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Aerodynamic Design, Analysis and Dynamic Modelling of a Horizontal Axis Micro Wind Turbine Blade using NACA 4412 Profile

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***Abstract-* This project primarily aims to investigate the aerodynamic characteristics of a small Horizontal Axis Wind Turbines (HAWT) with different blade tip configurations to enhance power generation efficiency and NACA 4412 aerofoil is used for turbine blade design, and analysis of wind turbine blade. The chord and twist angle distributions of the preliminary blade design are determined. The preliminary blade design i.e., simple tapered blade does not necessarily provide the best power performance under practical operation conditions and needs to follow further modifications and calculations. The optimization with the objective of enhancement of power performance and low speed starting behaviour is carried out. The optimization plays important role for good starting and low wind performance. In this work analysis is carried out for coefficient of performance of the blade and for starting behaviour of the wind turbine blade. The aerodynamic power and power coefficients curves are drawn for the optimized wind turbine.**

The result indicated that the modified design i.e., Twisted-Tapered wind turbine blade gives 41.09% higher power output and 41.89% higher coefficient of power compared to simple tapered blade design at 8m/s of wind velocities. The twisted profile offers better structural stability as compared to simple tapered profile. Compared to simple profile, the total deformation was reduced further by 2.69%, while the equivalent stress was reduced by 1.51%. Comparison of CFD results with experimental results showed a good agreement.

I. INTRODUCTION

Wind energy is the most promising renewable energy source. Harnessing wind energy has gained significance. Deployment of wind energy in the world has been increasing steadily. In many developing countries wind power is an efficient and key solution to solve problems of electricity shortage in remote places. Micro wind turbines fulfill the potential need of electricity for rural homes.

The blade is the key element of a micro wind turbine which converts the kinetic energy of the wind into electricity through generators. Aerodynamic shape optimization is one of the main research fields which is directly related to power production of a wind turbine

1.1 WIND TURBINE

A wind turbine is a device that converts the wind's kinetic energy into electrical energy. Wind turbines are manufactured in a wide range of vertical and horizontal axis types.

HORIZONTAL AXIS WIND TURBINE

Horizontal axis wind turbine (HAWT) has the main rotor shaft and electrical generator at the top of a tower, and must be pointed into the wind. Small turbines are pointed by a simple wind vane, while large turbines generally use a wind sensor coupled with a servomotor. Most have a gearbox, which turns the slow rotation of the blades into a quicker rotation that is more suitable to drive an electrical generator.

SMALL WIND TURBINES

A small wind turbine is a turbine used for micro generation, as opposed to large commercial wind turbines, such as those found in wind farms, with greater individual power output. Small wind turbines for residential use are usually having 1.5 to 3.5 meters' rotor blade diameter and produce 1 to 10kW of electricity at their optimal wind speed. Some turbines have been designed to be very lightweight in their construction allowing sensitivity to minor wind movements and rapid response to wind gusts. The generators of small wind turbines are usually 3-phase alternating current generators. Some models use single phase generators. The small wind turbine can be as small as 50W auxiliary power generators for a boat, caravan, and miniature refrigeration unit.

WIND TURBINE AERODYNAMICS

The main application of wind turbines is to generate power using the wind energy. Hence, the aerodynamics is a very important aspect of designing wind turbines. For most of the machines, there are many different types of wind turbines based on different energy extraction concepts.

However, the details of the aerodynamics depend very much on the topology same fundamental concepts apply to all turbines. Every topology has a maximum power for a given flow, and some topologies are better than others. The method used to extract power has a strong influence on this. In general, all turbines may be grouped as being either lift-based, or drag-based; the former being more efficient. The difference between these groups is the aerodynamic force that is used to extract the energy The most common topology is the horizontal axis wind turbine (HAWT). It is a lift-based wind turbine with very good performance.

The governing equation for power extraction is

$P = F * v$………………………………… [1.1]

Where, P is the power, F is the force vector, and v is the velocity of the moving wind turbine part.

The force F is generated by the wind's interaction with the blade. The magnitude and distribution of this force is the primary focus of wind-turbine aerodynamics. The most common type of aerodynamic force is drag. The direction of the drag force is parallel to the relative wind. Typically, the wind turbine parts are moving, altering the flow around the part. Fig (1) shows the basic wind turbine blade structure and the direction of wind and angle of attack.

