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Wind Generator Rotor Analysis fora Small Wind Farm

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ABSTRACT—This paper focuses on the works of designing a small scale wind turbine at arbitrary conditions and analyzing the structural integrity of the model via numerical simulation. The project interests are limited to geometric design of turbine blade, optimizationandaerodynamicaswellasstructuralanalysis.Design of Horizontal Axis Wind Turbine (HAWT) blade particularly for low wind speed areas is of primary concern to this project. The generation of wind turbine profile is based on Blade Element Momentum theory (BEM). Design parameters like angle of attack, tip speed ratio, aerodynamic coefficients, angle of twist, airfoil profile, chord length are addressed with the aid of this theory. A three dimensional blade is then obtained by extruding the two dimensional airfoil profiles to operate at a rated speed of 5m/s.

Numerical simulations are carried out using a commercial CFD solver ANSYS CFX which reveals the flow structure and aerodynamic characteristics. The results obtained from the combined use of open source software QBlade and CFD computation assure that the 2.5 m long blade made of Polyester resin could withstand extreme loading conditions and provided acceptable performance with regard to stress and deflection produced.

Index Terms—Design, Analysis, Small Scale Wind Turbine, QBlade

NOMENCLATURE

C_P = Coefficient of Performance C_L = Coefficient of Lift
α = Angle of Attack β = Angle of Twist ρ = density
λ (TSR) = Tip speed ratio
ω = angular velocity v = wind velocity

I. INTRODUCTION

Wind energy occupies a prominent space in the global energy production. Tremendous amount of energy can be harnessed by utilizing the available resources and the energy demand can be addressed. The utilization of wind energy dates back centuries old. It is one of the most viable sources of renewable energy and with the use of technology the reduced cost has it competing with other conventional sources of energy. The generation of power from wind can be done by using wind turbine. The turbine power production depends upon the interaction between the rotor and the wind. So the performance of wind turbine depends upon aerodynamic forces. Wind is characterized by speed [1] and direction which depend upon pressure gradient and local geography.

On a global scenario wind energy is the fastest growing renewable source of energy. Wind power contributes to 2.5% of the global electricity supply and this contribution has been increasing by 25% per annum over the last ten years. China leads the wind power production race by contributing 43% of the total power generated which accounts to 62 GW. Nepal also exhibits good potential of wind power generation. According to a study conducted by AEPC (SWERA) on an area of 6047 sq.km, the total feasibility amount of wind energy was estimated to be 3000 MW. Annapurna conservation has wind power density (WPD) of 300 Watt/m^2 and can yield 716 MW of energy. Some other independent studies and surveys have estimated the wind power capacity of 20 MW in Mustang district alone [1]. According to Alternative Energy Promotion Center (AEPC) among different renewable technologies installed in Nepal, wind energy has 21 installations and covers 12districts.

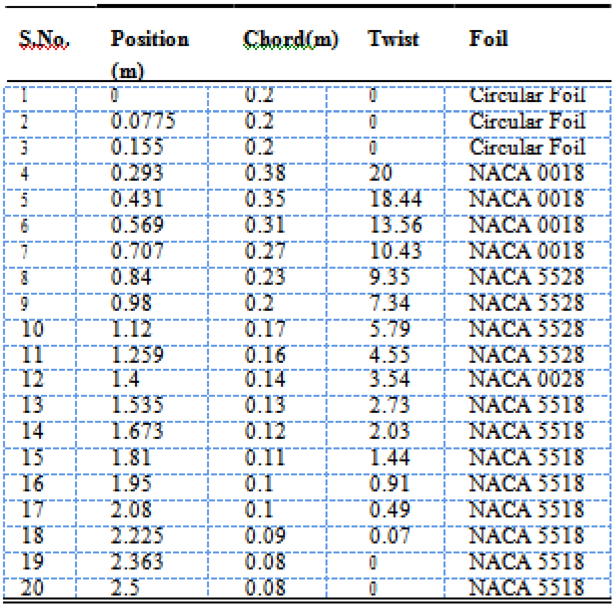
Small and irregular attempts have been made to generate power from wind. The first recorded effort to exploit wind energy in Nepal was undertaken with support from the USat an agricultural farm in Rampur in the 1970s. These efforts failed miserably and were a major setback in the development of wind power. In 1989 Nepali Electricity Authority (NEA) installed two 10 KW wind turbines in Kagbeni to facilitate 60 households but unfortunately both turbines broke down within a few months of operation. Investigation reported that the cause of failure was the lack feasibility study and site specific designs as the wind was inconsistent [2]. This fiasco suggested thatan appropriate design of a blade that would withstand extreme working conditions was necessary. It was also of high importance to predict the characteristic properties and performances of the turbine with respect to the flow phenomena and structural integrity. In the current scenario, computational analysis to analyze the designs has become a reliable solution in engineering applications. By implementing this trend in wind turbines, this paper addresses the current problem faced by Nepalese renewable energy sector and tries to overcome the same.The work presented in this paper is a part of research activity done at Kathmandu University as an initial step for designing a site dependent wind turbine rotor blades and making a computational analysis to know the strength of the designed blade at the designedconditions.

