Influence of Solidity and Wind Shear on the Performance of VAWT using a Free Vortex Model

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Abstract- Performance analysis of a VAWT and HAWT is highly complex due to fluid structure interactions and blade vortex interactions. However, there are simplified methods such as momentum theory to most expensive CFD models available for performance prediction. CACTUS is neither as simple as the momentum theory nor as complex as the CFD models, it is an open source code that uses the free vortex method to predict the performance of a wind turbine. In this paper, the effect of solidity and wind shear on the performance of an H-type Darrius VAWT is studied using CACTUS. Variation of solidity was achieved by changing the chord length (*c/R* =0.04-0.07) and number of blades (*N* =2,3). It has been observed that at lower tip speed ratio (TSR < 3) the turbine with longer *c/R* was found to be more efficient due to large wind interception by the blades; and at higher TSR (> 3) shorter *c/R* was more efficient due to relatively low wake blade interaction. The improvement in performance due increasing the number of blades is effective only up to a particular TSR. Effect of wind shear due to the tower height from the ground using the power law equation with values of power law coefficient ranging from 0.1 to 0.3 has also been studied. It is observed that the power coefficients of the VAWT under a turbulent boundary layer are in congruence with the experimental results.

Keywords: VAWT, solidity, vortex method, TSR, and wind shear

Nomenclature

c	Chord length
n	Wind shear exponent
l	Element center y coordinate
D	Turbine diameter
h	Tower height
H	Turbine height
N	Number of blades
P	Total power
R	Turbine radius
A_T	Turbine frontal area = DH
T	Turbine torque
Z	Height from the ground
u	Velocity at any arbitrary height from ground
C_m	Torque coefficient= $=T\Big/\left(0.5\rho U_{\infty}{}^{2}A_{T}R\right)$
C_p	Power coefficient $=P\Big/\left(0.5\rho U_{\infty}{}^{3}A_{T}\right)$
C_T	Element tangential force coefficient $=F_{T}\Big/\left(0.5\rho U_{\infty}{}^{2}A_{T}\right)$

F_T	Element tangential force
U_{avg}	Average wind velocity across the turbine
U_∞	Freestream velocity
δ_∞	Atmospheric boundary layer height
Θ	Azimuth angle
ρ	Density

1. Introduction

Wind turbines form an essential part of sustainable and renewable energy production. A major concern regarding installation of wind turbines is its suitability to different topographies. VAWTs are less affected by fluctuations in the wind direction; this feature makes it more suitable for power production in urban areas with highly unstable flows. Prediction of performance is required based on wind ability in the region. This performance prediction is complex due to fluid structure and blade vortex interactions. To design a wind farm or turbine, an analytical tool is required to predict the performance. Analysis and prediction of the performance of VAWTs can be broadly classified into four major types. The methods in increasing order of accuracy are Momentum methods, Circulation methods, Vortex methods and CFD full scale methods [16]. In momentum methods, various forces acting on the turbine are determined by equating it with the rate of change of momentum of wind across the rotor[2].The circulation methods include the effects of the interaction between the circulation bound to the blades and the wake vorticity. Vortex methods are a potential flow model that is based on the calculation of the velocity field about the turbine through the influence of vorticity in the wake of the blades. Open source codes based on the vortex method are VDART[4], VDART-TURBO[5] and CACTUS[6]. CFD is the most accurate method in which complete Navier–Stokes equations are solved to predict the aerodynamic performance of VAWT using different turbulence models[7]. CFD methods are accurate but more computationally expensive as compared to vortex methods. Vortex methods are further classified into two categories, free vortex model and prescribed wake model.

CACTUS[6] (Code for Axial and Cross-flow TUrbine Simulation) is open source code developed by Sandia National Laboratories and is based on the free vortex method. David, et al. [8] compares various computational models available for predicting the performance of Darrieus-type straight-bladed VAWTs. Vortex models are found to give the most accurate results but are computationally intensive compared to streamtube and cascade models. Iida, et al. [9] performed aerodynamic noise simulation using vortex method. The results obtained by vortex methods were compared with the momentum method and aerodynamic noise analysis was done for a particular TSR of 3.5 and at a rated speed of 12 m/s. The aerodynamic noise radiated from the rotor blades was solved using the Ffowcs Williams-Hawkings equation. In conclusion, vortex methods have the ability to capture the complex wake structures and the use of VAWTs (for the same power coefficient) as a low noise renewable energy system.

Dumitrescu and Cardos[10] uses a free vortex model incorporating dynamic stall effects. A comparison was made between the local tangential force coefficients C_T and the power coefficient C_p for various azimuthal angle for the TSRs (2.49 and 4.60). The results are congruent with the experimental data available for the turbine. The major conclusion drawn from the analysis was that the vortex method was effective in predicting the power coefficient in the dynamic stall region (TSR ranges from 1 to 4) and power coefficient predictions by the vortex model were better than the streamtube model in the unstalled regime, but underestimated the value in transition region (TSR ranges from 4 to 6).Zanon, et al. [12] modeled the vorticity distribution in the near and far wake using the single-wake panel model, double-wake panel model and single-wake models with prescribed point actuator model. It was observed that the dynamic stall affects the loads, as well as the development of the wake and simplifying a double wake as a single wake had discrepancies in case of high solidity turbines at lower tip speed ratios.