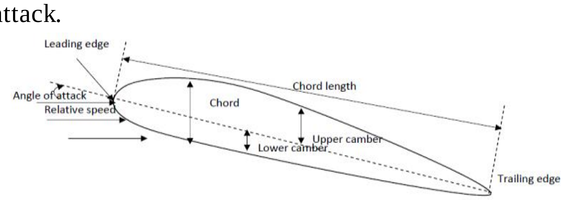

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Fig 1 Basic wind turbine blade structure

The thrust coefficient is another important dimensionless number in wind turbine aerodynamics and is given by,

$$C_T = \frac{T}{1/2\rho A V^2} \text{ ………………….} \quad (1.2)$$

The formula for lift and drag is given below.

$$C_L = \frac{L}{1/2\rho A W^2} \text{ ………………..} \quad (1.3)$$

$$C_D = \frac{D}{1/2\rho A W^2} \text{ ……………..} \quad (1.4)$$

Where C_L is the lift coefficient, C_D is the drag coefficient, W is the relative wind speed as experienced by the wind turbine blade, and A is the area of the wind blade.

$$W = V - U \quad \text{……..} \quad (1.5)$$

Where, 'U' is the rotational velocity in radians per second.

The tip speed ratio for the wind turbine is given by the following equation as

$$TSR = \frac{R \times w}{U_{in}} \text{ ……………..} \quad (1.6)$$

Where R (m) is the radius of the wind blade, ω (rad/s) is the angular velocity and Uin (m/s) is the inlet velocity. The input and output power through the wind energy conversion can be represented as equation (1.7) and (1.8), respectively.

$$P_{out} = T \times w \text{ ……… ……….. } \quad (1.7)$$

$$P_{in} = \frac{1}{2} \times \rho \times A \times U_{in}^3 \text{. ………..} \quad (1.8)$$

Where, ρ means the air density, 'A' means the cross sectional dimension of wind turbine, Uin means the wind speed, T means the torque, ω means the angular velocity of wind turbine, respectively. ρ can be represented as 1.225 kg/m3.

2. MODELLING

The geometrical scale down model of the wind turbine blade is represented below (Fig 4.1) gives the inlet and outlet parameters with continuum, obtained from the design configurations and applied before meshing.

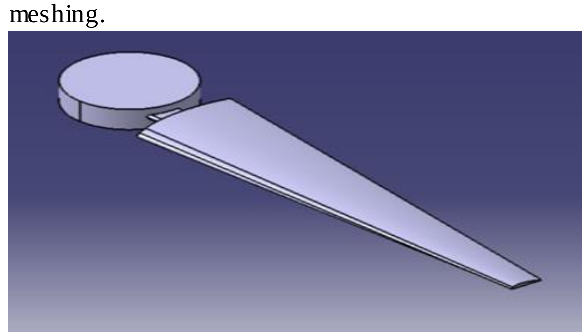


Fig 2 Twisted tapered blade

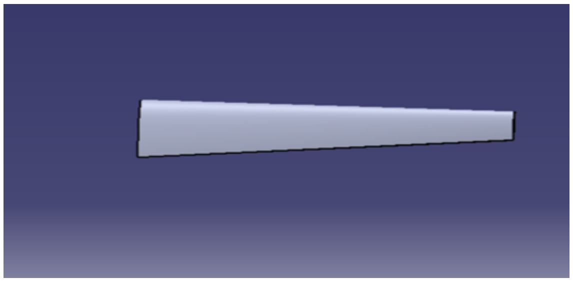


Fig 3 Simple tapered blade

3. RESULT AND DISCUSSION

Both analytical and experimental investigations were conducted on the selected NACA4412 profile, the results are presented for discussion in this chapter.

3.1 ANALYTICAL RESULTS

The table 3.1 represents the analytical results obtained from the CFD analysis at various wind speeds for wind turbine with NACA4412 airfoil having tapered profile. The model is of dimension (15x600) mm is tested for various inlet velocities.

The table 3.2 represents the analytical results obtained from the CFD analysis at various wind speeds for the wind turbine with NACA4412 airfoil having twisted and tapered profile. The model is of (15x600) mm with 7 degree twist at the tip is tested for various inlet velocities

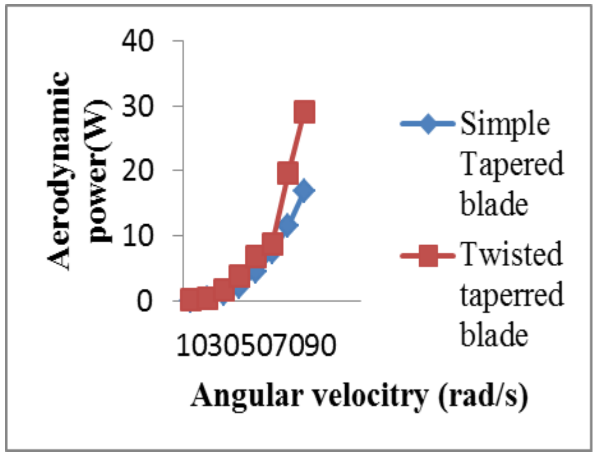
Table 3.1 Data obtained for wind turbine blade with NACA4412 airfoil with simple tapered profile

