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Reduction of Vibrations in a Vertical Axis Wind Turbine using Blade Design Modification

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Abstract – *This research paper serves the main purpose of improving a vertical axis wind turbine performance, by modifying the blade design, hence reducing vibrations of turbine blades. A standard NACA 0024 aerofoil blade was analyzed using the systems of Static Structural and Modal Analysis of Ansys 16.0. The blade was redesigned and optimized to reduce vibration fatiguing, faced during modal analysis. The proposed blade showed reductions in weight as well as vibrations. The randomness in vibrations was reduced, enabling ease of design and safety assurance at the engineer's end.*

Key Words: **Vibration, Modal Analysis, Aerofoil, VAWT, NACA, CFD**

1.INTRODUCTION

Owing to global energy crises, society is shifting towards renewable energy sources. A dominant machine to harness wind energy, Vertical Axis Wind Turbine is finding increasing applications as of today in urban installation. They find widespread use due to their ability to trap wind from all directions and low operating speed capability. However, a major problem encountered is turbine vibrations. These vibrations lead to noise, erratic movements, reduced efficiency, bearing failure, reduction in working life. This research aims to minimize these vibrations and hence the associated problems.

1.1 Vibration Fatigue and its Analysis

In Material Sciences, fatigue is the failure of material due to repeated loading. Vibration fatigue, which is the mechanical engineering term, defining the fatiguing of material due to forced vibrations of random nature. An excited structure responds to vibrations, depending on its modes of natural vibration. This leads to dynamic stresses on the structure. Material fatigue is governed by shape of the structure being excited, and the response produced. These parameters are usually analysed in the frequency domain. Modal analysis is a critical part in the analysis of vibration fatigue, predicting the dynamic stresses at different local points. It does so by displaying the natural modes and frequencies of the structure being studied. This paper incorporates modal analysis of conventional and modified structures.

1.2 Reduction of Turbine Blade Vibration

Blade vibration reduction is crucial in the design of turbomachinery. It is necessary to ensure that the fatigue limit is not overcome by turbine blades, to prevent blade failure. One approach is the snubbing mechanism [1], which physically restricts blade motion using shrouds as barriers to vibration. The approach adopted by this paper is blade profile modification, which alters the weight distribution and frequency response. This also changes the position of the centre of gravity, relative to the centre of rotation.

2. NUMERICAL MODELLING AND PARAMETERS

The turbine blade profile studied was NACA 0024, since it is the most efficient and widely used profile in VAWT design. A turbine blade of aspect ratio similar to a standard Vertical Axis Wind Turbine was designed on SolidWorks 2016.

Using ANSYS Workbench 16.0, Modal Analysis was carried out. Aluminium Alloy was used as material. The stresses and deformations were studied, and profile modifications were carried out, succeeded by re-analysis. Fine meshing with high smoothing was incorporated for optimal results. The blade was fixed at two ends. Wind speed was assumed to be 10 m/s to ensure functionality in a wide variety of environments.

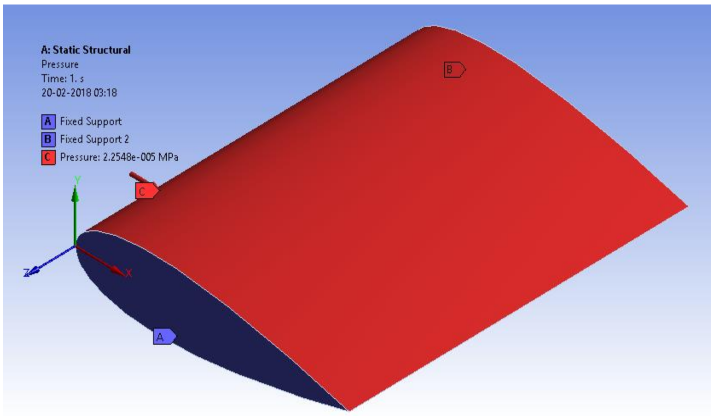


Figure 2.1: Boundary Conditions

CALCULATIONS:

The drag force on an aerofoil is given by the relation:

$$F_d = \frac{1}{2} C_d \rho A v^2$$

Where,

C_d = Coefficient of drag
ρ = Density of air
A =Area exposed to wind stream
v = Velocity of wind