Ferreira, et al. [13] considered a two bladed turbine to predict C_p and C_m. The aerodynamic models used were double-multiple streamtube model (DMST), the actuator cylinder model (AC), the U2DiVA code, the ARDEMA2D code, and the CACTUS code. The CACTUS result was found to be consistent with the other models (actuator cylinder, U2DiVA and ARDEMA2D), where the wake is being explicitly modeled. Michelen, et al. [6] of Sandia National Laboratories performed simulations using the CACTUS code to predict the performance of a three bladed, vertical axis, cross flow turbine with straight, constant chord blades. The first section used a NACA 63-618 airfoil throughout the entire span of the blade ignoring the transition region, while the second section simulated half the transition region as a circular cylinder. CACTUS simulations showed wake instability issues due to local regions of upstream flow because of the high chord to radius ratio (c/R=0.28). Similar simulations performed on another turbine model with lower chord-to-radius ratio (c/R=0.124) showed no wake instability issues. It was also observed that simulations under predicted the performance for the turbine whose blade was assumed to be cylindrical over half the span.

Murray and Barone [14] of Sandia National Laboratories compared the performance of a two bladed and three bladed, 5 m turbine both having a parabolic blade profile. The performance coefficient obtained from CACTUS for the two and three blade turbines were compared with experimental results which showed good agreement at both lower and high tip speed ratios. Effect of temporal resolution and wake velocity freezing on the average performance coefficient was also studied for the 34m turbine. It was observed that for 20 time steps resolution the wake velocity freezing had little detrimental effect on the average power coefficient while for 30 and 40 time steps resolution the average power coefficient was found to be very close to each other.

Literature shows that most of the analysis is done for 3 bladed turbines and that vortex methods are good enough to predict the performance of a turbine. CACTUS has great potential for predicting performance of VAWT with good degree of accuracy and is highly resource efficient, which makes it a good alternative over CFD methods. The objective of this paper is to study the effect of solidity and wind profile on the performance of a VAWT using CACTUS. The study of solidity allows the right selection of geometry of the wind turbine so as to ensure maximum output is obtained from it. The geometry should be optimum to make sure that under all conditions, the output will not be compromised to a great extent. The assumption of freestream attacking the wind turbine neglects lot of physics regarding the way in the wind is coming to the wind turbine. The performance of the wind turbine will be affected by the profile of the wind. Without assuming the wind shear, there are possibilities of over prediction of the performance of the wind turbine.

2. CACTUS Code

CACTUS is an open source code developed by SANDIA National Laboratories based on the Free Vortex method. The code written in the FORTRAN 95 programming language uses VDART3 code as the base.

CACTUS discretizes the blade and struts of the wind turbine into a number of vortex elements. Each blade element depending on the chosen blade profile is assigned a C_L and C_D for varying angle of attack and different set of Reynolds numbers. For every time step the bound vorticity associated with individual blade element is calculated using Kutta-Joukowoski theorem using the C_L data. For each blade element a wake vortex lattice (or bound vorticity) is defined which consists of trailing and span wise vorticity as shown in Fig.1.

For each time step the trailing and span wise vorticity is calculated using Helmholz theorem of conservation. Using the bound vorticity data available, the loads are calculated based on fixed point iteration technique. Murray and Barone [14] gives a more detailed information about

CACTUS, the solution methods and the various models used by it. CACTUS outputs various blade aerodynamic forces, detailed wake vortex trajectories, and performance parameters such as torque and power coefficients. CACTUS cannot capture the 3D effects in the transitional regions and gives inaccurate results when a turbine with high chord-to-radius ratio is taken into consideration [6].

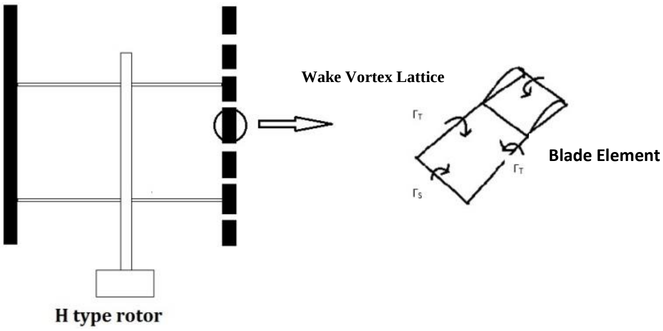


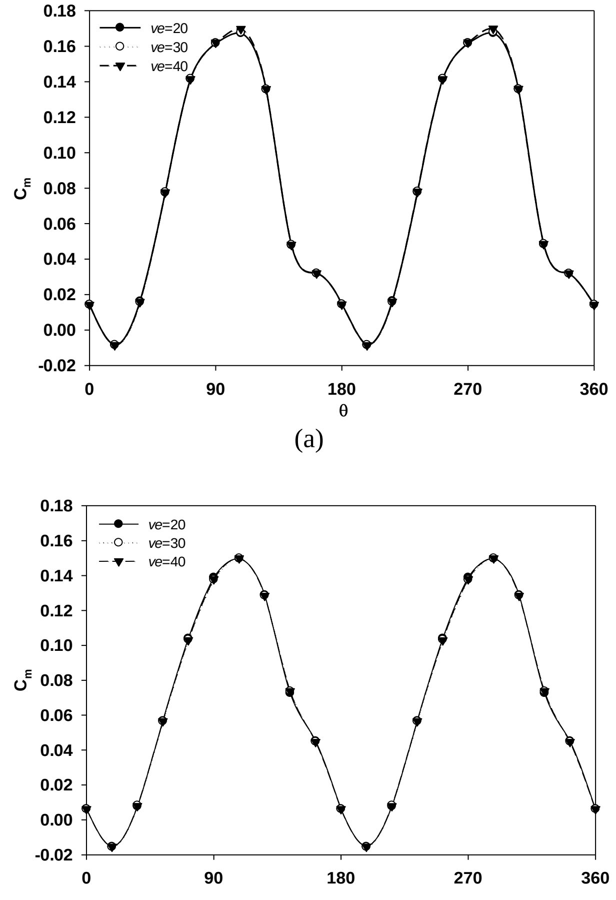
Fig. 1. Discretization of the blade into vortex lattice