Wind speed (m/s)	Rotor speed (rpm)	Angular Velocity (rad/s)	Torque (Nm)	Aerodynamic Power(*W*)	Tip speed Ratio	Coefficient Of power
1	121	12.69	0.00098	0.03	1.31	0.012
2	227	23.77	0.00424	0.31	1.4	0.030
3	331	34.66	0.0091	0.946	1.44	0.042
4	432	45.2	0.016	2.17	1.45	0.054
5	540	56.61	0.0286	4.37	1.47	0.069
6	639	66.9	0.0369	7.42	1.49	0.082
7	734	76.9	0.0505	11.6	1.5	0.0939
8	814	85.24	0.066	16.8	1.52	0.104

Table 3.2 Data obtained for wind turbine blade with NACA4412 airfoil with twisted tapered profile

Twisted Wind speed (m/s)	Rotor speed (rpm)	Angular Velocity (rad/s)	Torque (Nm)	Aerodynamic Power (*W*)	Tip speed Ratio	Coefficient Of power
1	120	12.66	0.0016	0.06	1.31	0.023
2	222	23.33	0.0067	0.46	1.41	0.045
3	329	34.49	0.0153	1.58	1.43	0.069
4	435	45.59	0.0283	3.87	1.46	0.095
5	541	56.63	0.0428	6.81	1.47	0.108
6	644	67.47	0.0649	8.66	1.48	0.137
7	747	78.27	0.0842	19.7	1.49	0.154
8	840	87.98	0.110	29.03	1.51	0.179

The fig 4 shows the variation of aerodynamic power with angular velocity of simple tapered and twisted-tapered blade. The aerodynamic power obtained for twisted-tapered blade is higher compared to simple tapered blade. From the graph it is evident that the aerodynamic power and the coefficient of power varies linearly with increase in velocity. Further, the twisted tapered blade profile generates higher power even at lower angular velocity of 20 rad/s and above. At higher values of angular velocity it increases drastically by about 41.09% at 80 rad/s.Fig 4 shows the variation of coefficient of torque with rpm for simple tapered and twisted-tapered blade. From the graph it is clear that the coefficient of torque for twisted-tapered blade is higher than that of the simple tapered blade, across all ranges of rpm (200-800rpm). At 200 rpm the increase was 58.07%, whereas the highest torque coefficient was 75.67% at 600rpm.



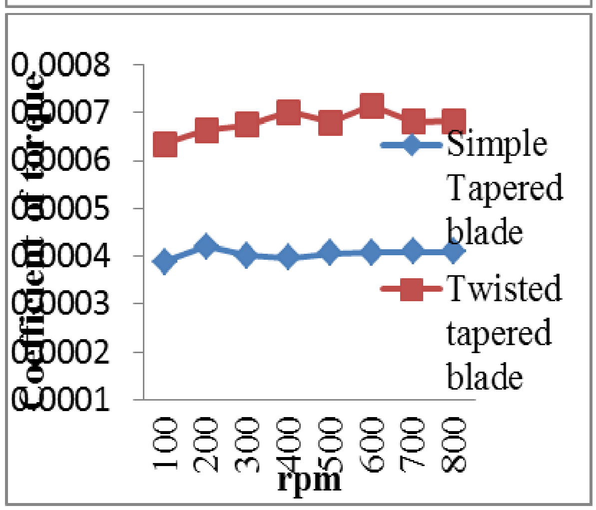


Fig 4 Variation of twisted blade and simple tapered blade value of aerodynamic power and coefficient of torque with angular velocity and rpm respectivel