II. BLADEDESIGN

Modern wind turbines are made with airfoil cross- sections. QBlade is an open source program for two dimensional and three dimensional design and simulation of wind turbine blade. Wind turbine blade profiles are constructed using the software QBlade which works on the principle of Blade Element Momentum (BEM) theory. BEM theory produces angle of twist and chord length for given cross section and rotational speed at finite number of profile, chord, twist and length. With the momentum theory, positions along the span of the blade. BEM theory treats a given cross section as an independent airfoil which possesses wind with a speed and direction that is a vector sum of the oncoming wind and the wind generated by rotation. The direction and magnitude of wind generated changes at different position along the span and so must the airfoil cross section [3]. The airfoil used is of NACA (National Advisory Committee for Aeronautics) series. NACA specifies the features of an airfoil bynumbers. Along the span of the blade 20 foils have been used. Among them three are circular foils and 17 are NACA foils. Along the tip of the blade NACA 5518 has been used because it produces good lift necessary for the power generation. In the NACA 5518 designation, among the four last digits the first number denotes the maximum camber of the airfoil at the chord line (in per cent of chord), the secondnumber gives the location of the point ofmaximum camber from the leading edge (in tenth of the chord) and the third and fourth numbers indicate the maximum thickness (in per cent of the chord) [4,5].

To obtain the three dimensional blade we have to define chord length, blade twist angle, tip speed ratio and rated wind speed. The equations based on BEM theory and Betz's law can be used to calculate the different design parameters. Table I below shows different values of necessary input parameters for QBlade to generate the blade profile and coordinates that were used for modeling.

TABLE I
DIFFERENT KIND OF FOILS ALONG THE SPAN OF THE BLADE



S.No.	Position (m)	Chord(m)	Twist	Foil
1	0	0.2	0	Circular Foil
2	0.0775	0.2	0	Circular Foil
3	0.155	0.2	0	Circular Foil
4	0.293	0.38	20	NACA 0018
5	0.431	0.35	18.44	NACA 0018
6	0.569	0.31	13.56	NACA 0018
7	0.707	0.27	10.43	NACA 0018
8	0.84	0.23	9.35	NACA 5528
9	0.98	0.2	7.34	NACA 5528
10	1.12	0.17	5.79	NACA 5528
11	1.259	0.16	4.55	NACA 5528
12	1.4	0.14	3.54	NACA 0028
13	1.535	0.13	2.73	NACA 5518
14	1.673	0.12	2.03	NACA 5518
15	1.81	0.11	1.44	NACA 5518
16	1.95	0.1	0.91	NACA 5518
17	2.08	0.1	0.49	NACA 5518
18	2.225	0.09	0.07	NACA 5518
19	2.363	0.08	0	NACA 5518
20	2.5	0.08	0	NACA 5518