3. Validation Studies

The SANDIA 5 m diameter VAWT research turbine was chosen for validation of the code. Validation was done for two and three bladed SANDIA turbine for which experimental data are available [14]. Table 1 gives the various parameters associated with the two and three bladed turbine. The SANDIA turbine was modeled in MATLAB using the geometry creation scripts included with CACTUS. The base of the turbine is located at a height of 4.57 m from ground. The wind has a constant velocity of 8 m/s with a uniform profile. The element number and time step independence study was done before benchmarking. The study was performed for TSR 4 and 5.5 with the turbine set to 162.5 RPM. All results are presented at the end of 30 revolutions. Three cases of vortex elements(ve) 20, 30 and 40 had been taken into consideration for the two bladed SANDIA turbine with 20 time steps per revolution. The instantaneous C_m of the final revolution has been plotted against θ as shown in Fig.2 for TSR 4 and 5.5.

Table 1. Turbine parameters- SANDIA turbine

Parameter	2 Bladed	3 Bladed
Diameter (D)	5 m	5 m
Height to radius ratio (H/R)	2.04	2.04
Chord Length (c)	152.4 mm	152.4 mm
Blade profile	NACA 0015	NACA0015
Rotor Solidity ($\sigma = Nc/D$)	0.16	0.22



(a)

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Fig. 2. Vortex element independence – SANDIA turbine (a)TSR 4 (b)TSR 5.5

Fig. 2 shows that; C_m predictions are the same irrespective of the number of vortex elements with a maximum deviation of 0.1%. The time steps independence study has been with 20 vortex elements considering 20, 30 and 40 steps per revolution(*ntr*). The instantaneous C_m variation for all cases for TSR 4 and 5.5 are shown in Fig. 3. Here the prediction with 20 ntr is 3.6% of that made with 30 *ntr.* Thus on the basis of this study all further simulations were done with 20 vortex elements and 20 time steps per revolution. The C_p predicted by CACTUS is validated against the experimental results available for the both SANDIA two and three bladed turbines [14] as seen in Fig. 4. The rotation rate is 162.5 RPM for the two bladed turbine and 150 RPM for the three bladed turbine. Results shown in Fig. 4 ensure that CACTUS and experimental results at both low and high TSRs for both the two and three bladed turbine are within a reasonable range. The maximum deviation seen is 21% for two bladed turbines and 19% for three bladed.

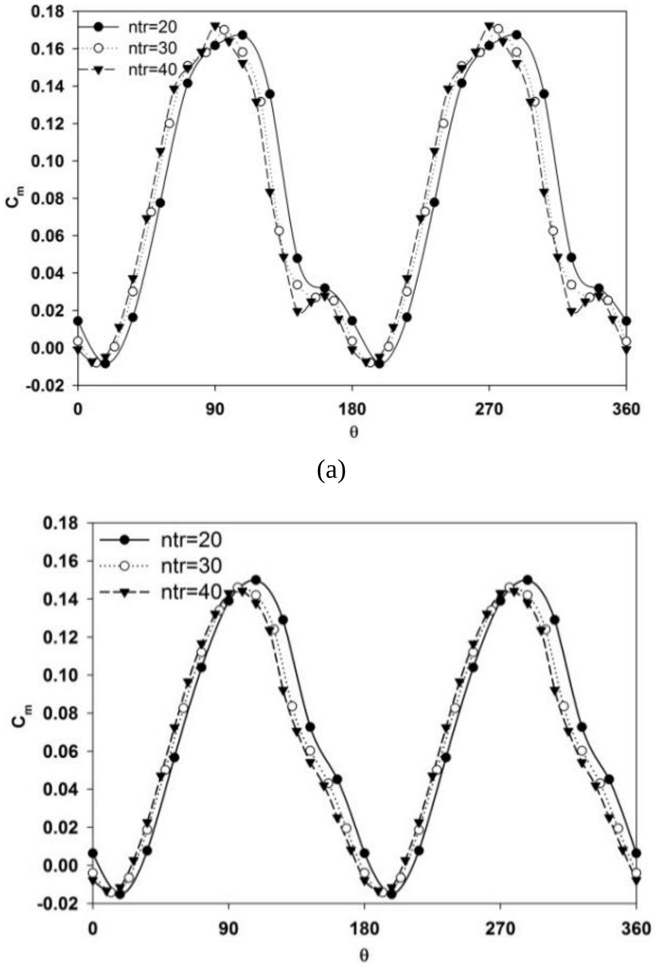

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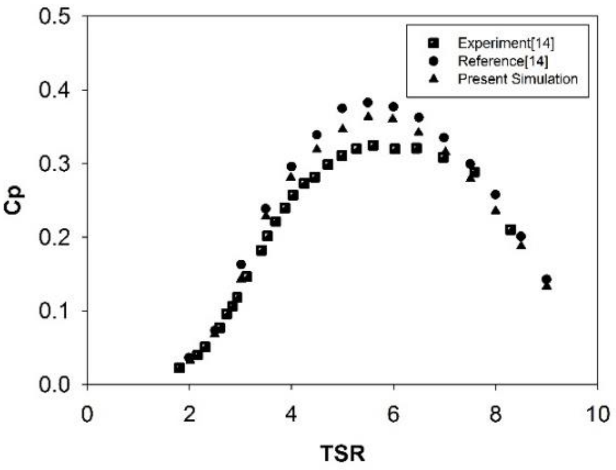
Fig. 3. Time step independence- SANDIA turbine (a) TSR 4 (b) TSR 5.5