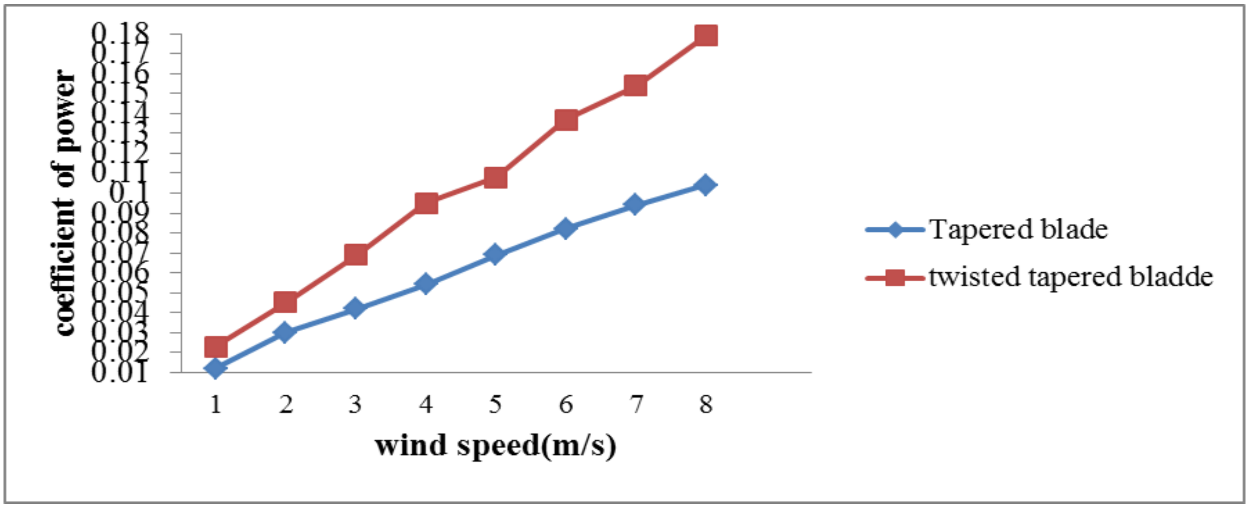


Fig 6 Variation of twisted blade and simple tapered values of coefficient of power

Fig 6 shows the variation of coefficient of power with wind speed of simple tapered and twisted-tapered blade. The twisted tapered blade has higher coefficient of power compared to simple tapered blade at working range of wind speeds (1 m/s to 8m/s). At 3m/s the power coefficient for the twisted profile was higher by 64.28% whereas it increased to 72.11% % at 8m/s, clearly showing the benefit of choosing the twisted profile

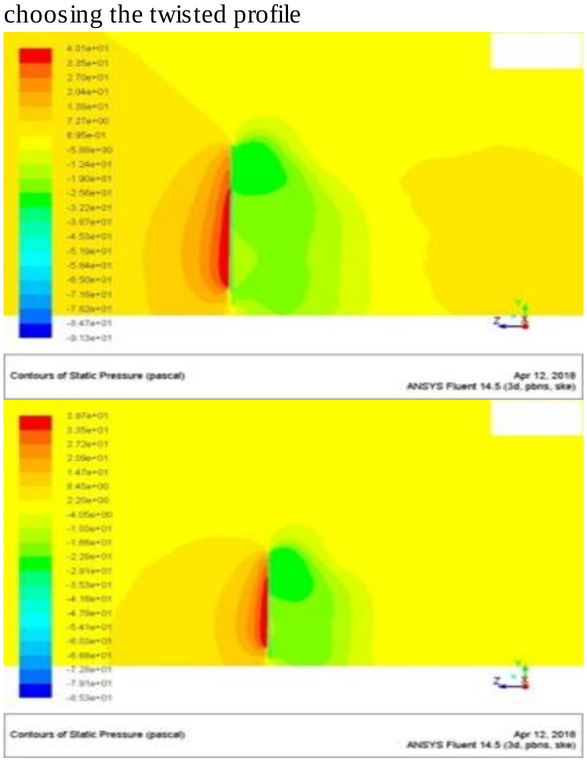
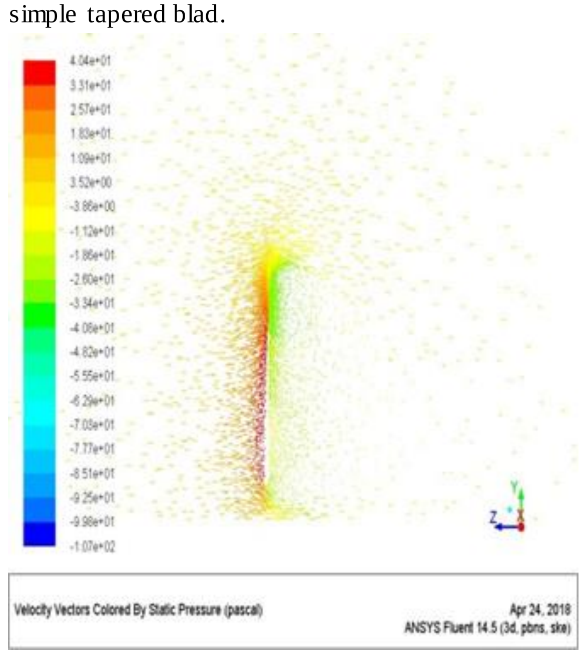


Fig 7 Pressure contour of the simple tapered and twisted tapered blade of the wind turbine at 8m/s for comparison

Figure 5.6 shows pressure contour of the simple tapered and twisted tapered blade of the wind turbine at 8m/s reproduced. From the figure it is evident the magnitude of negative static pressure decreases from -38.7Pa in case of simple tapered blade to -35.3Pa i.e. by 9.63% in twisted blade giving the additional lift. Figure 5.7 shows pressure vector of the simple tapered and twisted tapered blade of the wind turbine at 8m/s reproduced. From the figure it is evident that the pressure distribution and hence the lift is more uniform in case of twisted tapered blade as compared to simple tapered blade, indicated the flow is attached and delayed boundary layer separation. This means the twisted tapered blade is preferable over the simple tapered blad.