Thus, the pressure due to drag force is given by:

$$P_d = F_d / A$$

We have C_d = 0.368125 from CFD analysis (Fig-2.1),
ρ = 1.225 kg/m³, v = 10 m/s

Thus, $P_d = ½ * 0.368125 * 1.225 * (10)^2$
$= 22.5477$ Pa

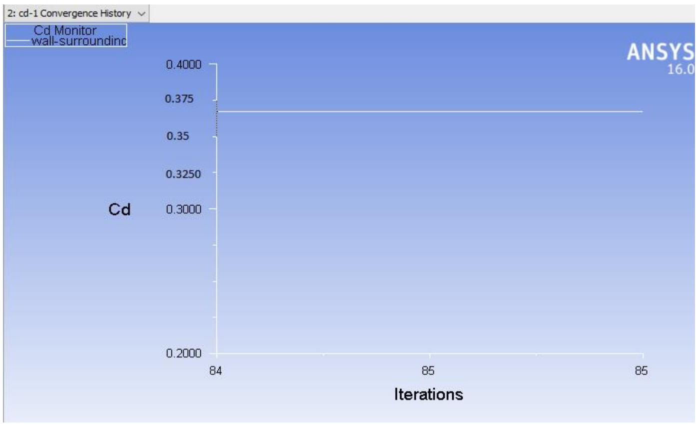


Fig -2.2: Solution convergence for Drag Coefficient

This pressure acts as the exciting force causing total deformation and local stresses.

3. MODAL ANALYSIS

Modal Analysis is the method of analyzing a structure's dynamic response to external excitation to determine the vibration characteristics (natural frequencies and mode shapes) of machine components. Pre-stressed Modal Analysis requires performing a Static Structural analysis first, which assumes steady loads and responses, neglecting inertial and damping effects. Modal Analysis can be done on ANSYS, Samcef or ABAQUS Solvers.

During this research, the first 5 modes of vibration were studied for both, solid NACA 0024 and modified aerofoils used as VAWT blades.

A. Static Structural analysis revealed the deformation(Fig-3.1.1) and elastic strain(Fig-3.1.2) due to pressure of incoming stream of wind.

B. Modal Analysis gave the mode shapes, frequencies and resulting deformations in fatiguing (Fig-3.2.1 to Fig-3.2.5).

3.1 Conventional Design (Solid Profile)

A. Static Conditions

Total Static Deformation appears as shown below. It is observed that deformation ranges from a minimum value of 0 mm to a maximum value of 1.1432 x10^{-6} mm over a span of 500 mm.

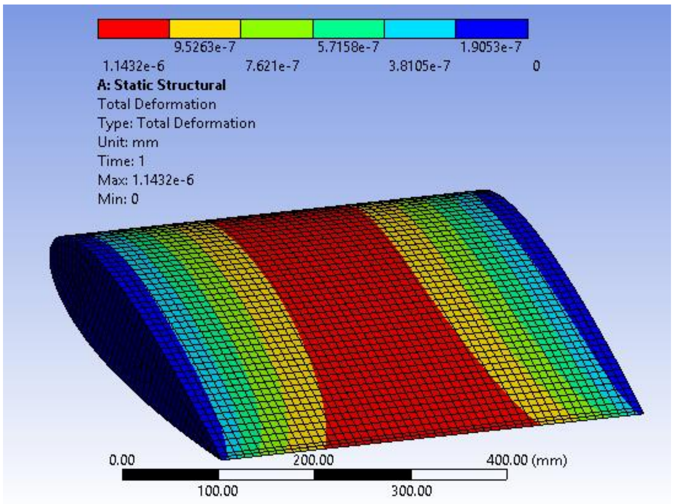


Fig-3.1.1: Total Static Deformation

Strain is defined by,

$$e_x = \frac{\text{Deformation in x−direction}}{\text{Length in x−direction}}$$

The Elastic Strain over the body appears as shown, the blade suffers maximum Elastic Strain of 3.248 x 10^{-8}, while the minimum value observed is 1.399 x 10^{-10}. These results served as inputs to the next part, Vibration Analysis.

