

INVESTIGATION OF EFFECTS OF TRAILING EDGE GEOMETRY ON VERTICAL AXIS WIND TURBINE THROUGH STRUCTURAL AND COMPUTATIONAL FLUID DYNAMICS ANALYSIS

Harsha Vardhan Jeeru

Post Graduate Student, Department of Mechanical Engineering, Chaitanya Engineering College, affiliated to JNTUK, Andhra Pradesh, India

Abstract - Wind energy is one of the rapidly growing sources of a green energy. Moreover the wind turbines can cover a wide range of power outputs compared to other green energy sources. The design and research of low speed wind turbine blades is beneficial to the use of wind energy. The research and development of VAWT for small power applications has been increased during the last eight years. Focusing on improving the VAWT airfoil profile less attention has been paid to the significance of VAWTs to maximize the turbine performance. By considering all statements above, a small scale VAWT is designed for Local wind conditions with improvement in trailing edge shape as well. In the work herein, the effect of the trailing edge profile on the performance of the SB-VAWT is investigated and a new VAWT blade is designed for local conditions. The numerical investigation is based on the Unsteady Reynolds Navier-Stokes equations combined with the transition shear transport model. The results are validated with experimental setup done by Bravo and McLaren. Based on the predictions a local wind turbine model is designed and different trailing edge shapes, are investigated using CFD fluent based on URANS with SST model. The deformations and stresses that are developed due to fluid flow over the surface of the blade are determined using Transient structural analysis in ANSYS workbench. The two main structural vibration analyses, modal and harmonic are also done to understand the behavior of structure under various kinds of loads for different materials and designs.

Key Words: Wind turbine, Aero foil, Composites, velocity

1. INTRODUCTION

Now days, energy shortage is becoming an increasingly relevant question. The world we live in today is one of global warming, deteriorating habitats, climate change, increasing oil prices, financial crises and wars. Much of this can be attributed to the depletion and lack of oil sources, and the methods countries are using to combat. Wind power is an important source of environmental-friendly energy and has become more and more important in the recent years. The amount of installed wind power is increasing every year and many nations have made plans to make large investments in wind power in the near future. In 900 A.D first wind mills were used by Persians in sailing boats, they were Vertical Axis Wind Turbines. During the middle ages, Horizontal Axis Wind Turbines were built in Europe and used for mechanical tasks such as pumping water and grinding grains etc.

1.1 Wind Turbine

A wind turbine is a rotary mechanical device that extracts energy from a wind flow and converts it into useful work. It converts kinetic energy from wind into electrical power. The wind imposes two driving forces on the blades of a turbine, lift and drag. A force is produced when the wind on the downward side of the airfoil must travel a greater distance than that on the windward side. The wind traveling on the windward side must travel at a greater speed than the wind traveling along the downward side. This difference in velocity creates a pressure differential. On the downward side, a low pressure area is created, pulling the airfoil in that direction. This is known as the Bernoulli's principle. Lift and drag are the components of this force vector perpendicular to and parallel to the apparent or relative wind, respectively. By increasing the angle of attack, the distance that the downward air travels is increased. This increases the velocity of the downward air and subsequently the lift.

1.2 Horizontal and Vertical axis wind turbines

H-rotor is an augmented version of Darrieus turbine with straight blades instead of using curved blades. The H-rotor has variable pitch to reduce torque pulsation and is self-starting. The advantages of variable pitch are high starting torque and lower blade speed ratio, a higher coefficient of performance, more efficient operation in turbulent winds and a lower blade speed ratio which lowers blade bending stresses. H-rotor does not require any yaw mechanism system. Straight or curved blades can be used in Vertical axis wind turbine.

2. ANALYTICAL MODELLING

The fixed-pitch straight-bladed vertical axis wind turbine (SB-VAWT) is one of the simplest types of wind turbines with only three main physical components, namely (a) blade (b) supporting strut and (c) central column. The main design parameters related to a smaller-capacity straight blade VAWTs are categorized and listed in Table -1. It should be mentioned that not all of the parameters are of the identical importance for a successful final product. Some of the parameters (like choice of airfoil, supporting strut configuration and shape, solidity, material) are more sensitive and critical than others.