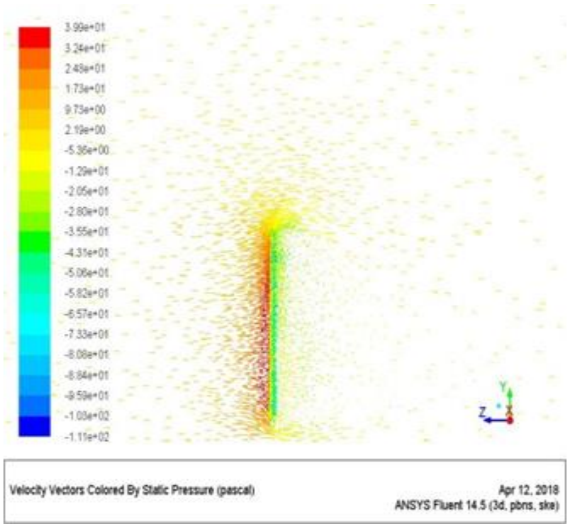
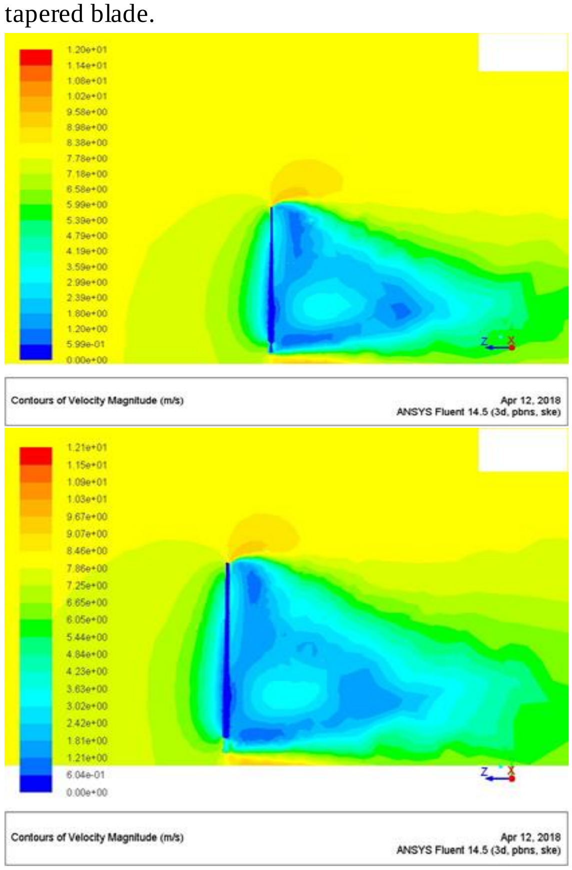


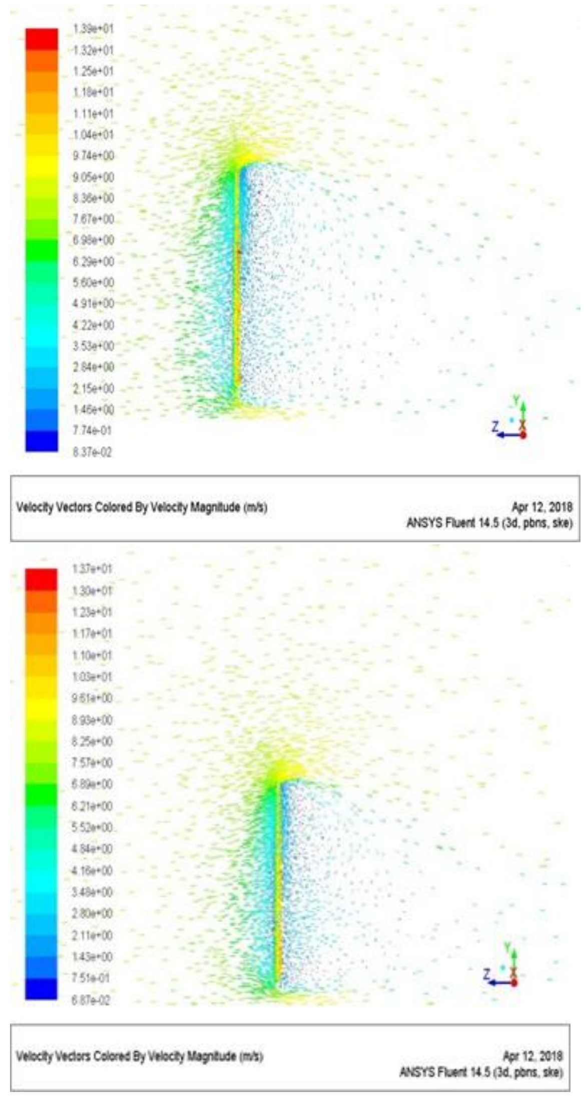
Fig 8 Pressure vector of the simple tapered and twisted tapered blade of the wind turbine at 8m/s for comparison

From the figure 5.10 it may be observed that there is slight increase in both the velocity contour and vector at higher wind speeds for a twisted tapered blade which offers lift advantage when compared to simple tapered blade.