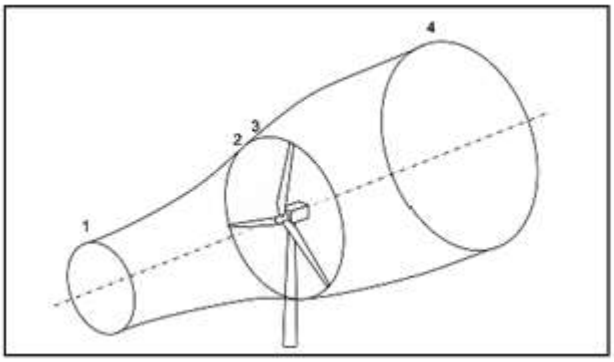


Fig. 1: Actuator disk model

Basic assumptions of the method are that the induced velocity in the rotor plane is equal to one half of the inducedvelocity in the ultimate wake, and that the flow can be analyzed by dividing the blade into a number of independent elements. Moreover the loads for each blade are uniformly distributed azimuth-wise, which means the rotor would have an infinite number of blades [6].

the relative wind speed for every section can be computed. This allows the calculation of the angle of attack and the derivation of the lift and drag coefficients of the respective profile. With these coefficients and the area of an element the normal and tangential force components, thus the thrust and torque of an element are computed. The elements' contributions can then be added up to yield the final thrust and torque of the whole rotor. For different ratios of wind speed and angular speed, characteristic curves and quantities of the rotor can be computed. Figure 1 shows the actuator disc.

2.1 Blade Element Momentum Theory

For the designed wind turbine, the following values are used: $\rho = 1.2\ kg/m^3$, v=5 m/s, d=5.4 m Hence from the above formula the calculated maximum power for the designed wind turbine becomes 1.7 KW.The efficiency of wind turbine depends upon the coefficient of performance C_P. In practice one cannot reduce the wind speed to zero, so a power coefficient C_P is defined as the ratio between the actual power obtained and the maximum available. A theoretical maximum for C_P exists, given by the Betz limit and is equal to 0.593. Modern wind turbines The classical Blade Element Momentum (BEM) theory couples the momentum theory or disk actuator theory, a operate close to this limit, with C_P therefore optimized [7].

up to 0.5, and are mathematical model of an ideal actuator disc, with the blade element theory, which describes the local events taking place at the actual blade. The blade is discretized into a finite number of blade elements. Two sections bound an element that sweeps the rotor plane on a circular path. The blade cross sections are defined by their radialposition, From the simulation graphs obtained in QBlade $C_P = 0.5$. So the actual power of the of the wind turbine for $\alpha = 6$ becomes850 W.

2.2 Wind Power

The amount of energy that can be exploited from free wind depends upon the swept area and kinetic energy of the wind. The power extracted can be expressed as

$$P = \left(\frac{1}{2}\right) \times A \times \rho \times v^3$$

III. RESULTS ANDDISCUSSION

3.1 CFDanalysis

The coordinates obtained from QBlade were imported to Solidworks for preparing a 3-D model. Some optimizations were made in transition regions. The fluid domain was created for one of the three blades to reduce the computational time. A tetrahedral mesh of 436600 nodes and 2480225 elements was used for discretization with boundary wall refinements. The inlet velocity of 5 m/s was directed normal to the inlet domain. A turbulence model of K-epsilon was used to define the turbulent flow phenomena and an RMS residual of 1E-4 was chosen as theconvergence criteria. The blade was defined as a no-slip wall whereas the fluid material was chosen to be air at 20^o C. This analysis predicts the steady state conditions which were done inside the premises ofANSYS-CFX.

From CFD analysis the pressure along the span of the blade is calculated which is used as the pressure load for the FSI analysis of the blade. Figure 2 shows the pressure side of the blade. It shows the colour variation indicating the pressure distribution along the span of the blade. The darker colour indicates low pressure and the lighter colourindicates high pressure regions. The starting torque is very high in the root portion of the blade and there occurs more stress whereas this phenomenon is not seen in the tip portion. The pressure distribution contour helps to increase the strength of the material where it is necessary and the material and design can be altered inaccordance.

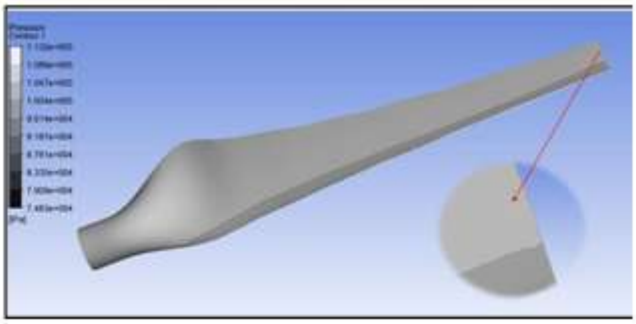


Fig. 2: Pressure side of the blade

Similarly in the suction side shown in Figure 3 thecolour indicates that the pressure is relatively lower than the previous face which in case in compensated by the increase in the velocity. There is pressure difference between thesetwo sides i.e. pressure side and suction side and this difference in the pressure results in the liftgeneration.