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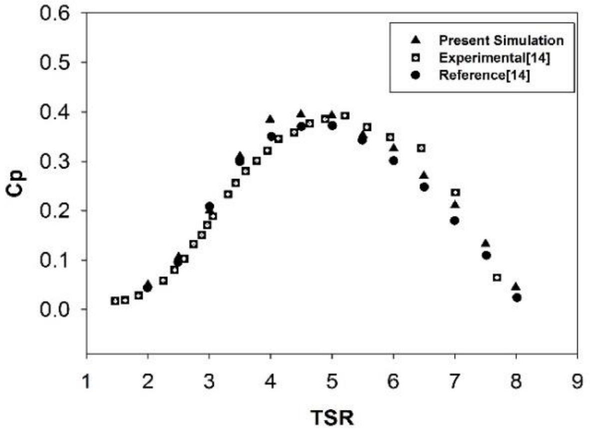


(b)

Fig. 4. Validation study- SANDIA turbine (a) 2 Bladed (b) 3 Bladed

4. Problem Description

The effect of solidity and upstream wind profile on the performance of a turbine is studied. The solidity of the turbine has been changed by changing the number of blades (*N*) and chord length (*c*). The range of σ varies from 0.04 to 0.105 with two and three bladed turbines. A VAWT with straight blades has been considered for the study, whose geometric parameters are summarized in Table 2. The effect of wind shear, seen within the atmospheric boundary layer on the performance of VAWT, has also been studied for two bladed turbine with σ =0.04. The wind shear is assumed with a power law equation and corrected for power law exponent(*n*), the calculated values of *n* vary from 0.11 to 0.28.

Table 2. Turbine parameters in the current study

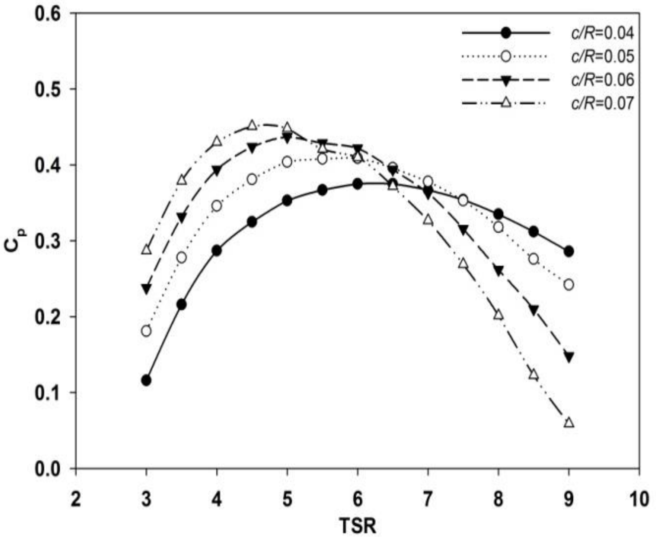
Parameters	Description
Number of Blade (*N*)	2 or 3
Height (*H*)	10 m
Diameter (*D*)	10.1 m
Chord length (*c*)	202/252.5/303/353.5 mm
Blade Profile	NACA 0015
Tower height (*h*)	4.5 m

5. Results and Discussion

The variation of performance due to the effect of different parameters is discussed. The results are represented numerically and graphically.

5.1 Effect of Chord Length

The effect of solidity on the performance of VAWT has been studied by changing the chord length. Chord lengths considered are 202, 252.5, 303 and 353.5 mm which correspond to *c/R*=0.04, 0.05, 0.06 and 0.07 respectively. Simulations were done for TSR's ranging from 3 to 9 for two bladed turbine and from 3 to 7.5 for the three bladed turbine. Each simulation was run for 30 revolutions or until convergence in C_p is achieved. The C_p has been plotted against TSR's for various *c/R* ratios as shown in Fig. 5. It is observed from Fig. 5a, that turbine with smaller *c/R* produces less power than turbine with larger *c/R* for TSR < 6.5 while for TSR > 6.5 the turbine with smaller *c/R* is found to produce more power than a turbine with larger *c/R*. A crossover in the performance is observed around TSR 6.5 for the two bladed turbines where other *c/R'*s showed similar power. Similar behavior is also seen with three bladed turbine as seen inFig. 5b, except that the crossover is seen at a lower TSR~5. To investigate this, the torque characteristics of the two bladed turbine is seen. Fig. 6 shows the instantaneous C_m based on the total torque contributed by both the blades and C_m based on the individual torque of the blades for *c/R*=0.04 (σ =0.04) and TSR 4. It is observed from Fig.6b that in single revolution when blade 1 is in the upwind region, blade 2 is in downwind region and vice versa. It is also observed that blade 1 in the upwind region (Fig. 7) contributes more to the C_m than blade 2 which is in the downwind region. The same can be said for blade 2 in the upwind region. However, the maximum C_m contributed by each blade in both upwind and downwind regions are equal. The above observation leads to the conclusion that C*m* or C_p vs θ characteristics can be taken into consideration for any one of the blade as both blades have similar contributions over a single revolution but at different time instants. Thus further comparisons are made considering the characteristics of blade 1 only. Fig. 8 shows instantaneous C_m as a function of the θ for *c/R*= 0.04 and 0.07 at TSR 4, 6.5 and 7.5 for the two bladed turbine.



