Energy Engineering
DOI: 10.32604/EE.2020.010666
Article

Experimental Study on Modal and Harmonic Analysis of Small Wind Turbine Blades Using NACA 63-415 Aerofoil Cross-Section

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Received: 17 March 2020; Accepted: 14 April 2020

Abstract: This work focused on modal and harmonic analysis of small wind turbine blades taken from the NACA 63415 series. The sandwich structure type composite blade is fabricated from GFRP and epoxy with Uni-vinyl hard foams of different alignments as stiffeners. In this work, the modal and harmonic analysis of different varieties of blades like solid, hallow and rectangular alignment blades is carried out by the finite element method using ANSYS 18.1 software. From Finite Element Analysis, the natural frequencies, amplitudes and mode shapes are obtained. Based on the working principle of wind turbine blades, the boundary conditions are applied. The experimental investigation is also done using a vibration test rig with specially designed fixtures. The forced vibration approach is used to analyze the responses of the blade with different forces and frequencies which gives the feasible study to define the effective blade structure. In addition to modal analysis, the harmonic analysis is also carried out for different materials to find the amplitude at different frequencies. The outcome of this analysis can be used as a reference for improving the structure and material properties of the blade.

Keywords: Wind turbine blade; NACA 63-415; Uni-vinyl foam; natural frequencies; amplitudes; mode shapes

1 Introduction

Wind turbine blades are typical structures having slender composite shells fastened to the root by a hub. In the service environment, wind turbine blades are affected by different forces and vibrations influencing the efficiency of the blades and leading to failure of the blade structure. Usually, the wind turbine blades are made of glass fiber reinforced epoxy, carbon fiber reinforced epoxy, and glass fiber reinforced polyesters. But the recent composite turbine blades are made of resin matrix with glass fibers having good dimensional stability and corrosion resistance. Vibration analysis is used to find the early cause of machine failure and hence allowing the machinery to be repaired before an expensive failure occurs. Modal analysis tells us about the modal parameters of structures under vibrational excitations. Harmonic analysis is also used to determine the response of steady-state linear structures under the application of loads varying with time. The main idea here is to evaluate the response of the blade to various frequencies and to obtain the graph of frequency versus response quantity. Using this harmonic analysis, dynamic response of wind turbine systems can be investigated both experimentally and analytically. This permits us to determine their mode shapes, natural frequencies and dynamic characteristics.

Ehsan et al. [1] investigated the noise generation and tower vibration characterization. He designed the tower in such a way that the noise emission is minimized. In his research work, the operational modal analysis was done using 24 accelerometers placed on the tower in two orthogonal lines for measurement. For finding operational deflection shapes and natural frequencies he used FDD technology. It was observed that when the turbine produces power, the initial three natural modes resonate significantly with great magnitud Ganesh et al. [2] did the comparative study between the GFRP blade and the GFRP blade with steel wire mesh for natural frequencies and deformation of mode shapes. It was observed that the natural frequencies for the first three modes of GFRP blade with steel wire mesh increase by 2%–3% than the GFRP blade. Also, the mode shapes for the first three modes showing that there is less variation in the deformation of the GFRP blade and GFRP blade with steel wire mesh. The natural frequencies obtained to give the resonant condition frequencies for both the blades. Larsen et al. [3] worked on identifying the natural frequencies, damping characteristics and mode shapes of wind turbine blades using modal analysis. For getting mode shapes, they adopted different experimental procedures on blade LM 19 m and considered an appropriate method for analysis. The selected experimental procedure is quantified by estimating the unsystematic variations. The results are obtained satisfactorily for natural frequencies, damping characteristics and the dominating deflection direction of investigated mode shapes. The blade LM19 m is experimentally analyzed and compared with the results of FEA modeling of the same blade. For few higher modes, substantial discrepancies between the natural frequencies originating from modal analysis and FE modeling are observed.

Cooper et al. [4] worked on the development of the vertical axis wind turbine. The double multiple stream tube type analysis is used as a tool to relate the stability of conventional VAWT blade designs. The vibrational analysis was carried out on the structure of the blades and the different mode shapes. Tartibu et al. [5] studied control of vibrations for lateral bending and vertical bending using pole placement with minimum order observer to perform numerical simulation using a loop simulation platform. The aeroelastic equation is used by the fitting of structural parameters and coefficients of aerodynamics based on six-order Sin6 models and shows the integral behavior of spanwise length. Rao et al. [6] carried out the modal and harmonic analysis for multi-leaf spring for different materials using ANSYS 12.1 and compared them with theoretical values. From the graphs of harmonic analysis, it is observed that E-glass/epoxy and carbon/epoxy have a high amplitude of response than other materials and Kevlar/epoxy, graphite/epoxy and steel have the low amplitude of the response. For E-glass/epoxy maximum amplitude value obtained is 2.5 mm at a frequency of 23 Hz. For carbon/epoxy maximum amplitude value obtained is 1.11 mm at a frequency of 9 Hz. The work done by Thorat et al. [7] provides great leverage in design optimization for better material utilization, weight reduction, elimination of major part for prototype testing and shorter design cycles. The vibration response from harmonic analysis at different locations can be observed. So change of necessary vibration level can be optimized. Chaudhary et al. [8] optimized the blade geometry and designed a micro wind turbine blade using SG 6043 airfoil crossection. The blade was simulated using finite element analysis software and the results obtained for deformations and stresse distribution were compared with an analytical results. It was found that design of blade is safe at 5.37 factor of safety when analzed using analytical method and at 6.72 factor of safety when analzed by structural method.