Table -1: List of design parameters

Category	Parameter
Physical features	Blade Shape (Airfoil)
	Number of Blades (N)
	Supporting struts type and shape
Dimensional	Central column
	Swept area
	Solidity
	Aspect ratio
Operational	Chord/Radius ratio
	Rated power output
	Rated wind speed
	Power coefficient
	Tip speed ratio
Balance of systems	Rotational speed
	Tower
	Braking system
Others	Load
	Material
	Noise
	Aesthetic

Power Coefficient (C_p) is a measure of wind turbine efficiency often used by the wind power industry. 'Cp' is the ratio of actual electric power produced by a wind turbine divided by the total wind power flowing into the turbine blades at specific wind speed. When defined in this way, the power coefficient represents the combined efficiency of the various wind power system components which include the turbine blades, the shaft bearings and gear train, the generator and power electronics. The 'Cp' for a particular turbine is measured or calculated by the manufacturer, and usually provided at various wind speeds. If 'Cp' is known at a given wind speed for a specific turbine then it is easy to estimate the electrical power output.

The SB-VAWT rotor solidity (σ) is defined as the ratio of blade surface area (NcH) to the frontal swept area ($2RH$) that the rotor passes through.

$$\text{Solidity} = \frac{Nc}{2R}$$

Where, 'N' = Number of blade

'c' = Chord

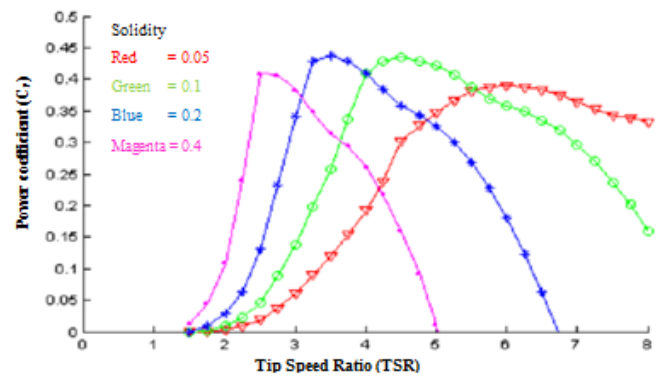
'H' = Length of the blade

'R' = Radius of the turbine rotor.

It represents one of the key design parameters. It is evident from the definition of ' σ ' that both the weight of the VAWT and manufacturing costs increases with increasing ' σ '. In general, a high solidity VAWT rotor turns slowly and produces high starting torque [72]. Thus, a high solidity turbine has an advantage in producing higher torque at low tip speed ratios.

The increase in solidity has the following drawbacks:

Chart -1: C_p (vs) TSR for various solidity



The modeling of a rotating domain consists of three blade sections and a stationary domain. It is created by using CATIA V5 R20 software. 3D single blade is modeled to carry out transient structural analysis along with modal and harmonic analysis. The length of blade is 3750 mm with chord as 400 mm. Along with the blade two struts are created to attach the central column. Struts are created with NACA 0015 airfoil with 200 mm chord. The positions of the strut on the blade are considered from literature by which minimum deformation of the blade are taken into account. The location and dimensions are as shown in Fig 1 (a) and (b).

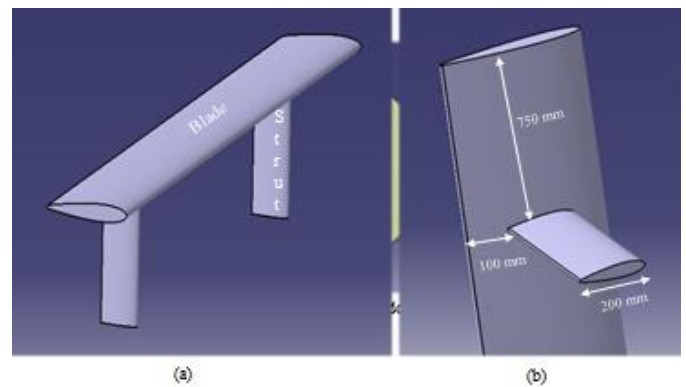


Fig -1: 3D single blade with struts

Transient analysis (sometimes called time-history analysis) is a technique used to determine the dynamic response of a structure under the action of any general time-dependent loads. This type of analysis is done to determine the time-varying displacements, strains, stresses, and forces in a structure as it responds to any combination of loads. Abbreviations used in thesis:

- GWEC - Global Wind Energy Council
- VAWT - Vertical Axis Wind Turbine
- HAWT - Horizontal Axis Wind Turbine
- TSR - Tip Speed Ratio
- FRP - Fiber Reinforced Plastic