(a) Velocity contour for Simple tapered

(b) Velocity contour for Twisted tapered



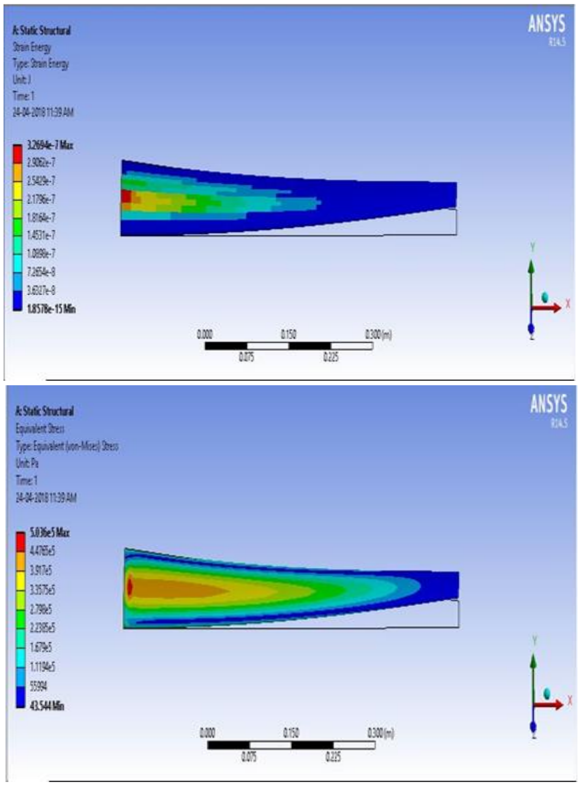
(a) Velocity vector for Simple tapered

(b) Velocity vector for Twisted tapered

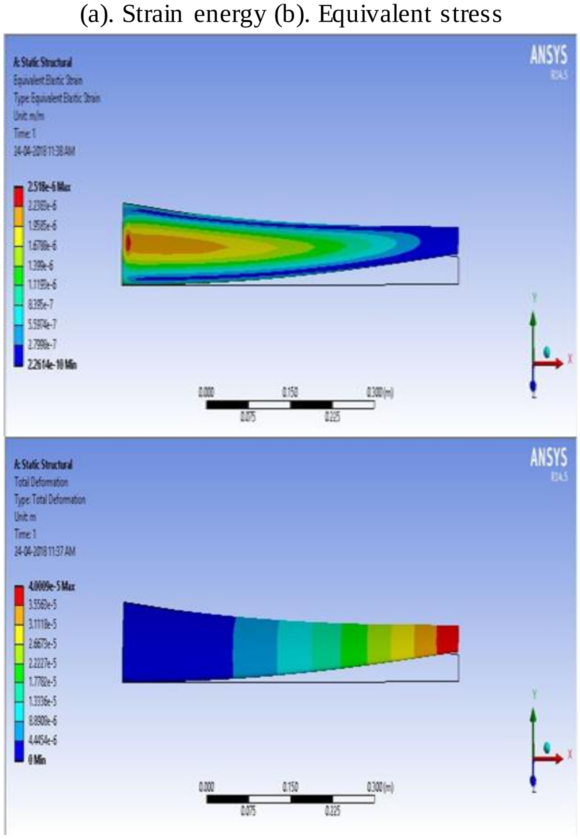
Fig 8 Velocity contour and velocity vector for simple tapered and twisted tapered blades at 8m/s

STRESS ANALYSIS

In order to ensure the stability of the blade profile to withstand higher velocity, stress analysis of the both simple and twisted tapered blades were done. Figure 5.11 represents the stress and strain distribution over the wind turbine blade having simple tapered profile.. From the figure it may be observed that the strain energy, equivalent stress and strain elastic are minimum at the blade tip, whereas the deformation is minimum at the base of the blade profile, suggesting a stable blade against any bending moment.