Krishnamurthy et al. [9] carried out dynamic analysis of wind turbine blades rotating with high speed. The transient and modal analysis studies are conducted using six DOF of 10 beam elements with freedom per node. The blade is fixed at the hub with five DOF constrained. It is found that natural frequencies of blade are varying at different rotational speeds. It is also observed that increase in speed is resulting in more variation of torsional modes as compared to flapwise and edgewise modes. Nambi et al. [10] conducted review study on wind turbine blades designed using blade element momentum theory. The performance of these blades was evaluated interms of tensile stress, compressive stress, shear stress, frequencies, modes and deformations. Both stall and pitch type wind turbine blades are also reviewed with different cut in and cut out speeds. Prajapati et al. [11] concluded from their work that the wind turbine blade with aerofoil section is safe as there is no resonance and its results are confirmed with modal analysis and also verified from the results of mathematical modeling. Mainly the stresses are developed in the hub region as it is located in a small area. The failure of the blades can be avoided by using stiffeners or increasing the thickness in the hub. Deepak et al. [12] found that the maximum stress is induced in the hub root fillet of the blade at 80 MPa wind pressure and in laminate blade profile at 26 MPa wind pressure. The blade and hub are within the yielding limits of materials. The deformation was found around 5.5 mm, which is a predictable pattern and within acceptable limits in linear static analysis. The small wind turbine designs pass all the loading conditions such as gravity load, centrifugal load at rotation. Tenguria et al. [13] designed a turbine blade with a horizontal axis using Glauert's optimal rotor theory. A computer program is developed for getting the thickness, chord and twist distribution along the blade that maintains the lift coefficient constant throughout the blade. The wind is blade divided into nineteen sections and each section has equal length. Using ANSYS with aerofoil NACA coordinates and blade material as E Glass-Epoxy, the blade is modeled and analysis is carried out. The results are compared with experimental values and found that the blade behavior is not symmetric.

Jeylam et al. [14] proposed the monitoring system to monitor all the parameters such as wind speed, direction, generated output voltage and current to analyze the turbine performance at all instants. Using this monitoring system, data can be obtained and stored for analyzing the wind turbine system at any time. Kumar et al. [15] analyzed the design process of winglets using Pro-E software and analysis is carried out using ANSYS in the standard method. From this analysis, we can get the outcomes in the assembling of the wind blade. Implementing the analysis outcome can reduce the blade noise level up to 25% as compared to the plain blade. In operating the blade, the wind speed limits can be optimized and improved for the winglet attached blade. Reddy et al. [16] evaluated the aerodynamic performance of a horizontal axis wind blade with variable speed and fixed pitch through two and three dimensional CFD analysis. The blades design and power output calculations are done with Q-Blade software using blade elemental theory. Comparative study also carried out on power output characterstics for existing blades as well as designed blades. Manikandan et al. [17] studied the characteristics of airfoil profile of NACA 63215 series wind turbine blades. The existing wind turbine blade design was compared with the modified blade design having winglet and the efficiency was also evaluated. It was observed that inclusion of winglet at the blade tip increased the efficiency and also reduced the noise level under blade working conditions.

Kumar et al. [18] created the wind turbine model in CATIA and then imported to ANSYS workbench for the modal analysis. The models developed include some approximation. From the modal analysis, the deformation of the blade due to wind impact is created on parts like blade, tail, tower, and base. The modal analysis was used to find the frequency of the modal to avoid experimental vibration measurement. In a small wind turbine system, vibrations occur due to the impact of wind on the blades. By implementing vibration dampers on the existing wind turbine, vibrations can be reduced. The most important properties like natural frequencies damping and the mode shapes can be determined by the ANSYS workbench modal analysis method. Mathew et al. [19] designed the composite windmill blade for static analysis and under the same loading conditions, the performance of different composite blade materials is compared. The strain, stress, and deformation are validated with FEA software. The results showed that blades made of epoxy carbon and structural steel have undergone less deformation with less stress values but structural steel blade has shown extreme variations. This study concluded that epoxy carbon is a much suitable material for a windmill blade. Ren et al. [20] studied the structural dynamical modeling of a wind turbine. An analytical model capable of predicting the natural frequencies of wind turbines has been proposed based on the free interface component modal synthesis method. The present model employs a thin-walled composite beam theory that can be used effectively for the analysis of tubular thin-walled composite blades. Flexible subsystems such as blades and towers are discretized using Galerkin's method that is computationally efficient compared to the traditional finite element method when applied to compute the dynamic behavior of wind turbines. The results obtained with the present model are in agreement with the ANSYS results. The component modal synthesis method is adopted for modelling the wind turbine blade to study its structural, dynamic characterstics and aeroelastic behavior. The model developed here will be extended to include the effect of aerodynamic loads arising from the imposed wind field. This model also will be used for the analysis of the stability problems of the wind turbine.