RNG	-	Re Normalized Group
CBT	-	Cyclic Butylene Terephthalate
NFC	-	Natural Fiber Composite
FSI	-	Fluid Structure Interaction
GCI	-	Grid Convergence Index

3. CFD ANALYSIS

Four trailing edge shapes have been implemented for the traditional NACA 0015 where the sharp trailing edge is set as the base airfoil from which trailing edge is modified into rounded and two blunt trailing edges. Rounded T.E is created with radius of 10% of the airfoil thickness and this resulted in thicker T.E in order to smooth the airfoil surface. S-blunt and R-blunt are created from cutting of 10% of the chord from rear end of sharp and rounded T.E respectively

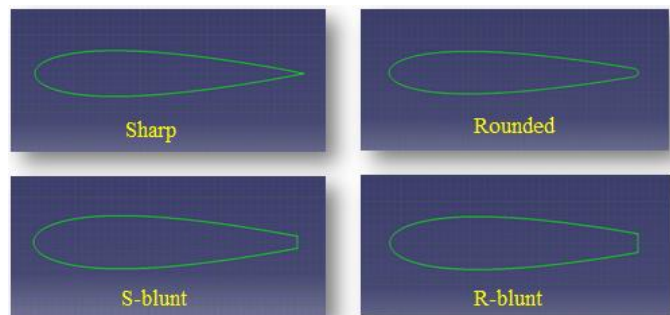


Fig -2: 3D Trailing edge shapes

Design values for fluid domain:

Length of rectangular region = 87.5C

Width of rectangular region = 50C

Radius of circular rotating region = 8.75C

The Computational domain created is completely meshed by structured and unstructured 2-D Cells (triangles or quadrilaterals cells) by using edge sizing, face sizing, inflation and other refinement options in Meshing module of ANSYS 15.0. To differentiate both stationary and rotating domain, the two regions are imported separately from CATIA V5 to Geometric Modelling module of ANSYS as two different zones using "ADD FROZEN" option.

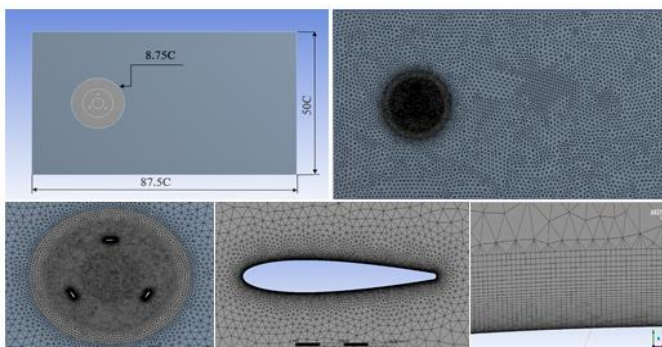


Fig -3: Mesh of model

Two regions are considered one is circular rotating region which contains three equally spaced airfoils of NACA 0015 and a rectangular stationary region which surrounds the circular region.

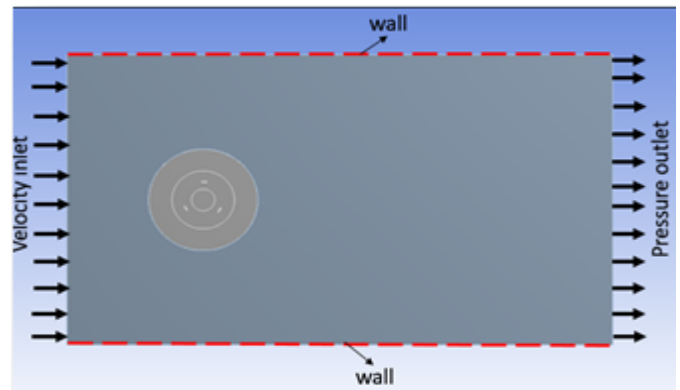


Fig -4: Boundary conditions of fluid domain

3.1 Computational Simulation

The simulation begins with first order scheme for temporal in order to ensure stability of the simulations. Time step size of sufficiently small of order 10^{-3} where turbine completes one full revolution (360°) in 72 time steps and it takes 20 iterations per time step. After few revolutions higher order schemes are employed to ensure better prediction, finally turbine convergence is achieved in 6 revolutions. Convergence assessment is done when periodic torque achieves quasi- steady state called Rolling Average Convergence (RAC). Three positions has been selected to visualize and analyse the flow around the airfoils - 0° , 120° , and 240° .