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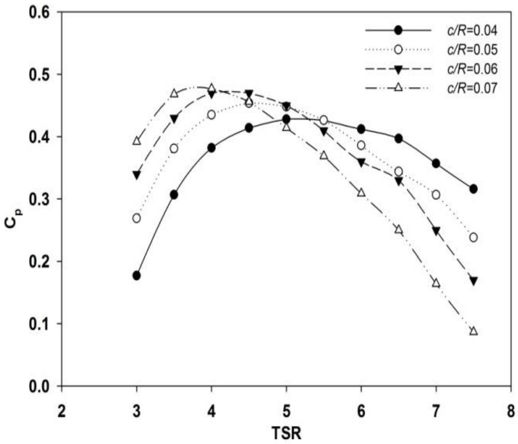

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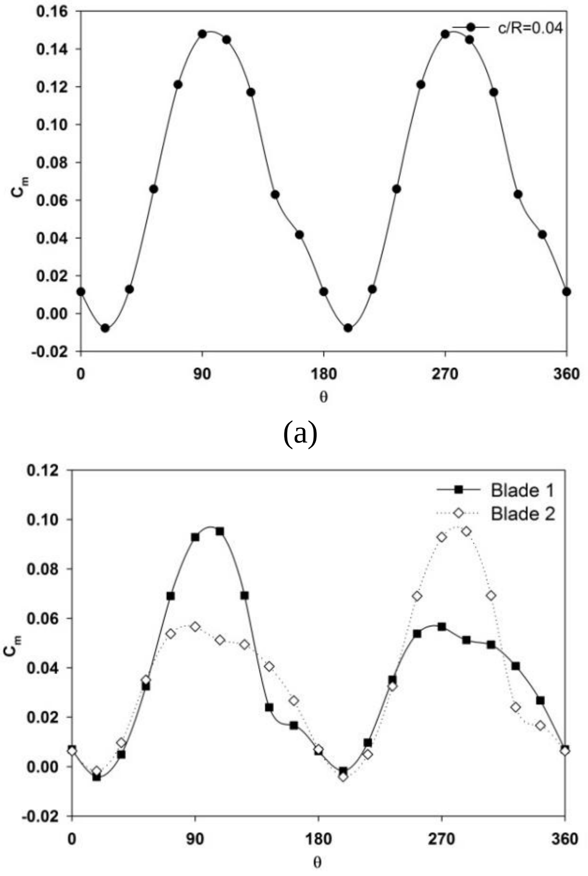
Fig. 5. Variation of C_p with TSR (*c/R*=0.04,0.05,0.06 and 0.07) (a) 2 Blades (b) 3 Blades



(a)

(b)

Fig. 6. Variation of C_m with angle of rotation of blades (2 Blades, TSR 4) *(a)c/R*=0.04 *(b)* Blade 1, 2

It can be seen from Fig. 8 that with decrease in *c/R* the torque contribution reduces and this explains the behavior seen in C_p(Fig.5) and it is seen across all TSR's shown in Fig. 8. The reduction in torque reduces with increases in TSR. At lower TSR's the turbine with longer chord produces more power in the upwind region as the area over which the blades intercept the wind is more resulting in more torque and thus more power. Also the change seen in the downwind region is responsible for the crossover in C_p. At TSR 4 the C_m change is same for both *c/R* [Fig. 8a] but there is a considerable reduction in C_m at TSR 7.5 [Fig. 8c]. It can be seen from Fig. 8b and 8c that due to wake-blade interaction, the torque generated by the blades decreases in the downwind region and this is more prominent in blades with longer *c/R*. Although the power produced in the upwind region increases with increase in chord length, the power produced in the downwind region is lowered due to stronger wake-blade interaction. This can be seen in Fig. 9 which shows C_m vs θ at TSR 4, 6.5 and 7.5 for σ=0.04 and 0.07. It can be observed from Fig. 9a that there is not much variation in torque values in the upwind region (*σ =0.04)* for the TSR's considered but in the downwind region there is considerable effect. The same effect is observed with the three bladed turbine as seen in Fig. 10 which shows C_m as a function of θ at TSR 4 for *c/R* 0.04 and 0.07.

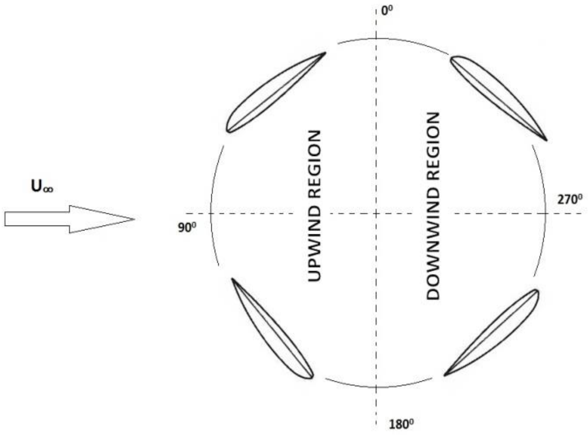
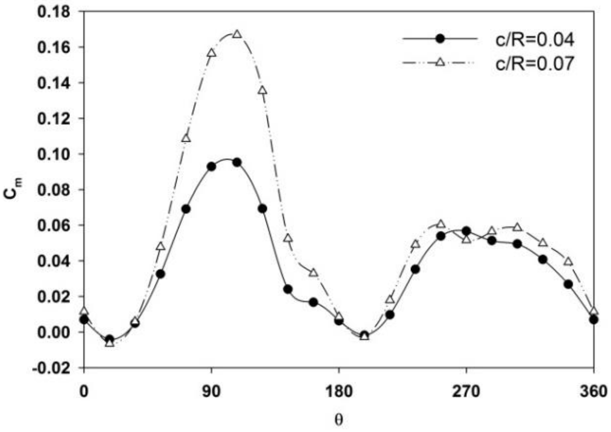


