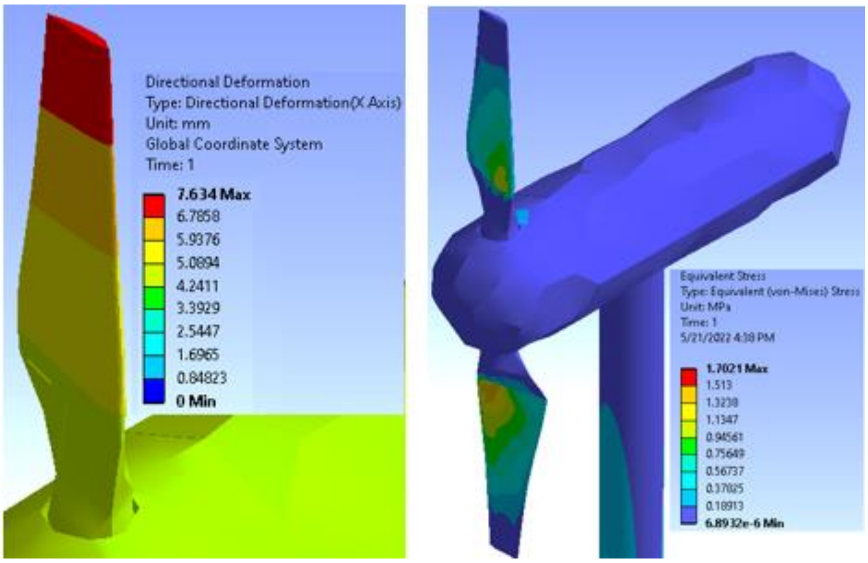

Fig. 6. Tip deflection and Von-Mises stresses in aluminium 1060 alloy blades (wind speed – 15 m/s)

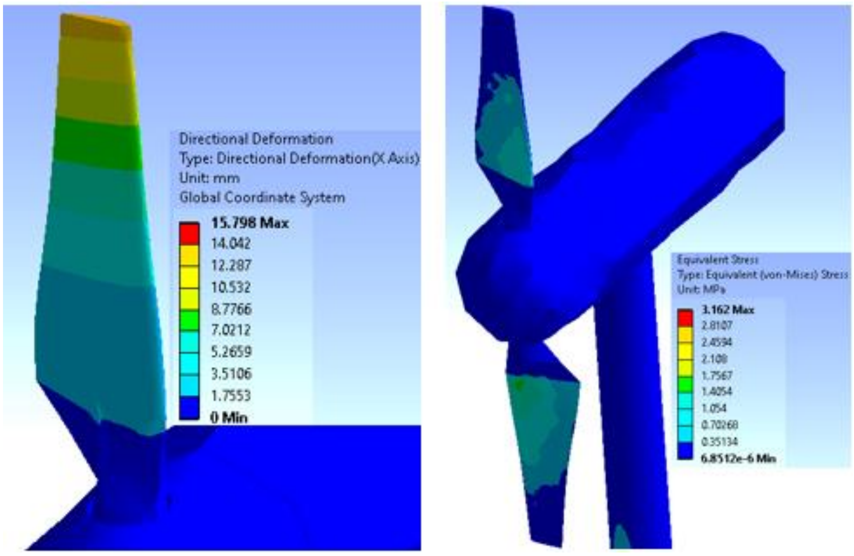

Fig. 7. Tip deflection and Von-Mises stresses in composite blades (wind speed – 15 m/s)

The maximum level of tip displacement and stress in the blades were calculated by varying the wind speed from 5 m/s to 30 m/s. Variation of blade tip displacement and maximum equivalent stress in the blade as a result of varying wind speed for both blade materials are shown in Figure 8 and Figure 9. Both the tip displacement and the stress were found to increase with increase in the wind speed. The maximum tip deflection was found to be 30 mm and 56 mm for aluminum alloy and composite blade, respectively when the wind speed was kept at it maximum value (30 m/s). Similarly, slightly more stress (6.5 MPa) was calculated in the aluminum blades compared to 5.5 MPa in composite for the same wind speed.