The present work focused on blade model geometry consisting of a chord, airfoil distribution, optimal blade weight and use of stiffeners like Uni-vinyl foams to increase the output of overall blade performance. The main objective of this work is the development of a 1 kW optimized power blade model to obtain the maximum efficiency. Here, three blade models like Solid blade, Hallow blade and Rectangular alignment blade are considered. The solid blade uses 5 layers and the gap between layers is filled with chopped standard matt. The other two blades are made of 4 layers with chopped standard matt of 2 layers with weaving roving type fiber of 1 layer $[0^0/90^0]$ of 400 GSM, Weaving roving type fiber of Triaxial type fiber of 1 layer $[0^0/45^0/90^0]$ of 1200 GSM. The rectangular alignment blade uses a stiffener made of Uni-vinyl foam and placed inside the airfoil crossection of the blade. For all these three blades, the modal analysis is carried out for modal parameters such as frequencies and modal shapes on the structure of the blades. The performance of these blades has been evaluated by analyzing the responses using finite element models and experimental methods.

2 Finite Element Analysis

2.1 Modelling of Blade

The nomenclature of an aerofoil blade is shown in Fig. 1. The aerofoil shape usually supports to generate the lift using Bernoulli's effect. Experiments were done on many aerofoil shapes with different wind speeds to study its effect on the noise and power output. Various aerofoil shapes are developed by the National Advisory Committee for Aeronautics (NACA) for applications in wind turbines and aircraft. The aerofoil profile (i.e., shape) of a turbine blade will change the length of the blade by getting flatter and narrower towards the tip of the blade to optimize the lift and minimize drag forces [8].

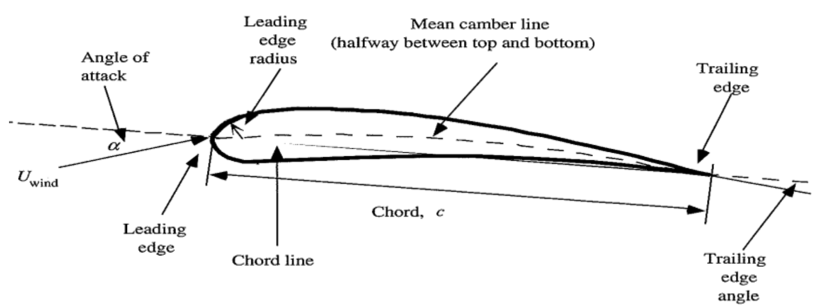

Figure 1: Aerofoil nomenclature [8]

From NACA 6-series, NACA 63-415 aerofoil profile blade is widely used in small wind turbine applications due to its better aerodynamic efficiency. In NACA 63-415 blade designation, the number "6" indicates the series and the second digit describes the distance of minimum pressure area in tens of percentage of chord. Here the area of minimum pressure is 50% of the chord back. The number 3 indicates the drag coefficient near its minimum value and over a range of lift coefficients of 0.3 above and below the designed lift coefficient. The next digit 4 indicates the lift coefficient in tenths (here, 0.4) and the last two digits represent the maximum thickness in percentage chord (here, 21% of chord).

The dimensions and the design details of the blade corresponding to the NACA 63415 aerofoil are imported from the NACA source. The coordinates corresponding to the aerofoil were plotted and joined to obtain the required geometric model. The model shown below is modeled by dividing and making as multi-section solid. The planes were formed along the cross-sectional geometry blade span. For finding the area of the blade, first it is drawn in AutoCAD and then the total area is evaluated as shown in Fig. 2.

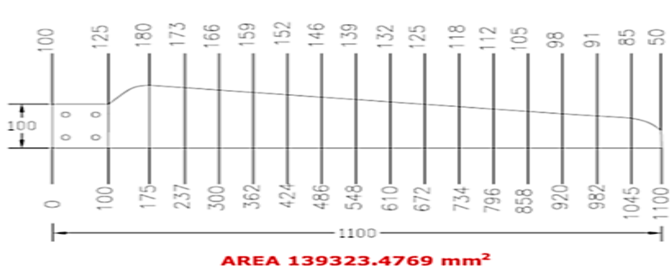

Figure 2: Blade geometry area = 139323.4769 mm²

These multi-sections are combined with a flow of solid using ratio coupling mode. More attention is taken in creating closing points of these multi-sections. The standard method is to model a part in CATIA and importing the file into ANSYS. But a single body of geometry is accepted by ANSYS.