- 0° - flow is attached and the separation may only be present due to transition of the flow.
- 120° - Dynamic stall conditions (strong separation and vortex shedding).
- 240° - boundary layer separation and vortex shedding settles down

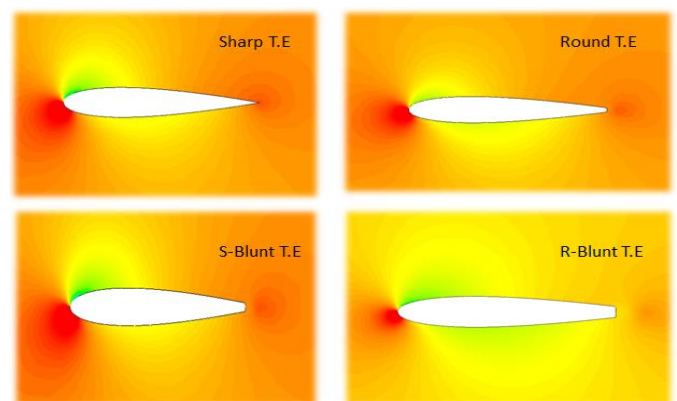


Fig -5: Pressure contours at 0° azimuthal angle for all trailing edges

All pressure contours are similar but with a slight difference in the rounded trailing edge profile. Flow near the airfoil is attached and adverse pressure and laminar separation bubbles do not significantly affect the flow. All contours of vorticity are similar i.e. no effect of trailing edge profile plays around the airfoil.

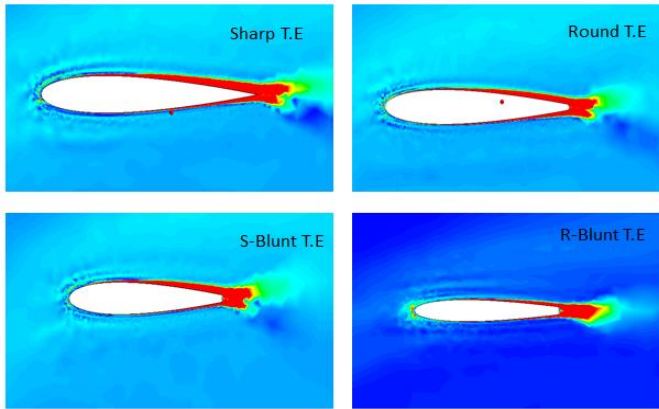


Fig -6: Vorticity contours at 0° azimuthal angle for all trailing edges

Observations of lift and drag coefficient for one turbine revolution at 1.75 and 2.5 TSR:

- Lift coefficient does not change until it approaches the dynamic stall regime i.e angle of attack (α) $\leq 30^\circ$.
- Beyond $\alpha > 30^\circ$ effect of T.E is clearly seen.
- Downstream lift coefficient is higher for Round, Sharp, S-blunt, R-blunt T.E's
- Drag coefficient is higher for rounded one among all T.E.
- For TSR=2.5, rounded T.E profile produces more lift coefficient which is peak at $\alpha = 20^\circ$ compared to sharp, S-blunt and R-blunt T.E
- The drag coefficient is even maximum for Round T.E in both upstream and downstream side