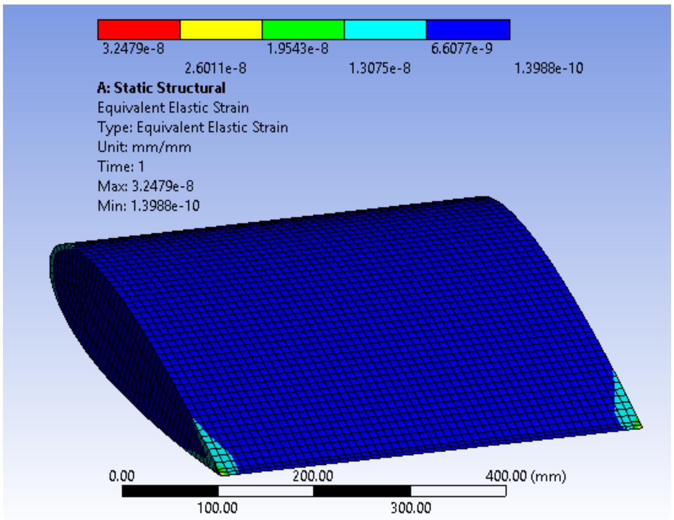
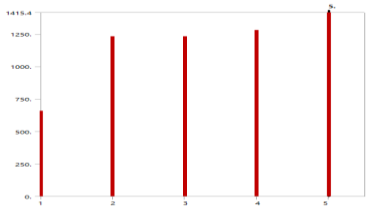


Fig-3.1.2: Equivalent Elastic Strain

B. Vibration Conditions

The first five frequencies range from 658.67 Hz for the principle mode to 1415.4 Hz for the fifth mode. Thus, whenever harmonic force frequency would equal that of the structure, it would cause resonant vibrations in the structure.



Tabular Data

	Mode	Frequency [Hz]
1	1.	658.67
2	2.	1229.9
3	3.	1230.1
4	4.	1279.9
5	5.	1415.4

Fig-3.1.3: First five modal frequencies

Corresponding to these frequencies, the body underwent Total deformations as a result of fatigue failure.