Fig. 7. Upwind and downwind regions in the domain of the flow



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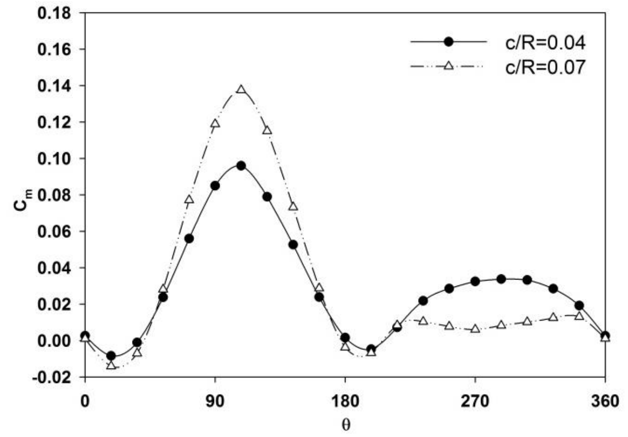

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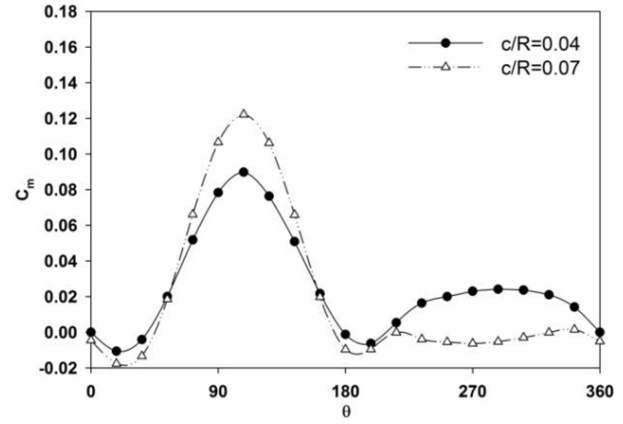
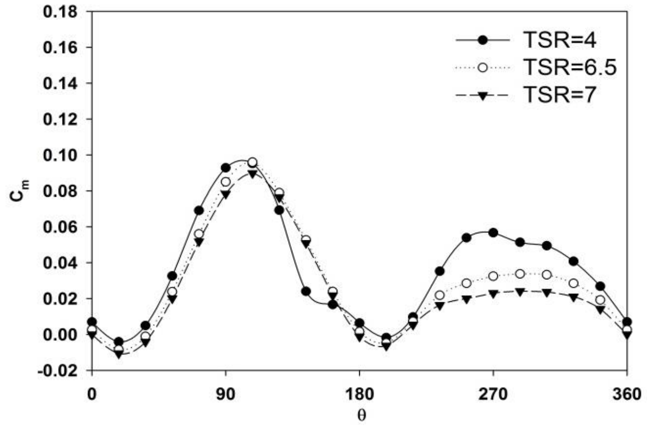


(c)

Fig. 8. Variation of C_m with angle of rotation of blades (2 Blades, *c/R* 0.04, 0.07) (a)TSR 4 (b)TSR 6.5 (c)TSR 7.5



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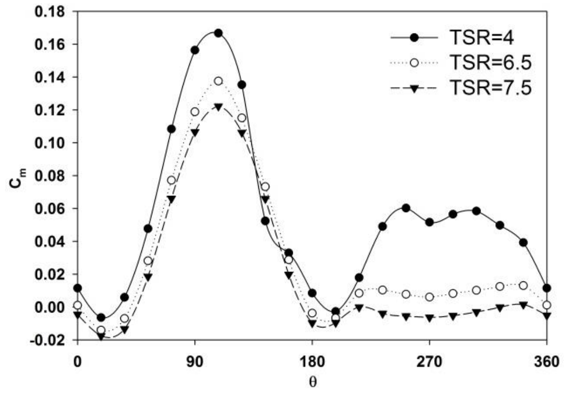


(b)

Fig. 9. Variation of C_m with angle of rotation of blades (2 Blades, TSR 4, 6.5, 7.5) *(*a) *σ =0.04 (*b) *σ =0.07*