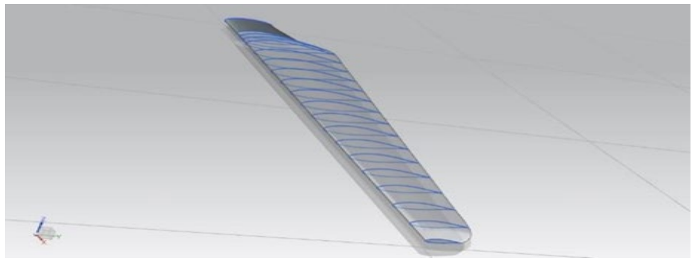

Figure 3: 3D model of the aerofoil blade

There are a different number of coordinate points depending upon the chord length and each of them is imported from the NACA source for the 3D geometric modeling of the aerofoil blade as shown in Fig. 3. For example, below are the coordinates for a chord of 100 mm.

2.2 Mesh Generation

Fig. 4 shows the generated tetrahedron mesh and these tetrahedrons are fit into the curvatures of the blade. Instead of using the patch conforming method, we used patch independent method, where the minimum size of the element and maximum size of the element can be defined. By doing so, smaller elements can also be generated on the curvatures wherein they fit properly. The details of the generated mesh are: Number of nodes = 11249, Elements = 2681, and Transition ratio = 0.272. For the meshing type, the tetrahedral element shape was used. Based on the mesh convergence study graph, the ideal mesh global edge length is 3.42 mm as could be seen in Fig. 5.

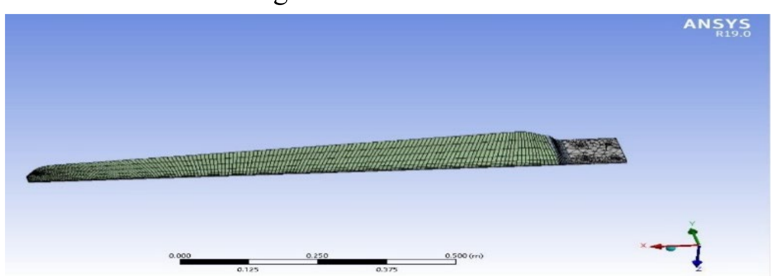

Figure 4: Mesh generation in ANSYS

Table 1: Material properties of a blade

Sl. No	Material used	Modulus of Elasticity E(N/mm^2)	Poisson ratio	Density (Kg/m^3)	Yield stress (N/mm^2)
1.	GFRP + Epoxy	1.8 × 107	0.28	1800	265
2.	UV Foam	86328	0.24	320	--

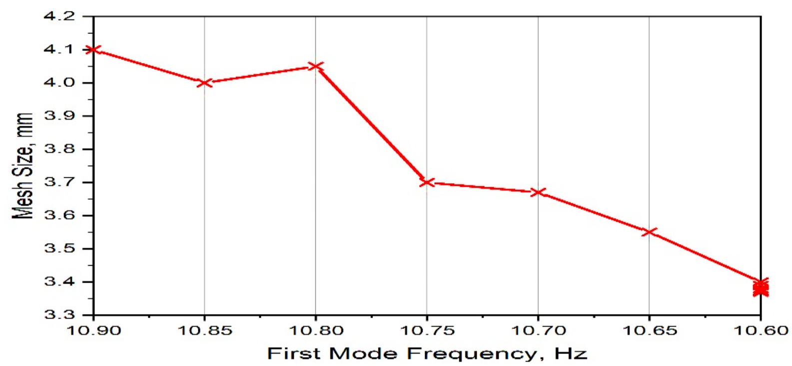

Figure 5: Mesh convergence graph

2.3 Modal and Harmonic Analysis Using ANSYS

Modal analysis is a methodology that allows reliable and fast identification of system dynamics in complex structures. Modal analysis refers to predicting and measuring the frequencies and mode shapes of a given structure. Modal analysis is performed using finite element modeling software ANSYS for GFRP + Epoxy blade with different sections. One end is fixed i.e., the flat end of the plate is fixed like cantilever beam type which is used as a general purpose blade fixed into the hub.

The connection of hub and blade could be regarded as fixed, and all degrees of freedom are restricted at the root for modal analysis and does not require to apply loads. After solving with the solver the vibration modes of all the orders and frequency results could be observed in post-processor.