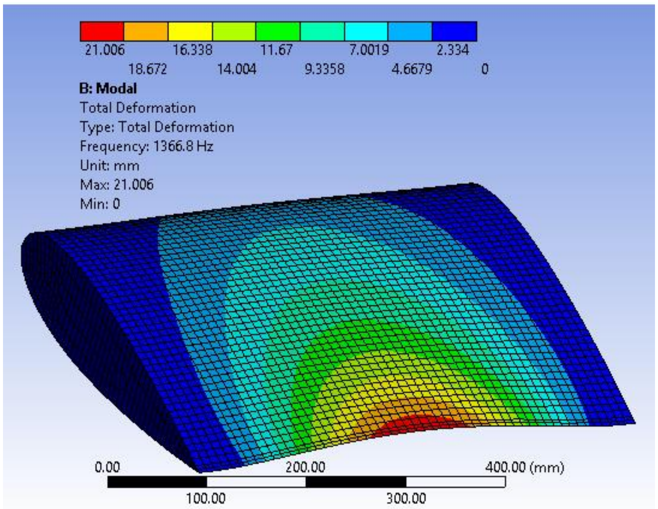


Fig-3.1.4-a: Mode 1

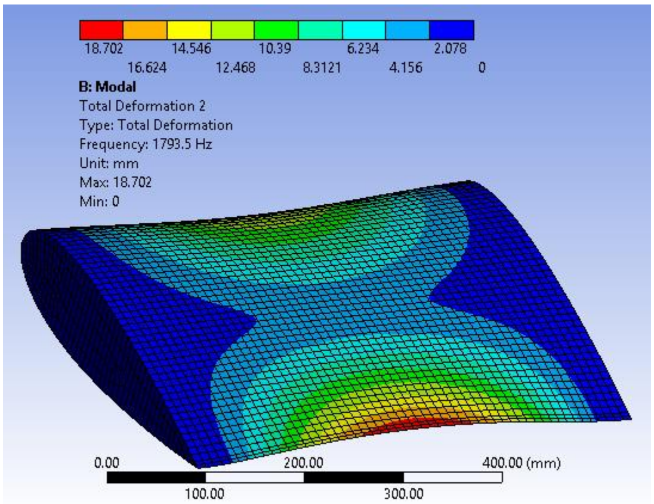


Fig-3.1.4-b: Mode 2

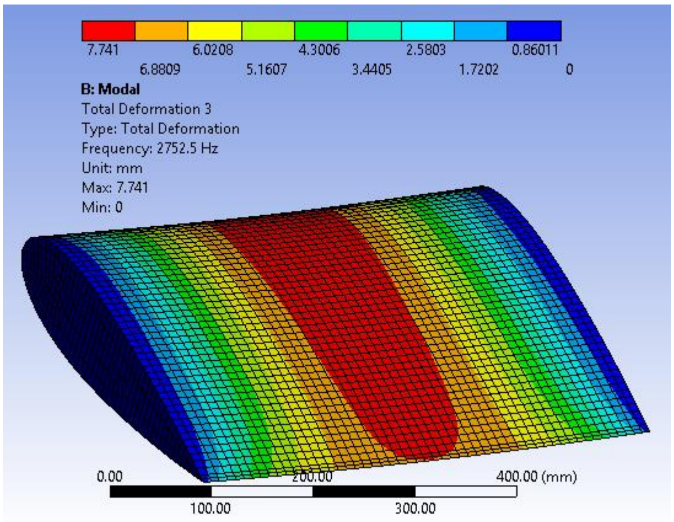


Fig-3.1.4-c: Mode 3

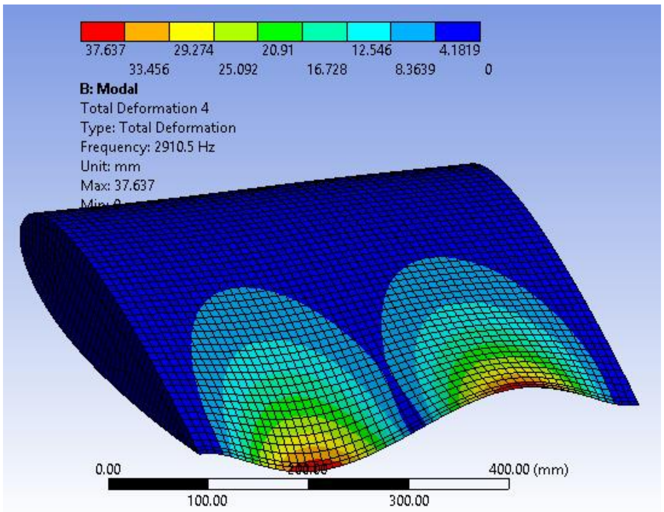


Fig-3.1.4-d: Mode 4

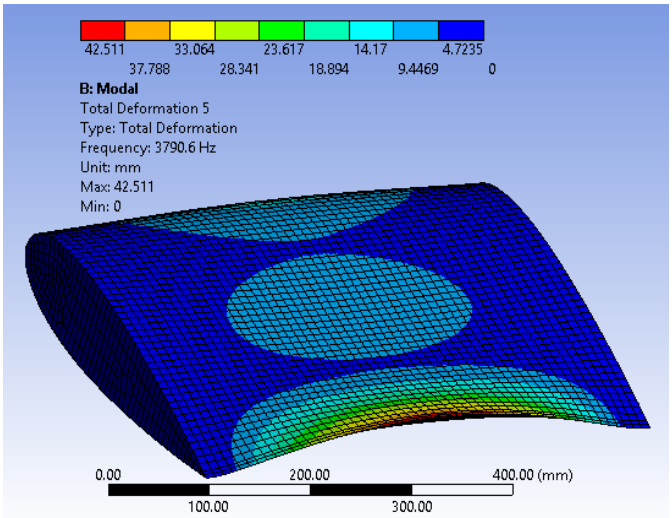


Fig-3.1.4-e: Mode 5

The above results indicate the following:

1. Minimum deformation is 7.7 mm for the Third mode.
2. Maximum deformation is 42.5 mm for the Fifth mode.
3. The Total deformation varies randomly over the modes of vibration. This is undesirable while designing a VAWT subject to vibration constraints, because in case the turbine is designed for the third mode, it will fail in the fifth mode due to drastic change in deformation.