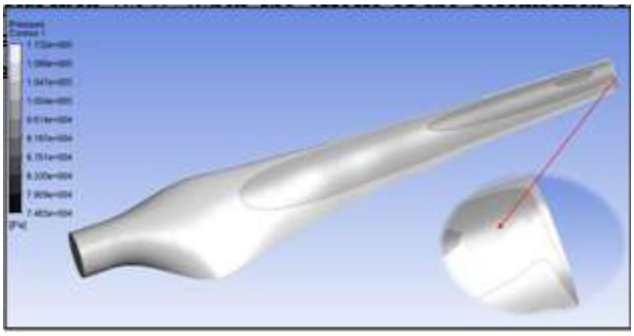


Fig. 3: Suction side of the blade

The analysis involved the study of power generated at various wind speed other than the rated speed in the range of 1 to 20 m/s. Figure 4 shows that the coefficient of lift attains maximum value when the angle of attack is 18 degrees. Figure 5 shows a graph where the dependency of the power produced by the turbine on the velocity of the headwind is quite noticeable. Above that angle stalling would occur and the coefficient of lift starts to decrease with increasing angle of attack.

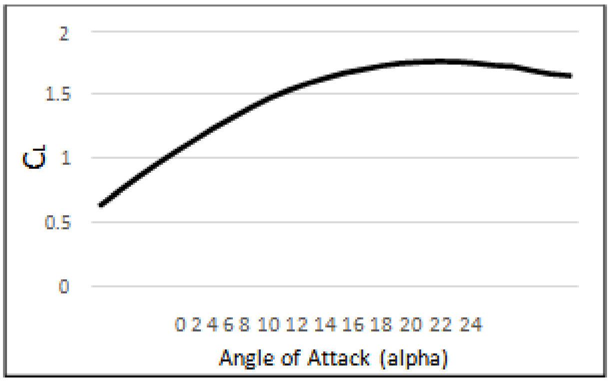


Fig. 4: Relation of Coefficient of Lift and angle of attack

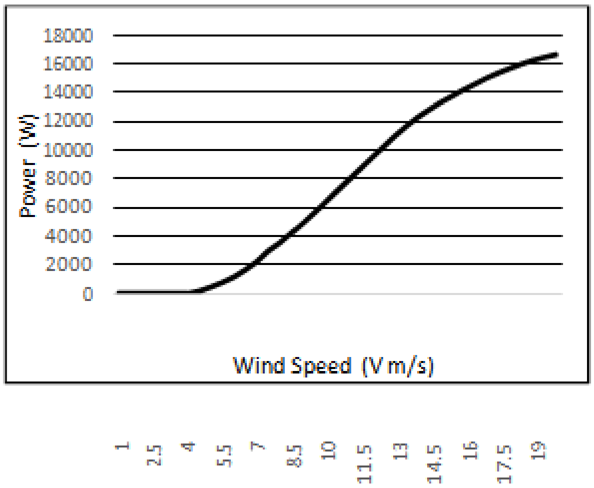


Fig. 5: Power generated at different wind speeds.

3.2 Structuralanalysis

Fluid structural Interaction (FSI) was conducted with the pressure distribution obtained from CFD and deflection as well as stress was obtained. This analysis was necessary to test the structural integrity of the blade model under extreme loading conditions. The solution of CFD was the setup for the structural analysis. When flowing fluid comes in contact of a solid surface it experiences pressure as it deforms and in turn applies another form of pressure on the solid. This interaction is known as Fluid Structure Interaction (FSI). When the effects of the deformation of the fluid flow are neglected it is termed as one- way FSI. In this study oneway FSI was preferred for the ease ofcomputation.