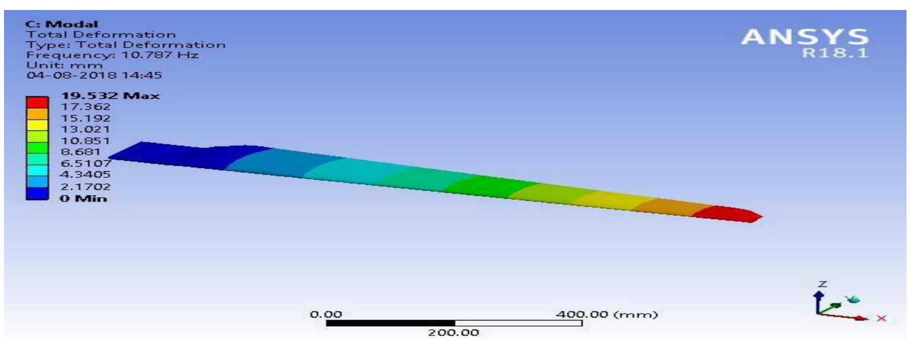

Figure 6: Deformation at Mode 1

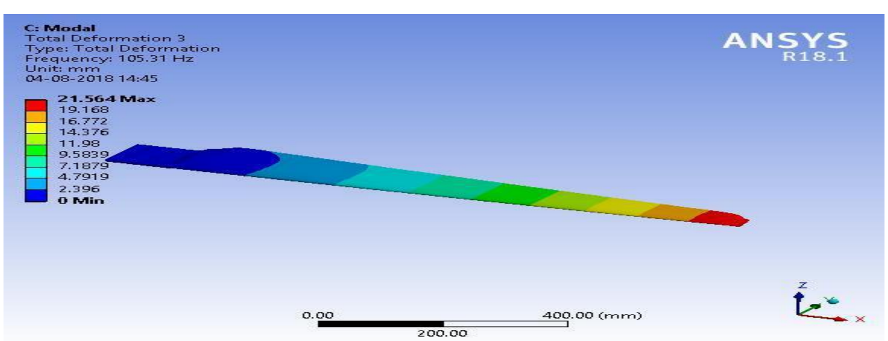

Figure 7: Deformation at Mode 3

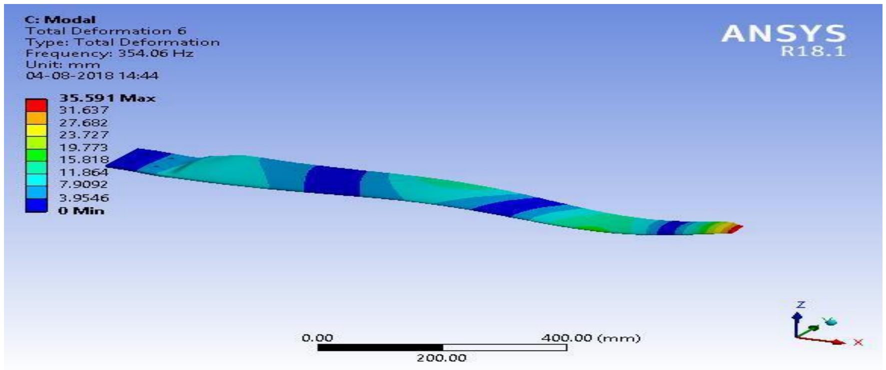

Figure 8: Deformation at Mode 6

Modal analysis is executed on all varieties of the blade and the corresponding mode shapes are developed. Figs. 6–8 show the mode shapes of R22 blade developed using Glass Fiber Reinforced Plastic, epoxy and carbon fiber sheet placed at the tip. From the above table, the frequencies are obtained from the ANSYS 18.1 results, which will be compared to the experimental values by conducting the same testing on the blade. Modal analysis is conducted and the results are used to conclude the best performance of blade under these boundary conditions of modal analysis. Whenever we change the boundary conditions, then its deformation results will be changed as per forces and stresses are developed on the blade. So we are providing the practical condition blade used i.e., blade is fixed at the hub of the rotor. Similarly, the fixture is also used for practical conditions.

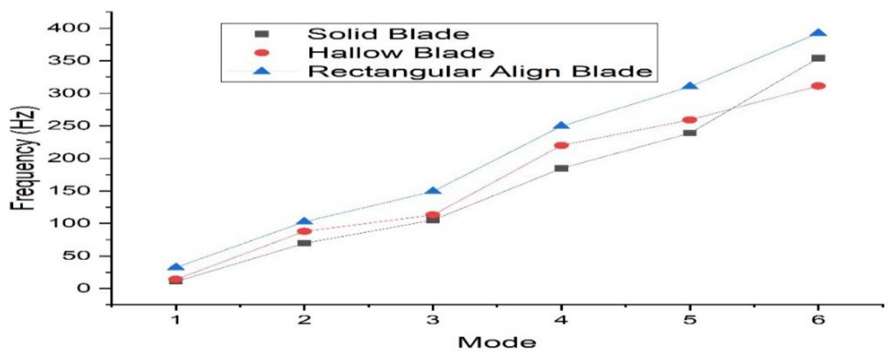

Figure 9: Mode *vs.* Frequency graph of blades

Fig. 9 shows the variations in frequencies of different modes sections of solid, hallow and rectangle alignments blades. The graph represents the frequency curve and also called a structure elevation curve of the blade, which defines the blade condition at a given mode. The frequencies obtained from the ANSYS analysis will be compared to the experimental values by conducting a similar test on the blade. The maximum frequency of 363.76 Hz is obtained at mode 6.

3 Fabrication of Blade

The NACA 63415 series is preferable and suitable for small wind turbine blade models that can be operated at a load of 1 kW power. The blade as shown in Fig. 10 is designed with a length of 1100 mm and a chord portion of 190 mm maximum at the tip. In this work, the three different categories of blades are prepared and they are solid blade, hallow blade and rectangle align the blade.