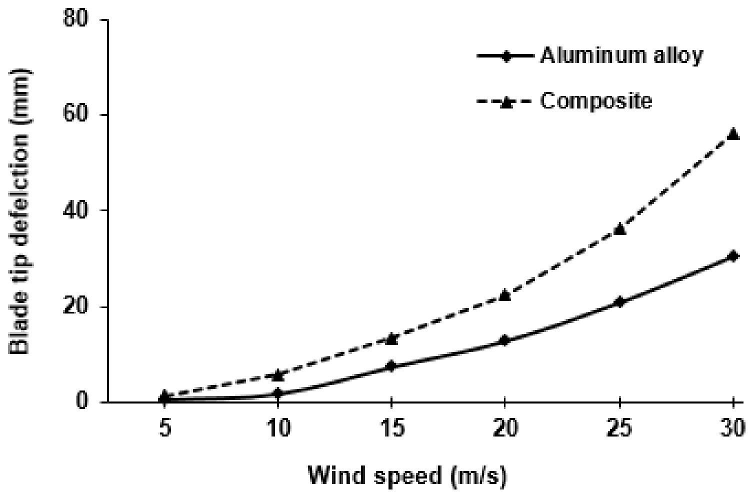

Fig. 8. Variation of blade tip deflection with wind speed

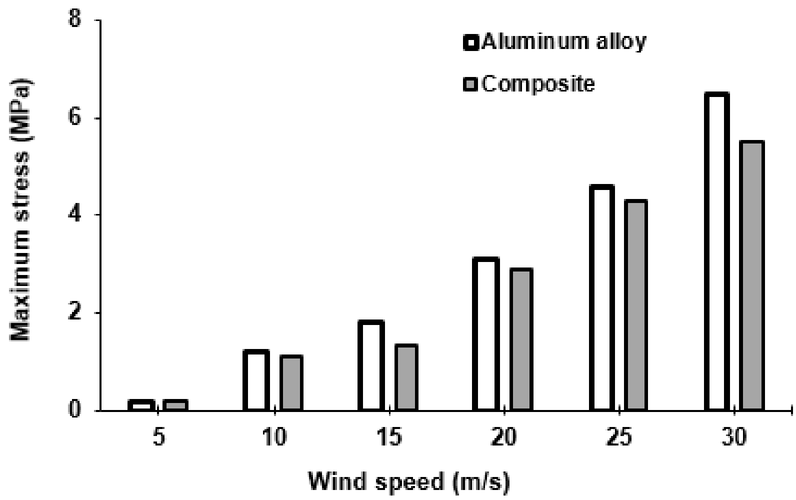

Fig. 9. Variation of maximum stress with wind speed

A wind turbine blade (NREL 5MW) comprising of carbon fiber epoxy composites, glass fiber and PVC foam core enhanced with stiffeners was analyzed in Ref. [26]. The maximum and minimum effective stresses were 108.8 MPa and 60.9 MPa for blade angular position of 120o and pitch angle of 15^{o}. The lower stress found in the current study was due to the use of polyester and without stiffeners. A wind mill blade made of Aluminum and Glass Fiber Reinforced Polymer (GFRP) under wind load was analyzed in Ref. [27]. A static structural analysis was performed using ANSYS Workbench software. A stress of 84.4 MPa and total deformation of 95.9 mmm was found when AL R250 was used in the analysis. 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.

3.3 Modal Analysis

We performed the modal analysis of the considered NACA-4415 wind turbine blade by computing its natural frequencies and mode shapes. For modal analysis we applied fixed boundary conditions at the root of the blade. Figure 10 shows four modes shapes of the considered wind turbine for aluminum 1060 alloy whereas the same are shown for composite laminated structure in Figure 11. For both the cases the most critical modes shape is noted to be mode shape 5. The natural frequency for Aluminum alloy the frequency reaches a value as high as 2.322 Hz. A three time lower value of 0.828 Hz is observed in the case of composite material structure. The frequency obtained in case of composite material is around 35% of that obtained with Aluminum alloy. A relative higher value of 0.173 mm deflection is observed with the composite material structure compared to a value of 0.112 mm in case of Aluminum alloy. The natural frequencies in the other three mode shapes shows a similar behavior with even more lower values with composite material compared to Aluminum alloy. Similar to mode shape, the deflections in case of mode shapes 2, 3 and 4 are still comparatively higher than in case of composited materials. The aerodynamic performance of the two types of blades used in the current study may be further studied by finding the power output and pressure coefficients as studies in Ref. [28].