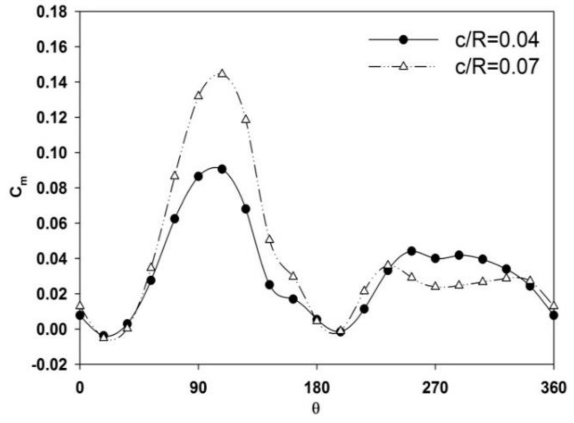
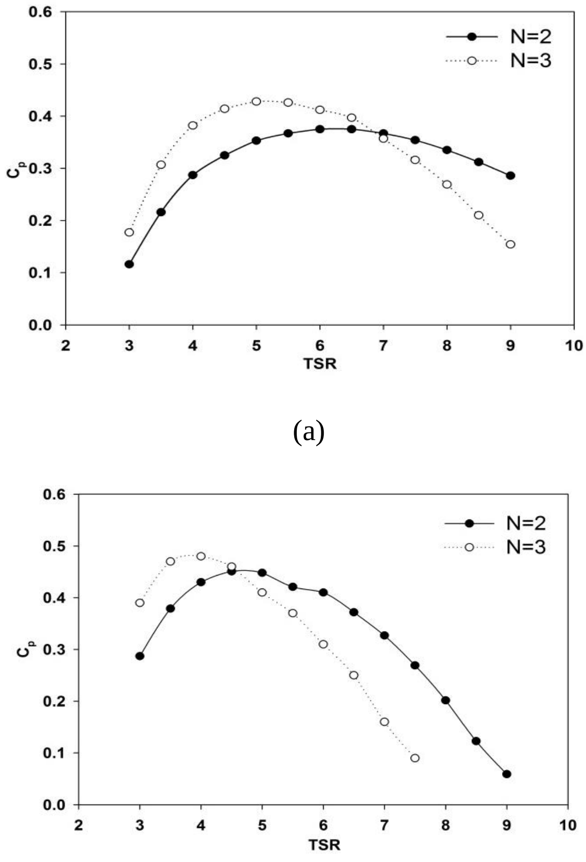


Fig. 10. Variation of C_m with angle of rotation of blades for TSR4 (3 Blades, *c/R* 0.04, 0.07)

5.2 Effect of Number of Blades

The effect of number of blades on the performance of a VAWT has been presented for both two and three bladed turbine having *c/R* 0.04 and 0.07. Fig. 11 shows the performance characteristics of both two and three bladed turbines for *c/R* 0.04 and 0.07. It is observed from Fig. 11 that the peak power produced by the three bladed turbine is higher compared to the two bladed one and the former attains the peak power at lower TSR. At lower TSR's the three bladed turbine provides more performance as the area over which the blades intercept the wind is higher for the three bladed turbine compared to the two bladed one. At higher TSR's the performance of the three bladed turbine is reduced due to stronger wake-blade interaction in the downwind region. As expected the crossover in performance shift towards left at higher *c/R* ratio due to stronger wake-blade interaction which dominates at low TSR values.



(a)

(b)

Fig. 11. Variation of C_p with TSR for (*N* 2, 3) (a) *c/R* 0.04 (b) *c/R* 0.07

5.3 Effect of Wind Shear

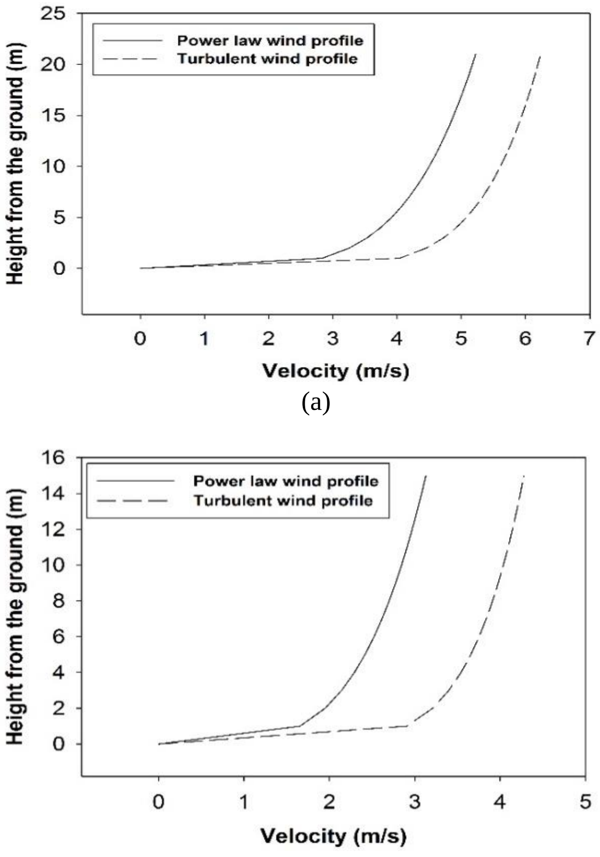
The effect of wind shear on the performance of a VAWT has been studied using a power law equation given by Eq. (1).

$$U = U_\infty \left(\frac{z}{\delta_\infty}\right)^n \qquad (1)$$

The value of wind shear exponent *n* for each free stream velocity and boundary layer reference height is given by Justus correction formula given as