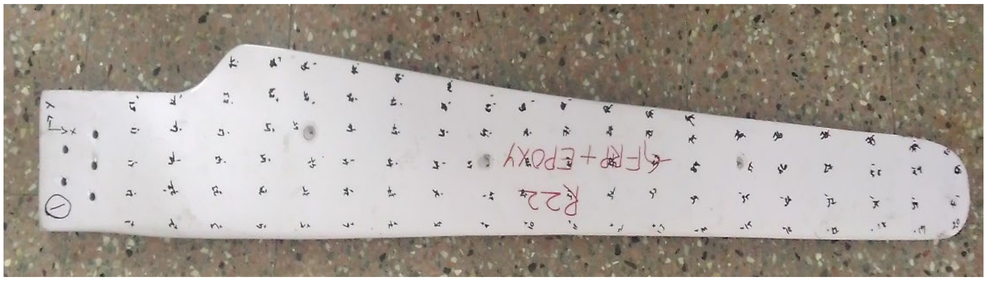

Figure 10: NACA 63415 aero foil fabricated blade

In rectangle align blade the uni vinyl hard form is cut a cross-section of 35 × 750 mm and used as stiffness rib inside the hallow blade. The blade is molded with two halves of a lower and upper portion of the blade made of a sandwich structure.

Figure 11: Stiffener rib of rectangle alignment in one half blade

Which is prepared using biaxial glass fabric reinforced polymers. The addition of UV foam inside the blade will enhance the strength of the blade structure. Fig. 11 shows the lower portion of a blade with a UV foam structure. The blades are fabricated using hand lay-up techniques and different materials like epoxy, hardeners, promoters, accelerators, catalysts, etc., are used.

4 Experimentation

The experimental modal tests and harmonic analyses were carried out for the blades manufactured from GFRP + EPOXY with a carbon fiber sheet at the tip. In this work, DEWESOFT 7.1 software is used for experimental analysis. The experimental set up is shown in Fig. 12.

4.1 Modal Test Setup

In the modal test setup shown in Fig. 12, the blade is fixed at one end like a cantilever beam using a specially designed hub and the Kistler 8776A50 sensor is attached at the other end. This accelerometer sensor is used for sensing the range of frequencies in the blade. This sensor is a simple and constant-current signal conditioner. These sensors are easy to operate and can be interfaced with signal analysis, data acquisition and recording instruments. Using Kistler 9712B50 hammer, dynamic response of a mechanical structure, either in the development phase or in an actual using environment can be readily determined by impulse force testing. Kistler Type 971xB instrumented hammers are used to deliver a measurable force impulse (amplitude and frequency content) to excite the mechanical structure under test. Using an FFT analyzer, the transfer function of the structure can be determined from a force pulse generated by the impact of a hammer at different locations and the response signal can be measured with an accelerometer. The complete experimental output is monitored using DEWE 43 USB data acquisition system having an ultra-portable, high quality, 24-bit data acquisition system with 4 inputs selectable as IEPE (Integrated Electronics Piezo-Electric), voltage or tachometer inputs. The Industry-standard SMA connectors are used for input with optional adapters for other connectors. The size, tough packaging, and power from USB make it ideal for mobile use. Internally there is a comprehensive signal conditioning for IEPE or voltage with anti-alias filters and all these are controlled by software available in the computer setup.

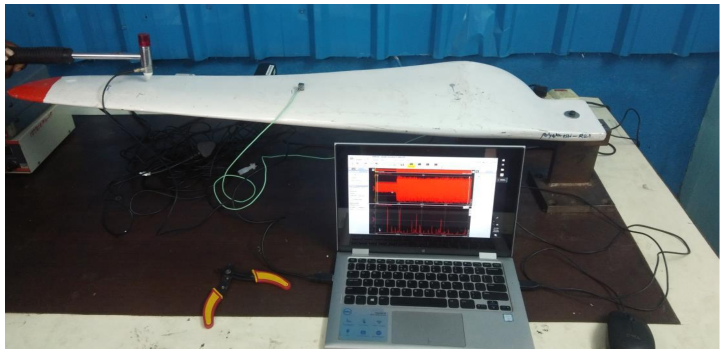

Figure 12: Modal test experimental setup

After completing the setup, marking the equal denominations on the length of the blade for applying the load and set up the sensors. Making the sensors to respond under different load conditions and software receives the frequency values with various ranges.

4.2 Harmonic Test Setup

In the harmonic test setup shown in Fig. 13, fixing of the blade is similar to modal analysis. In this test set up, a 9100Z portable electromagnetic shaker at the center of the blade portion via force transducer is used to create the possibility of altering the dynamics to the blade. The 9100Z Portable Shaker table is the ideal tool to field check accelerometers, velocity transducers and proximity probes over a wide operating frequency and amplitude range. The unit is a small, handy, completely self-contained vibration reference source, and can be conveniently used to validate the entire channel of transducers through measurement, monitoring, or recording systems. An integrated precision quartz reference accelerometer and the shaker table are built with robust carbon fiber composite armature flexure supports and these are capable of simulating vibration on payloads up to 800 grams. The Portable Shaker Table allows users to perform the calibrations over a frequency range of 5 Hz to 10 kHz, and closed-loop level control makes the shaker much easier to use compared to other portable field calibrators. Also, direct BNC connection to the reference accelerometer allows users to check the integrity of the shaker and reference.