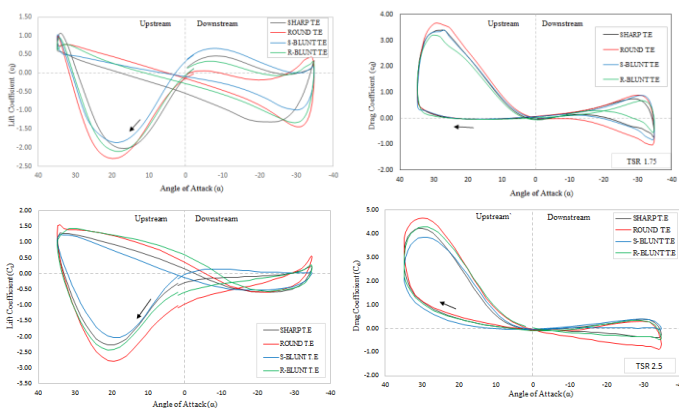


Fig -7: Lift and drag coefficient at 1.75 and 2.5 TSR

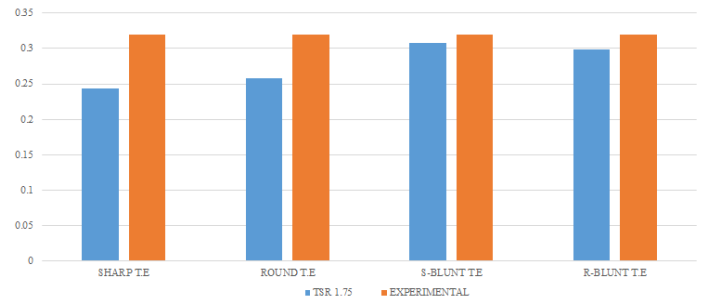


Fig -8: Comparison of power coefficients

4. TRANSIENT STRUCTURAL ANALYSIS

It known that turbine performance is dependent on the material of the blade and there is fluid forces that acts on the turbine blade when it rotates, thus the blades of the turbine must have enough strength to resist the fluid forces. During this interaction of fluid and turbine blade is necessary as the blade experiences stress on its surface. One can compute this stress by performing a fluid structure interaction (FSI) analysis.

In case of a Vertical Axis Wind Turbine (VAWT) blade, the load on the blade due to the interaction of fluid changes its direction and magnitude of loads continuously in one rotation. In the present study a 3D single blade of the VAWT is considered to study the structural analysis. The blade geometry is imported from CATIA V5 into ANSYS transient structural to perform a FSI analysis. This chapter gives a detailed description of the steps involved in performing the fluid structure interaction analysis on a VAWT blade. The fluid structure interaction is done by considering the loads on the VAWT blade.

Fluid-Structure Interaction (FSI) analysis is an example of a Multiphysics problem where the interaction between two different physics phenomena, done in separate analyses, is taken into account. From the perspective of the present application, an FSI analysis consists of performing a structural in the application, with some of the loads (forces or temperatures, for example) coming from a corresponding fluid analysis or previous CFD analysis. In turn, the results of the mechanical analysis may be used as loads in a fluids analysis. The interaction between the two analyses typically takes place at the boundaries that the mechanical model shares with the fluids model. These boundaries of interaction are collectively called the fluid-structure interface. It is at this interface where the results of one analysis are passed to the other analysis as loads.

However, in the present study it is assumed that the deformations are quite small and the variation of deformations with time is relatively slow. Thus, a one way fluid structure interaction is performed on the VAWT blade by transferring the forces from the Fluent analysis system, as a load which is fluid pressure distributed over the surface of the blade of VAWT in transient structural analysis. Transient

analysis (sometimes called time-history analysis) is a technique used to determine the dynamic response of a structure under the action of any general time-dependent loads. This type of analysis is done to determine the time-varying displacements, strains, stresses, and forces in a structure as it responds to any combination of loads.

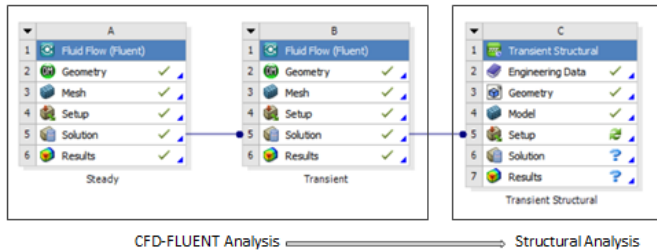


Fig -9: Fluid Structural Interaction Connection

In case of VAWT blade, the solution step in transient analysis of fluid flow fluent is connected to Transient Structural Analysis setup step as shown in Fig 6.1 to import the loads of fluid involved onto the solid 3D blade surface. Materials and its properties which are to be assigned as blade materials are entered. In the view of VAWT blade, six different materials are selected and assigned as shown in table below.

Table 2: Material properties

No	Material	Volume Fraction (%)	Young's Modulus (GPa)	Yield Strength (MPa)	Density (kg/m ³)	Poisson Ratio
1	Aluminium - 2024	-	73	620	2780	0.320
2	E - Glass Epoxy	55	70	2000	1900	0.280
3	Flax Epoxy	46	35	280	1400	0.360
4	Jute Polypropylene	60	11	74	1460	0.396
5	Fiberglass Polyester	30	6.9	86	1356	0.325
6	Fiberglass Polypropylene	20	3.7	44	1024	0.346

The results of transient structural analysis of round trailing edge for different materials are tabulated. The results comprise total deformation and von-Mises stresses at each and individual time steps. For the aluminium material, the maximum total deformation and maximum von-mises stress values, the maximum deformation is obtained in the middle of the blade at 1500 which is found to be 0.078 mm are shown in Fig 6.6 due to loads that are acting on the blade and also the boundary conditions. The maximum stress is obtained at 900 angular position due to max load at that particular time step (ref. table 6.2) and stress value is 3.1276 Mpa which is occurred at the tip of the strut due to fixed support.