Moreover, the weight of the blade is 36.5 kg which is a downside due to high material cost and bending failure in the framework supporting the blades. (Refer to Table-3.1)

Properties	
Volume	1.3186e+007 mm³
Mass	36.526 kg
Centroid X	167.8 mm
Centroid Y	-1.511e-002 mm
Centroid Z	-250. mm

Table-3.1: Physical Properties

3.2 Proposed Design

A research was done to overcome the limitations of the original turbine blade. Weight was reduced. Vibration is independent of weight, rather it varies with the distribution of weight in the body depending on its size and shape. Without changing the material, an optimized cross-section was designed and analyzed.

1. Design Specifications

The design uses a framework of 3 ribs which are slotted for weight reduction, and are used to support a hollowed profile as shown in Fig 3.2.1-a, b, c

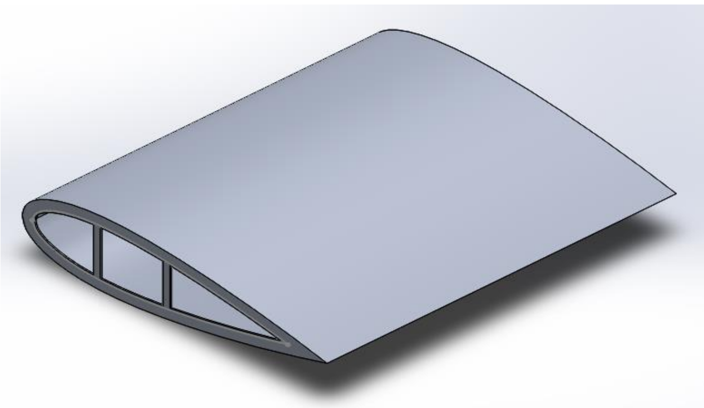


Fig-3.2.1-a: Model of proposed aerofoil blade

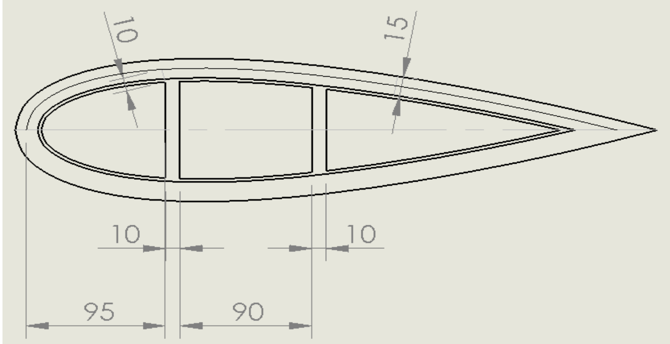


Fig-3.2.1-b: Profile Cross-section (mm)

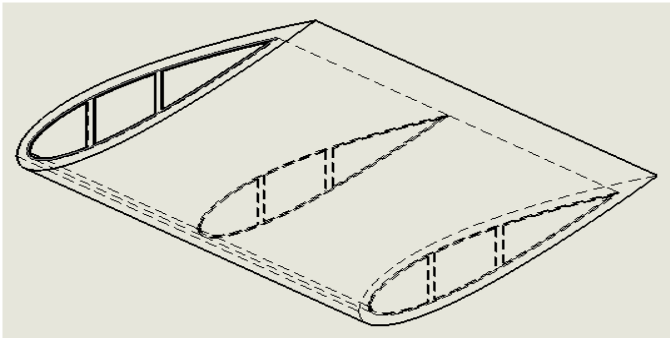


Fig-3.2.1-c: Isometric view

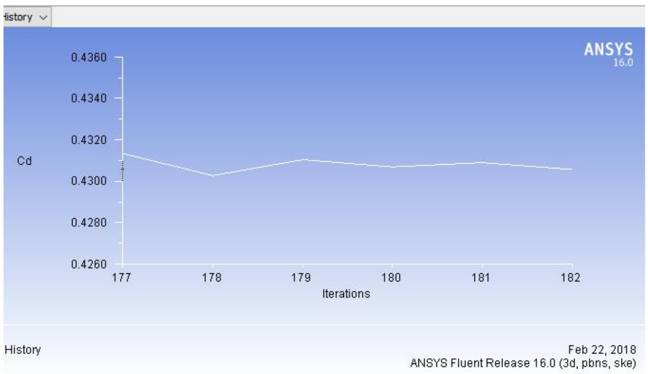
2. Analysis

CFD Analysis revealed that the coefficient of drag remained same for the new profile.