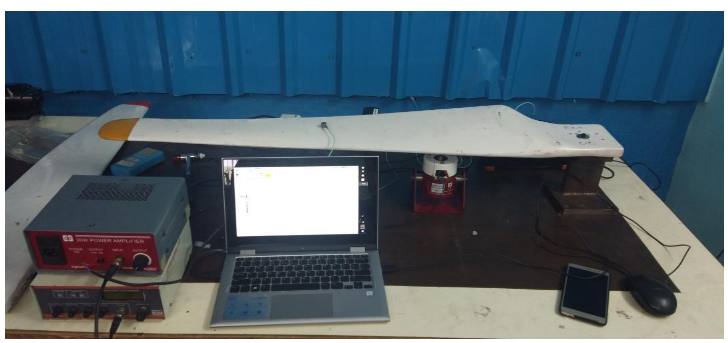

Figure 13: Harmonic test experimental setup

The portable shaker table allows users to perform calibrations over different frequency ranges and the shaker is set up below the blade and produces frequencies about 40 Hz to 360 Hz. The amplitude is recorded at their respective frequencies by using software and data acquisition system.

5 Results and Discussion

Results obtained from modal and harmonic analysis for the blade material of GFRP + Epoxy are presented here. Figs. 14–16 show the graphs obtained from modal analysis through experimental work done on solid, hallow and rectangle alignment blades. In this work, the transfer function ('g' defines the gravity unit for acceleration and 'n' represents the newton unit for force) and frequency developed are considered on Y-axis and X-axis, respectively.

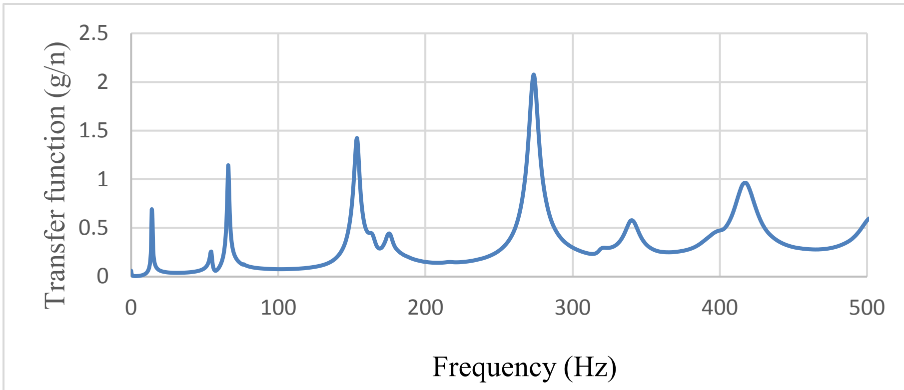

Figure 14: Modal test analysis graph on solid blade

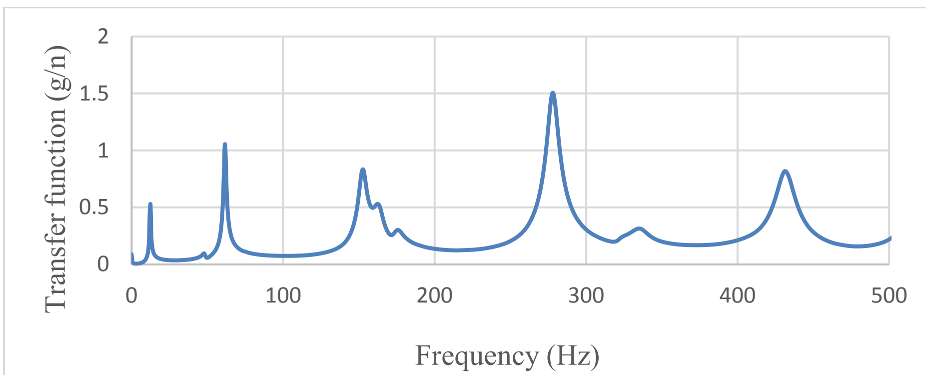

Figure 15: Modal test analysis graph on hallow blade

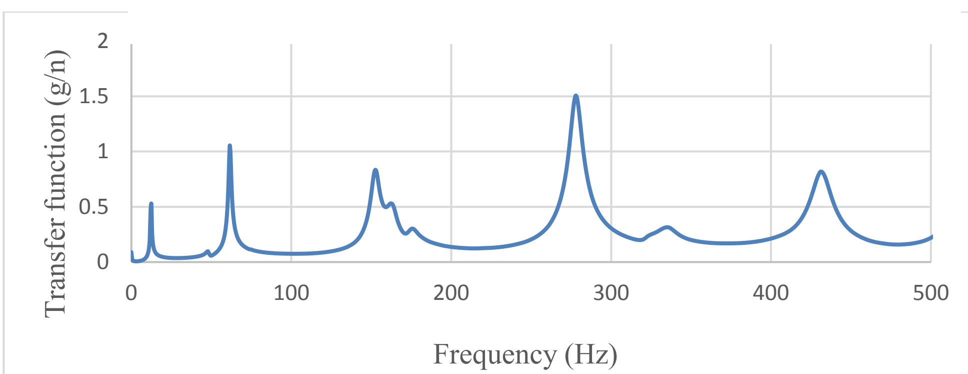

Figure 16: Modal test analysis graph on rectangle align blade

The first modal analysis is done using ANSYS 18.1 and the obtained values are compared with the experimental results. Experimental and ANSYS results calculated in Fig. 17 reflect that all experimental modal analysis results coincide with ANSYS values. It is observed that the 3 blades are subjected to modal analysis to obtain both analytical and practical responses and their results approximately match with the values of different modes of results.