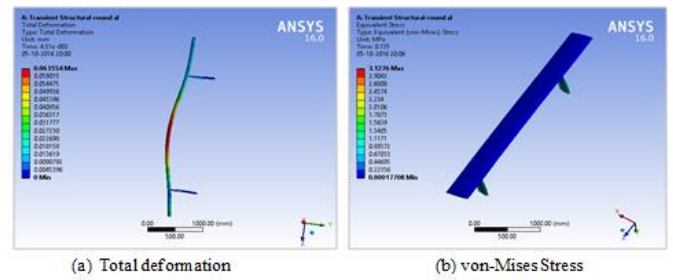


Fig -10: Aluminium-3D VAWT Blade

The present work is of step by step procedure of transient analysis for blade by importing the load developed in the CFD analysis which is Fluid Structure Interaction. A comparative study of transient analysis is done on six different materials like aluminum 2024 which is conventional one, E glass epoxy, Flax epoxy, Jute polypropylene which are natural composites, Fiberglass polyester, Fiberglass polypropylene are synthetic composites. For all the above materials described, the transient analysis for the three different trailing edge-shapes namely Round, Gurney flap and wedge trailing edge designs are done. Transient loads developed on the blade are higher for the rounded one on comparing the deformations and stress for the three designs.

5. MODAL AND HARMONIC ANALYSIS

Modal analysis is the study of the dynamic properties of structures under vibrational excitation. It is an important tool in vibration analysis and diagnosis. The primary and most important objective of modal analysis is to determine the natural frequencies and mode shapes of the test structure. A resonance condition exists when the frequency of excitation due to any source coincides with a natural frequency of the test structure. Therefore it is necessary to know the natural frequencies of the test structure to be monitored prior to the experimentation.

In the course of designing the blade, vibration has to be considered as it is important to avoid dynamic instability in the form of resonance. Resonances can cause fatigue damage and rapid failure. Deformation patterns (bending, twisting,) at these resonant frequencies take on a variety of different shapes depending on the excitation force frequency. In this chapter, the detailed description is given on modal analysis of vertical axis wind turbine by using ANSYS software.

5.1 Procedure for modal analysis in ANSYS

The following steps are followed for modal analysis

- Importing 3D CATIA wind turbine single blade model
- Defining the material properties
- Mesh generation
- Applying boundary condition.
- Solving the problem
- Reporting results

5.2 Results of Modal Analysis

The six types of materials are applied to this wind turbine blade. Various modes of vibration of wind turbine blade model are observed. The first twenty natural frequencies and their mode shapes are generated for Aluminium 2024, E-Glass epoxy, Flax Epoxy, Jute polypropylene, Fiber Glass polyester, Fiberglass polypropylene of wind turbine blade at free load for round trailing edge geometry with fixed struts as boundary condition. The same procedure is repeated for the remaining gurney flap and wedge trailing edges. The mode shape frequencies and its corresponding deformation for the Aluminium material are given in Table 7.1 which are resulted from modal analysis by using ANSYS software

Table 3: Pressure contours at 0° azimuthal angle for all trailing edges

Mo de No.	Round		Gurney Flap		Wedge	
	Frequ ency (Hz)	Max Deform ation (mm)	Frequ ency (Hz)	Max Deform ation (mm)	Frequ ency (Hz)	Max Deform ation (mm)
1	27.475	4.3878	27.082	3.066	27.223	3.0726
2	29.544	3.4791	27.578	3.883	27.684	3.8738
3	56.559	7.7807	50.733	6.198	50.885	6.1903
4	65.295	3.2075	66.251	4.968	66.167	4.7396
5	80.783	4.5733	67.898	4.979	67.848	5.2012
6	96.361	7.2531	75.998	4.441	75.8	4.4406
7	143.67	5.4394	116.53	4.872	116.5	4.8685
8	146.96	7.1686	132.61	4.481	132.76	4.4816
9	206.74	7.5746	220.22	7.145	220.43	7.1483
10	253.50	5.2039	247.76	4.686	249.05	4.6737
11	296.10	14.560	293.34	7.283	293.36	7.2789
12	367.80	6.9239	323.34	10.00	323.37	9.9906
13	373.58	10.263	336.14	7.462	336.17	7.4611
14	401.93	7.6364	365.49	6.801	365.94	6.8172
15	434.68	6.2117	399.61	7.091	400.04	7.1094
16	443.35	16.540	444.45	7.229	444.63	7.2164
17	599.74	7.1357	455.28	5.421	455.89	5.4539
18	611.77	9.6656	564.18	5.056	564.19	5.0563
19	673.68	7.1375	617.32	6.854	617.68	6.5974
20	676.03	10.832	650.39	6.331	651.35	6.0823