Thus, Modal Analysis was conducted for Modified blade, using same material, conditions of pressure, supports. The results revealed were interesting, as are shown below.

C_d was increased advantageously, to a value 0.4306
Thus, Drag Pressure increased to P_d = 26.37 Pa.

The increase in drag pressure and drag coefficient were found to be 17 %. Since VAWTs function on drag force, the increased pressure will assist turbine rotation.



A. Static Conditions

Total Static Deformation appears as shown below. It is observed that deformation ranges from a minimum value of 0 mm to a maximum value of 3.0945 $\times 10^{-6}$ mm over a span of 500 mm.

Thus, this value lies within the permissible limit and the increase is marginal.

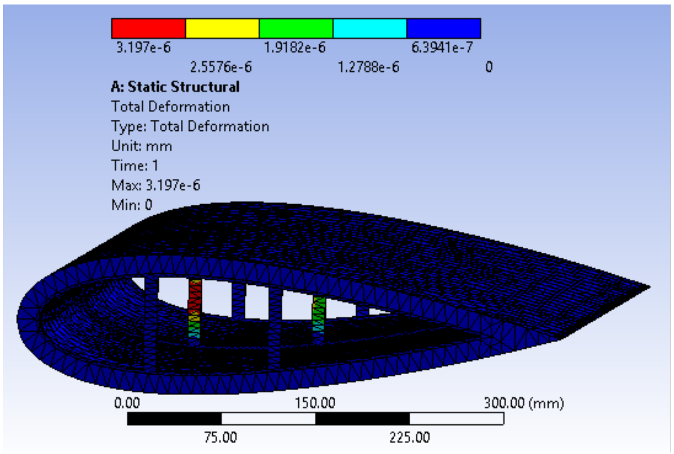


Fig-3.2.1: Total Deformation

The Elastic Strain over the body appears as shown, the blade suffers maximum Elastic Strain of 4.097 $\times 10^{-8}$ mm, while the minimum value observed is 1.782 $\times 10^{-16}$ mm.

Again, the strain is very minimal compared to permissible limits.

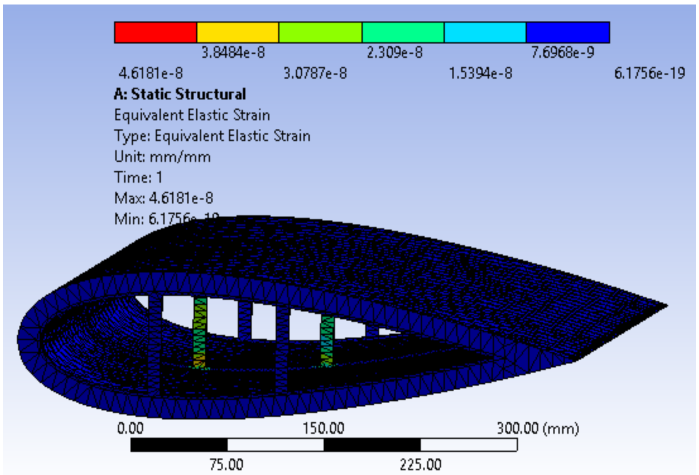
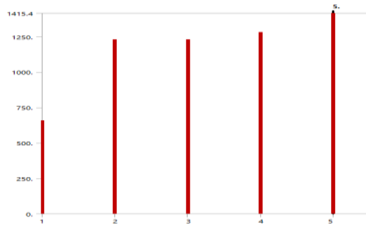


Fig-3.2.2: Equivalent Elastic Strain

Even though the static deflections are slightly higher, they are much lower than the safe limits of yield stress, and hence it is a good compromise to reduce weight and modal deformations for a minor increase in static structural results.