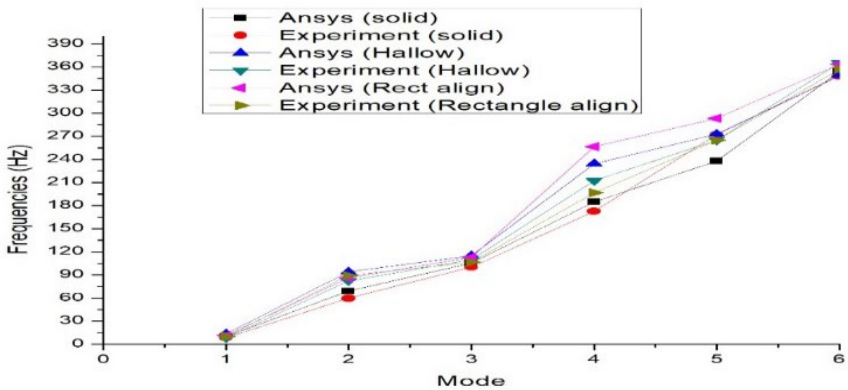

Figure 17: Cumulative comparison on modal test

But in some modes, they act as extremely critical conditions which are subjected to

- For solid blade, the maximum frequency of 354.06 Hz is obtained for analytical conditions whereas 348.23 Hz is obtained as the maximum frequency for experimental conditions.
- For the hallow blade, the maximum frequency of 349.07 Hz and 365.52 Hz is obtained for analytical and experimental conditions, respectively.

For the rectangular UV foam blade, the maximum frequency of 363.76 Hz is obtained for analytical conditions and 356.92 Hz is obtained for experimental conditions.

From the results of modal analysis, it can be observed that the best performance of blades is achieved with rectangular UV foam alignment. For this blade, the natural frequencies obtained are similar in both theoretical and experimental conditions. So it can be suggested that the most probabilistic best performance blade is a rectangular blade with UV foam alignment rather than a hallow and solid blades.

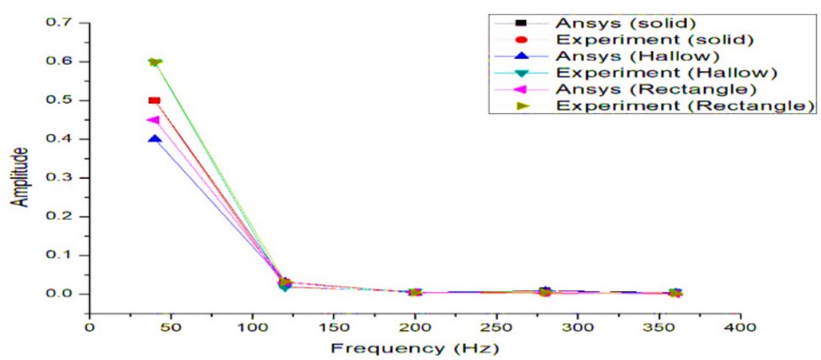

Figure 18: Cumulative comparison on harmonic test

From the harmonic analysis graphs, the resonance frequencies are identified for all the cases considered in this work. The maximum amplitude obtained at a frequency is matched with the natural frequency obtained from ANSYS values as shown in Fig. 18.

6 Conclusions

In this work, modal and harmonic analysis for small horizontal axis wind turbine (HAWT) blade made of different materials is carried out using ANSYS 18.1 and the results obtained are compared with experimental results. From the modal analysis results, it can be concluded that the solid blade had obtained three natural frequencies which are approximately similar to the ANSYS results (8.545 Hz at mode 1, 59.814 Hz at mode 2, and 272.217 Hz at mode 3). Hallow blade had obtained two natural frequencies which are matched with analysis results (8.545 Hz at mode 1, and 264.84 Hz at mode 5). For rectangular

UV foam type blade, it is observed that the frequencies are matched with analysis results which are 89 Hz at mode 2 and 196.69 Hz at mode 4. From a harmonic analysis, it can be concluded that the rectangular blade with UV foam alignment has shown better performance than the other two blades. Hence the blade with rectangular UV foam alignment can be suggested for improving the reliability of small wind turbine blades through the development of aerofoil structure and also by reducing the noise level in the running condition under pressure. The wind turbine blades play an important role in the absorption of energy from wind. Subsequently, the blade has to be designed more carefully to enable it to absorb the energy with its greatest efficiency.

Acknowledgment: The authors are thankful to this institution Vellore Institute of Technology (VIT), Vellore, Tamilnadu, India for its extended support.

Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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