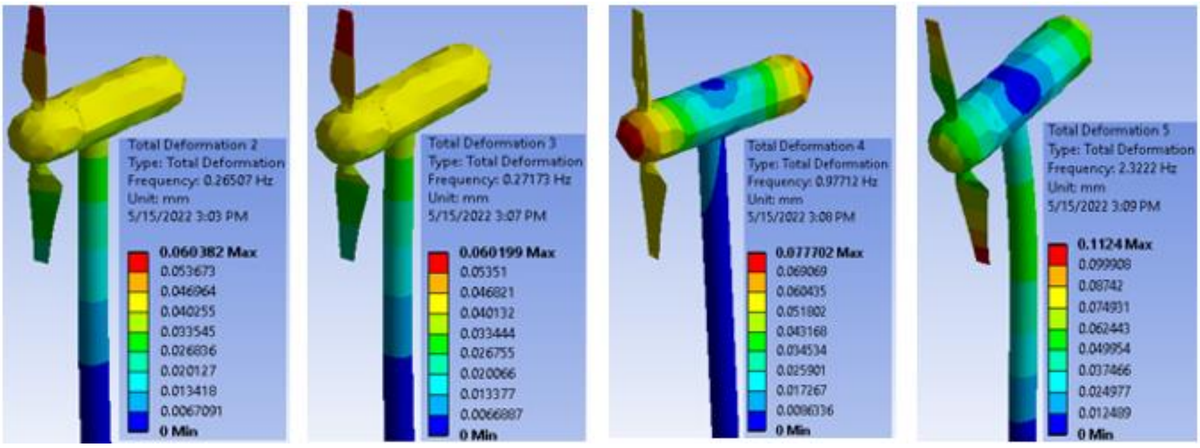

Fig. 10. Mode shapes of aluminium 1060 alloy blades

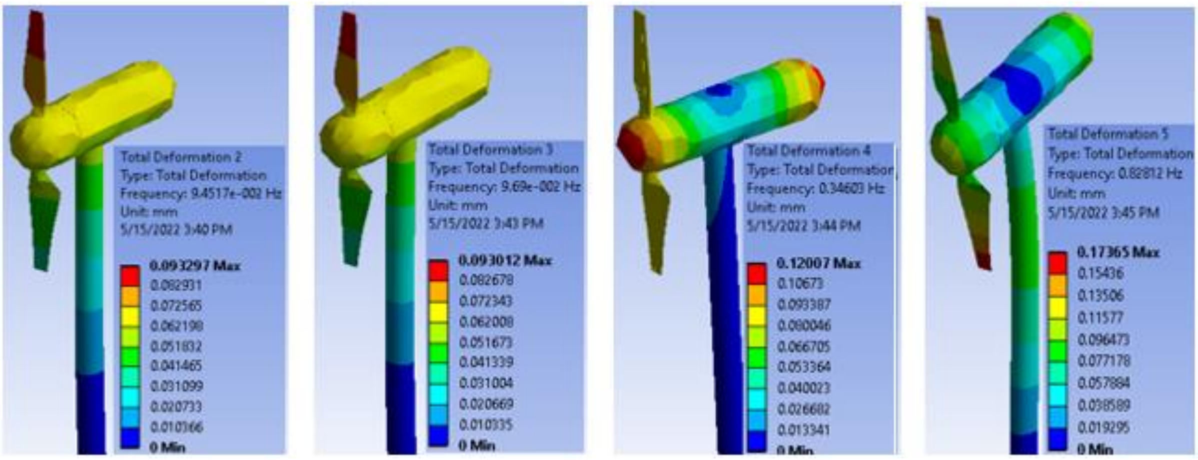

Fig. 11. Mode shapes of composite turbine blades

4. Conclusions

Complex geometry and loading conditions on wind turbine is inherently a high multi-disciplinary area. Computer-Aided Engineering (CAE) software can be efficiently used to model and analyze complex geometry and loading conditions associated with wind turbines. A coupled three-dimensional model of RM1 NACA-4415 wind turbine was developed for the purpose of analysis for stresses and deformation in the blades. Maximum deformation was obtained at the tip of the blades and the maximum stresses were noticed in the areas closed to the centers of the blades. Numerical simulations allow analysis of wind turbines at reduced cost and may help the industry to design and fabricate large scale wind turbines. The current model may be further improved by modeling the blades with composite materials under various volatile wind and environmental conditions. This range of wind speed (5-30 m/s) has been widely used in the available literature. The main objective of the current study was to analyze blade turbine under normal wind loads. More simulations may be run to find the strength and performance of wind turbine made of the aforementioned materials under extrema loadings. Here, only simulations results are presented in this study. Further research is required to validate these results either by conducting experiments using a scaled model of wind turbine or with experimental results published earlier.

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