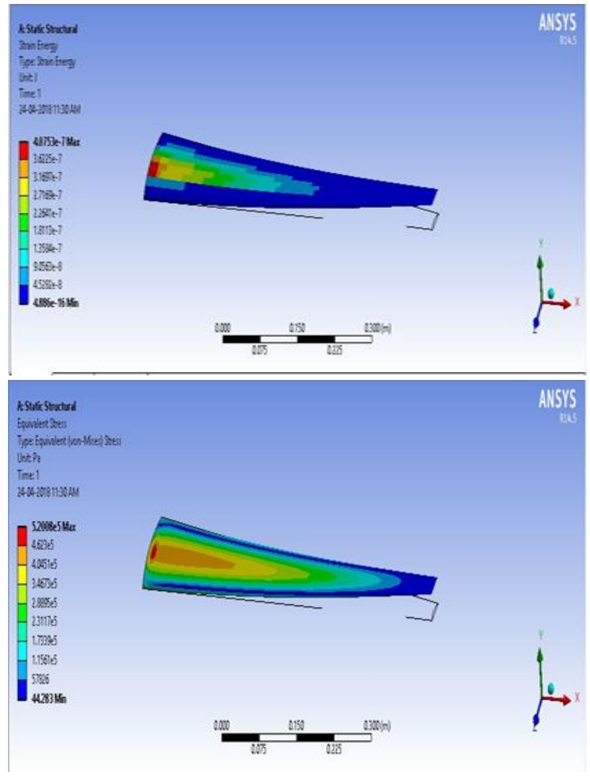
(a). Strain energy (b). Equivalent stress



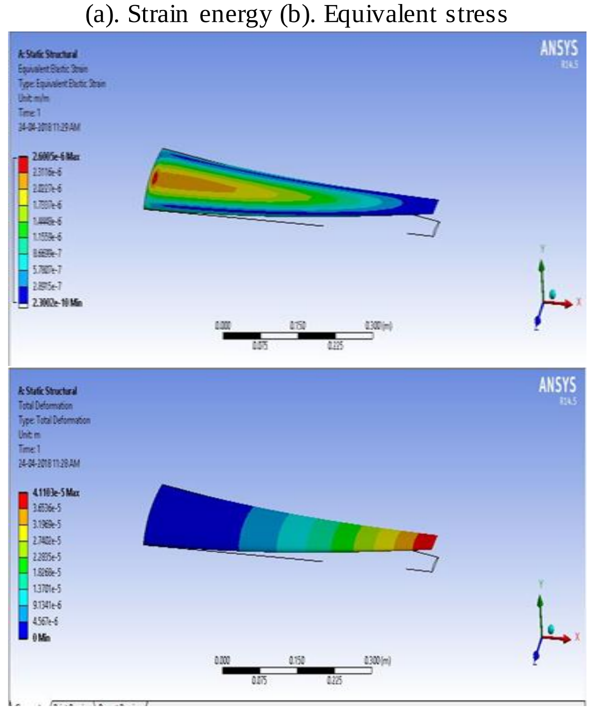
(c).Equivalent elastic strain (d). Total deformation

Fig 9 Stress and strain distribution over simple tapered wind turbine blade

Figure 5.12 represents the stress and strain distribution over the wind turbine blade having twisted tapered profile and suggests the stress and strain values over the wind turbine blade.



(a). Strain energy (b). Equivalent stress



(c). Equivalent elastic strain (d).Total deformation

Fig 10 Stress and strain distribution over twisted tapered wind turbine blade

DISCUSSION

The strain energy, equivalent stress and strain elastic are minimum at the blade tip, whereas the deformation is minimum at the base of the blade profile, suggesting better capability of the blade against any bending moment, as compared to the simple tapered profile. The total deformation is reduced further by 2.69%, while the equivalent stress was reduced by 1.51%.