B. Vibration Conditions

The first 5 modes of vibration will be as shown:



Tabular Data

	Mode	Frequency [Hz]
1	1.	658.67
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3	3.	1230.1
4	4.	1279.9
5	5.	1415.4

Fig-3.2.3: First five modal frequencies

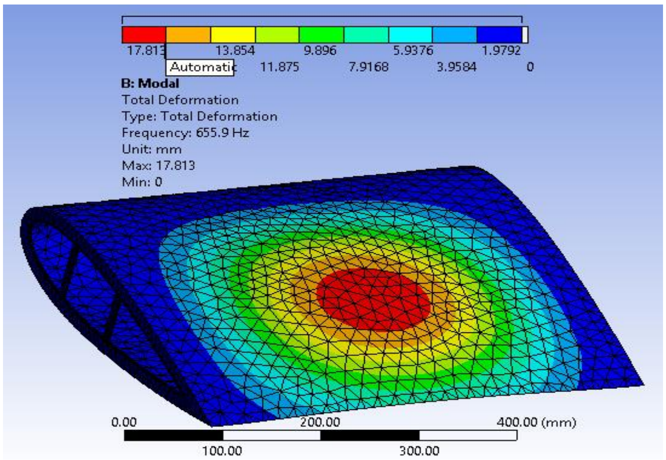

Fig-3.2.4-a: Mode 1

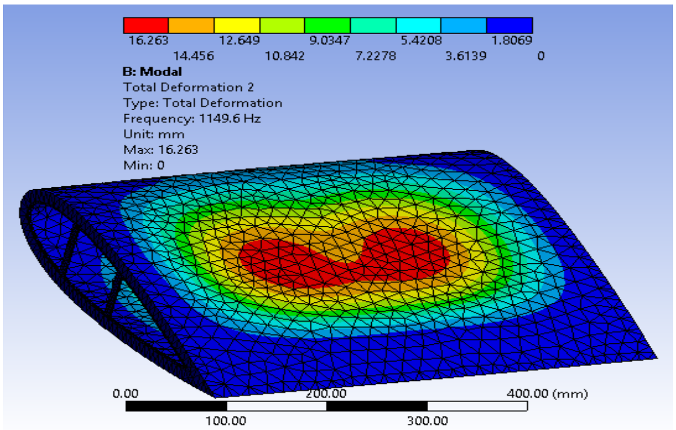

Fig-3.2.4-b: Mode 2

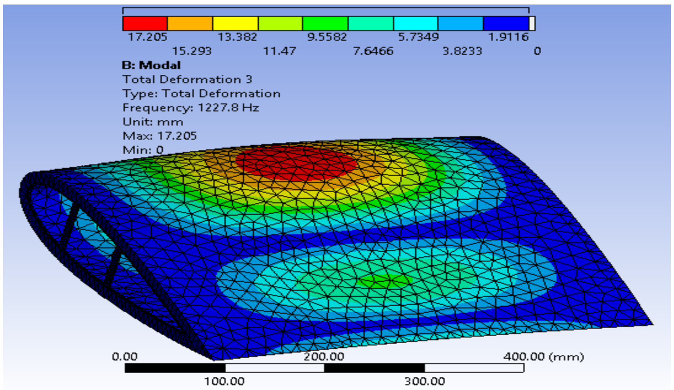

Fig-3.2.4-c: Mode 3

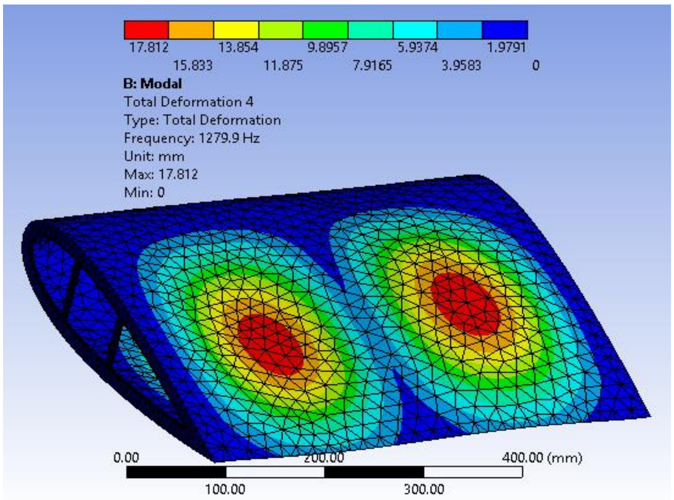

Fig-3.2.4-d: Mode 4

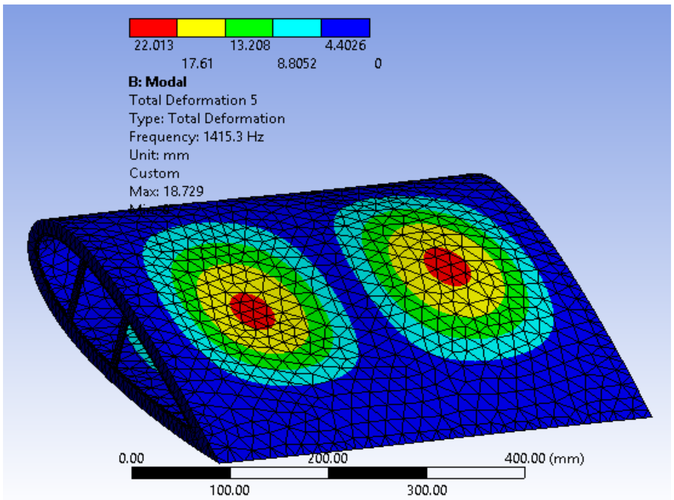

Fig-3.2.4-e: Mode 5

The above results show that:

1. Minimum deformation is 16.3 mm for the Second mode.
2. Maximum deformation is 18.7 mm for the Fifth mode.
3. The Total deformation shows negligible variation over the five modes of vibration. The range of deformation over the modes is just 2.4 mm compared to the earlier case where this value was 34.8 mm which is useful in vibration-based VAWT design.

The blade weight showed a large reduction, to more than half the value, as a weight of 17.9 kg was observed. (Table-3.1)

Properties	
Volume	6.4793e+006 mm³
Mass	17.948 kg
Centroid X	194.09 mm
Centroid Y	5.8019e-002 mm
Centroid Z	-248.37 mm

Table -3.1: Physical Properties

4. RESULTS

The conventional NACA 0024 aerofoil and modified design of the blade were subjected to-

A) Fluent Analysis to compute aerodynamic forces;

B) Static Structural

C) Modal analysis to reveal modal deformations in fatigue conditions. The results of the analyses conducted are tabulated below:

SR. NO	PARAMETER	NACA 0024 BLADE	PROPOSED BLADE DESIGN
1.	Material	Aluminium Alloy	Aluminium Alloy
2.	Weight (kg)	36.53	17.96
3.	Drag Coefficient	0.3681	0.4306
4.	Static deformation (mm)	1.143×10^{-6}	3.775×10^{-6}

Table-4.1: Comparison of Results of Fluent and Static Analyses

SR. NO	MODAL DEFORMATIONS (mm)	NACA 0024 BLADE	PROPOSED BLADE DESIGN
1.	Mode 1	21.0	17.8
2.	Mode 2	18.7	16.3
3.	Mode 3	7.7	17.2
4.	Mode 4	37.6	17.8
5.	Mode 5	42.5	18.7