5.3 Procedure for harmonic analysis in ANSYS

For harmonic analysis the following steps has to be followed:

- Importing the geometry from CATIA.
- Feeding the Material properties.
- Mesh the wind turbine blade.
- Applying boundary conditions and the loads
- Set frequency range
- Solve the problem

5.4 Results of Harmonic Analysis

The harmonic response of wind turbine blade for materials Aluminium 2024, E-Glass epoxy, Flax Epoxy, Jute Polypropylene, Fiber Glass Polyester and Fiber Glass Polypropylene are analysed using harmonic analysis for different trailing edges. The harmonic force is considered from transient analysis i.e. maximum deformation load in a complete revolution of turbine on blade. For round trailing edge profile geometry, the harmonic force of magnitude $F_x = 834.16$ N, $F_y = 14.01$ N is taken as input and the range of frequencies are defined from respective modal analysis. For Gurney Flap and wedge trailing edge profile geometry VAWT blade, harmonic input is considered accordingly and results are tabulated below along with round trailing edge.

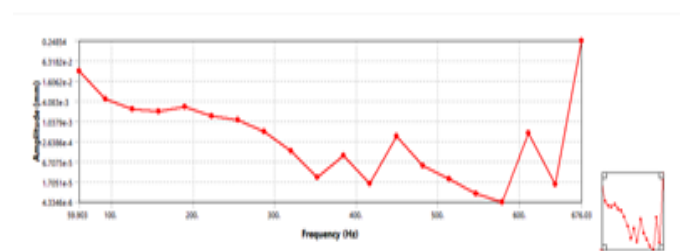


Fig -11: Results of Harmonic analysis for Round trailing edge of NACA 0015

The modal analysis is done for three trailing edge shapes namely Round, Gurney Flap and Wedge using ANSYS workbench. However for each trailing edge model, six different materials of which conventional, synthetic and natural composites are considered for analysis. From the modal analysis, the first twenty natural frequencies and mode shapes are identified for individual materials for the three trailing edge shapes and also range of frequencies are noted. It is observed that for Flax Epoxy and Aluminium 2024 range of frequencies are high and similar where lower range frequencies are identified for other materials. Furthermore harmonic analysis is done for all three trailing edge shapes to observe the response of blade under harmonic load for each material is studied.

4. CONCLUSIONS

The detailed understanding of trailing edge shape importance is captured by writing the values of Lift, Drag and Moment coefficients and from flow visualizations of pressure and vorticity contours as well. The CFD analysis is done with the 2D Unsteady Reynolds Averaged Navier-Stokes equations (URANS) combined with the transition Shear Stress Transport (SST) in order to account for the transition in the boundary layer regions. It is found this combination predicts good as that of real working conditions. From the transient structural analysis, it is concluded that the maximum deformation and von-mises stress formed due to the fluid loads on solid blade material are determined for each individual materials and designs and are attained in between 600 and 900 positions of the

turbine. From modal and harmonic analysis, it is concluded that the mode shapes obtained for Round, gurney Flap and wedge are different due to changes in mass distribution of geometry. Six different materials of traditional, synthetic and are selected to blade material and for these the first twenty modes shapes are obtained and noted the resonance frequencies. Furthermore, harmonic analysis is carried out to study the behavior under fatigue loads. It is concluded that the blade materials chosen can bear the loads as the deformations and stresses are below the design criteria. The designed 3D single VAWT straight blade which is extruded NACA 0015 airfoil section using CATIA V5 is saved in .IGES format and imported. The struts of VAWT blade are also done using NACA 0015 airfoil section. The model is meshed with tetrahedral elements forming 14516 nodes and 7272 elements of 3D blade.

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