VALIDATION OF EXPERIMENTAL RESULTS WITH COMPUTATIONAL RESULTS

Most important part of CFD analysis is validation of the analytical results with

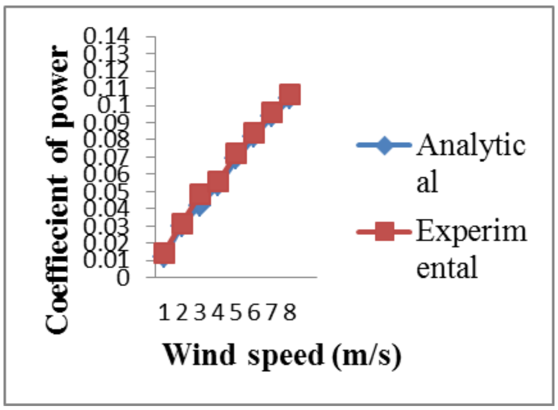


Fig 11 Validation of Analytical values with Experimental outcome

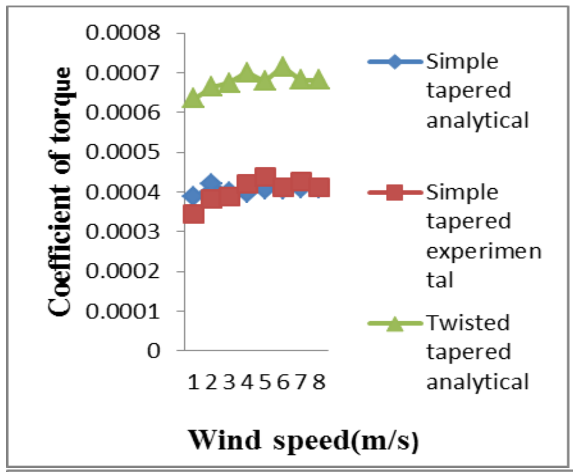
experimental outcome. In order to validate the data extracted from analytical results, a series of experiments were conducted mounting the simple tapered blade profile on a wind tunnel test section. Based on the results obtained, a comparison was made and the same is presented in the following figure 11. It is evident that both experimental and analytical values are in good agreement and hence it may be concluded that the outcome from the CFD analysis is reliable. Based on this conclusion, we may further infer that the outcome from CFD analysis for the twisted tapered profile is also reliable.

4 COMPARISON OF EXPERIMENTAL RESULTS WITH ANALYTICAL RESULTS

Table 3.4 Comparison of experimental data with analytical data obtained for wind turbine blade with NACA4412 airfoil (simple tapered profile)

Wind speed(m/s) (W)	Torque (N/m)		Co-efficient of torque		Aerodynamic power (W)		Co-efficient of Power (C_P)		% increase in aerodynamic power
	Experimental	Analytical	Experimental	Analytical	Experimental	Analytical	Experimental	Analytical	
1	0.0014	0.00098	0.000345	0.00039	0.03	0.037	0.012	0.0146	2.16
2	0.0058	0.00424	0.000383	0.00042	0.31	0.319	0.030	0.0316	5.3
3	0.00122	0.00091	0.000388	0.000401	0.946	1.108	0.042	0.0481	1.4
4	0.0214	0.016	0.0004216	0.000396	2.17	2.63	0.054	0.0562	1.48
5	0.0398	0.0286	0.0004376	0.000406	4.31	4.52	0.069	0.0723	4.7
6	0.062	0.0369	0.000413	0.000407	7.42	7.64	0.082	0.0842	2.6
7	0.086	0.0505	0.000425	0.0004089	11.6	11.9	0.0939	0.0963	2.8
8	0.099	0.066	0.000411	0.0004092	16.8	17.1	0.104	0.106	1.9

Fig 12 shows the comparison of coefficient of torque at different wind speeds ranging from 1m/s to 8m/s , based on experimental and analytical data. It may be observed that both the values are in good agreement with no objectionable deviation.



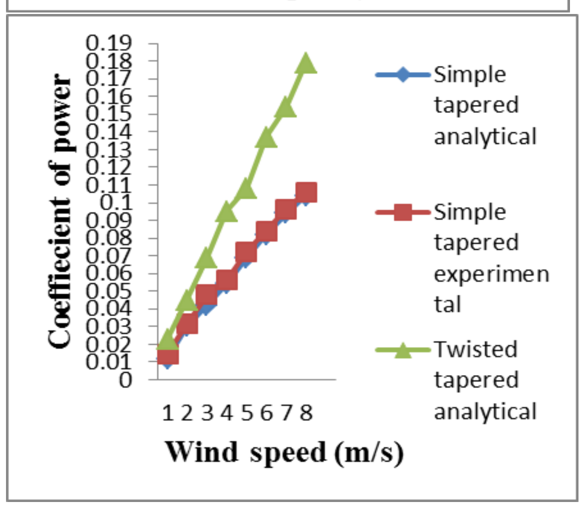


Fig 16 Comparison of experimental and analytical value of coefficient of torque and coefficient of

power of simple tapered blade and twisted tapered blade

Fig 16 shows the comparison of experimental and analytical value of coefficient of power of tapered blade. The graph shows that both the experimental and analytical results are in good agreement.

CONCLUSION

In this project the viability of NACA4412 profile as a potential micro wind turbine blade for use at lower wind speed was considered. Accordingly both analytical and experimental investigations were made using a fabricated NACA4412 blade profile at wind speeds ranging from 1m/s to 8m/s. Simple tapered and twisted tapered profiles were considered for CFD analysis. Based on the outcome, the following conclusions are drawn.

The highest aerodynamic power for the wind turbine blade with NACA4412 airfoil having tapered profile at 8 m/s was 17.1W from experimental analysis. However, the twisted tapered profile developed 29.03 W for the same parameters of the testing range.

The, blades with NACA4412 airfoil having twisted tapered profile have better performance for the constant and variable wind speeds. There is an increase in aerodynamic power up to 41.09% at 8m/s with twisted blade profile as against the simple tapered profile.

The twisted profile offers better structural stability as compared to simple tapered profile. Compared to simple profile, the total deformation was reduced further by 2.69%, while the equivalent stress was reduced by 1.51%.

The wind turbine blade with twisted tapered profile uses the concept of both lift and drag at different angle of attack from root to tip; hence the wind turbine having twisted tapered profile is more efficient than tapered profile blade.