6.	Range of Deformation (mm)	34.8	2.4

Table-4.2: Comparison of Results of Modal Analysis

The results show that in the second case, material was same, but mass of the model was lower, drag coefficient was higher. The total static deformation was lower.

Further, the Modal deformations were lower for the modes 1-2 and modes 4-5. Mode 3 showed some higher deformation. The deformation range was lower in the proposed design.

5. CONCLUSIONS

The research indicated that the proposed blade design displayed better results than the conventional design in numerous aspects. The salient features observed were as follows:

1) Weight Reduction of 51% was achieved in the proposed design. This reduces material cost, reduces inertia and required starting torque of rotor, enables simpler material handling systems. The Bending Moment is reduced on connectors, and thus bending failure is avoided.

2) Coefficient of drag increased. This increased drag force, which is the main driving element of a vertical axis turbomachine.

3) I) The variation of modal deformations in the proposed design was negligible, compared to large earlier, random fluctuations in deformation. In case the conventional turbine was designed in a particular mode of low deformation, it would fail in another mode of higher deformation.

   II) On the other hand, if designed for higher deformations, it would be overdesigned for other modes. The new model enables the design engineer to design the turbine for any of the modes of vibration, without worrying about failure in the other modes.

4) Average modal deformation was reduced to 33% of Initial value. Randomness in vibrations was eliminated.

5) Static deformation and Elastic Strain increased negligibly and was well below the permissible limit of static failure.

REFERENCES

[1] "A model to study the reduction of turbine blade vibration using the snubbing mechanism": Paolo Pennacchi Steven Chatterton Nicolò Bachschmid Emanuel Pesatori Giorgio Turozzi