TABLE III
PROPERTIES OF THE STUCTURAL MATERIAL

Material	Polyester Resin (E-Glass Fiber)
Density	2.64gm/cm^3
Young's ModulusofElasticity	77
GPaPoisson'sRatio	0.23
BulkModulus	4.7531×10^{10}
ShearModulus	31301 MPa
Temperature	25°C

Mesh grids were generated on the blade geometry and it was given fixed support in the lowermost root section. This configuration had the blade acting like a cantilever beam.The rotational velocity of 52.35 rad/sec anticlockwise was given in the z-component of the blade. The Pressure load imported from the CFX solver result was applied onthe blade. The maximum pressure load is 0.103729 MPa and the minimum pressure is 0.045385MPa.

After FSI was conducted important results were obtained. Maximum deflection of 16.626 mm was seen in the tip of the blade whereas the bottom part of the blade shows no deflection at all. There is no deflection in the root portion of the blade and the trend continues almost up to the half span of the blade. Figure 6 shows the deflection of the blade.

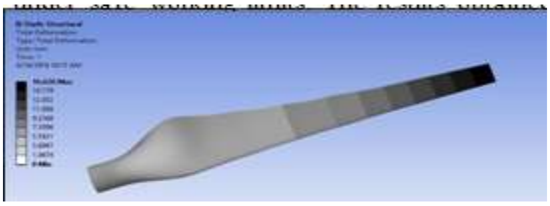


Fig.6: Total deformation of the blade

The equivalent stress on the blade is depicted by the Figure 7. The maximum equivalent stress is 29.841 MPain the mid span of the blade. Maximum deflection occurs at this position because the blade acts as a cantilever beam.The equivalent stress in the suction side of the blade is relatively low at almost all portions of the blade as compared to the pressure side of the blade. In this side also the stress concentration is greater at the mid span of the blade. But itis not as high as it is on the pressure side of the blade. The ultimate stress of the polyester resin (E-glass) is greater than the maximum stress obtained after FSI on the blade i.e. 29.841 MPa. From this observation it can be said that the design of the blade is under the safelimits.

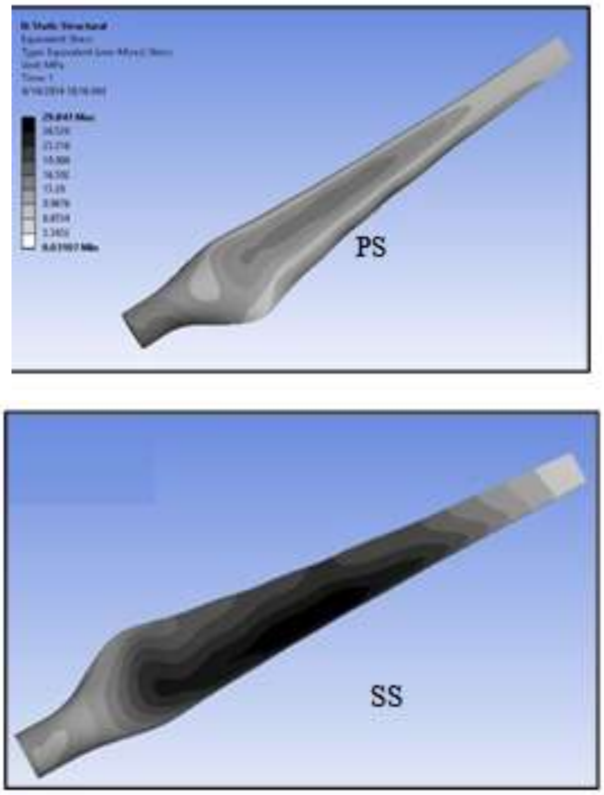


Fig. 7: Equivalent stress on blade

IV. CONCLUSION

Combined results from QBlade and CFD have shown that for blade generated with NACA 5518 air profile and operating in the wind speed range of 1 to 20 m/s and a rated speed of 5 m/s, the best angle of attack is 6° and the best coefficient of performance is 0.5. A 2.5 m long blade was designed and it could produce 850 W of power. The blade was tested for working conditions using numerical simulation and was under safe working limits. The results obtained from this work are motivational for the installment of a wind turbine as it assures the good performance of rotor and provides reliability regarding the structural integrity of theturbine.

V. ACKNOWLEDGEMENT

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