$$n = \frac{0.37 - 0.088 \ln(Uref)}{1 - 0.088(\frac{Zref}{10})} \qquad (2)$$

Z_{ref} is constant based on the terrain. A value of 444m has been chosen for Z_{ref}, assuming a grassy terrain for the wind turbine placement. The values of U_{ref} have been calculated from different values of tip speed for a RPM of 165.5 for the two bladed turbine. Fig. 12 shows the wind profile intercepted by the wind turbine blade for a TSR of 5.5 and 4. The velocity profiles are plotted up to the length of the wind turbine from the ground. It is evident that the wind profile change the value of wind velocity intercepted by the blade thereby affecting the performance of the turbine. From Fig. 13, the trend of the coefficient of power with TSR shows an increase in TSR values which peaks at 4.66. This peak performance of the VAWT is supported by the findings of S. Brusca, et al. [17], wherein a performance of a comparable VAWT has been studied. The peak of C_p 0.214 happens in the range of 4.25 – 4.46 TSR. The C_p with consideration for wind shear results is comparatively lower than the value predicted by simulations without wind shear effect and experimental. The wind shear considerations gave higher value than the Sandia CACTUS simulation and the experimental data till a TSR value of 3.5. After a TSR of 4.5 there is a decrease in C_p which is much larger than expected. The peak value of power coefficient was also under predicted by a large margin of 58%. Comparing the *n* values for these key TSR values it shows that for an $n > 0.212$ the C_p decreases. The validity and applicability of the code for performing wind shear calculations can be tested by doing the study with a turbulent boundary layer profile. For the corresponding study a wind shear exponent of 1/7 was used, as suggested by the CACTUS code. The C_p values obtained showed good agreement with the experimental data. It predicted the peak value of C_p with good accuracy. Hence the code is capable of predicting the wind shear effect. The loss of C_p in a power law wind profile is due to a lot of momentum loss arising due to the wind profile. Hence we can safely assume that the experimental results presented were for turbulent wind profile than a laminar or constant wind profile.



(a)

(b)

Fig. 12. Comparison of power law wind profile to turbulent wind profile for a TSR of (a) 5.5 and (b) 4

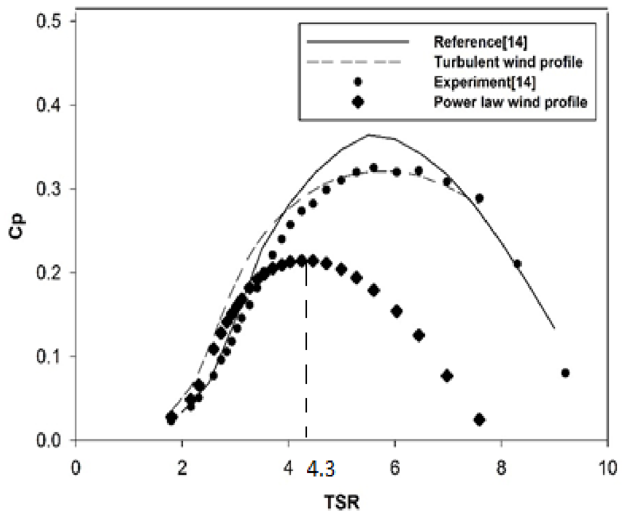


Fig. 13. The variation of C_p with TSR for various wind profiles compared against the CACTUS and experimental simulation by SANDIA

6. Conclusions

CACTUS simulations have been done to investigate the effect of solidity and wind shear on the performance of a VAWT. The following conclusions are made.

It is observed that at lower TSR's turbine with longer *c/R* has higher C_p than a turbine with shorter *c/R*. This is due to larger area over which the blade intercepts the wind. At higher TSR's the turbine with shorter chord length is more effective as the wake-blade interaction is lower in the downwind region.

At lower TSR's a three bladed has more C_p than a two bladed one due to larger area over which the blade intercepts with the wind, but at higher TSR's since the wake-blade interaction becomes stronger the effectiveness of three bladed turbine is lower compared to the two bladed one. It is also observed that the crossover in performance occurs at lower TSR's for three bladed turbine as against two bladed with increase in *c/R* due to stronger wake-blade interaction in the downwind region.

Wind shear shows a considerable effect on the performance prediction of a VAWT. When a flat wind profile is assumed across the turbine, maximum power can be generated, but as the wind gradient increases the performance reduces by a significant extent. It is observed that as the wind gradient increases the tangential force acting on the blade decreases resulting in lower production of power. It is also observed that the percentage reduction in power with respect to a flat profile increases with increase in TSR. This shows that wind profile has to be taken into account for performance prediction.

This study can aid the selection process of the wind turbines, thereby helping to obtain maximum output from the installed turbine. The geometric parameters if adequately taken care, can increase the productivity of the turbine and prove to be more economically viable even in small scale. The wind turbines can be used in every household with low investment and high outputs, which can reduce the non-renewable energy dependence.

Further scope for the study can include the type of airfoils to be used and the best wind and terrain conditions for the working of the wind turbine.

References

[1] F. Trivellato a and M.R. Castelli, On the Courant-Friedrichs-Lewy criterion of rotating grids in 2D vertical-axis wind turbine analysis. Renewable Energy, pp. 53-62, 2014.

[2] I. Paraschivoiu, O. Trifu, and F. Saeed, "H-Darrieus Wind Turbine with Blade Pitch Control", International Journal of Rotating Machinery, pp. 7-8, 2009.

[3] Wilson, R.E., Wind Turbine Aerodynamics. Journal of lndustrial Aerodynamics, pp. 357-372, 1980.

[4] Kristian Dixon, Carlos Simao Ferreira, and C. Hofemann, "A 3D unsteady panel method for vertical axis wind turbines", The proceedings of the European Wind Energy Conference & Exhibition EWEC Brussels. pp. 1-10, 2008.

[5] Brownlee, B.G., A vortex model for the vertical axis wind turbine, Master Thesis in mechanical Engineer. Texas Tech University. 1988.

[6] Carlos Michelen, et al., "CACTUS Open Source Code for Hydrokinetic Turbine Design and Analysis: Model Performance Evaluation and Public Dissemination as Open Source Design Tool", Proceedings of the 2nd Marine Energy Technology Symposium, 2014.

[7] K. M.Almohammadi, et al., "Effect of Transitional Turbulence Modelling on a Straight Blade Vertical Axis Wind Turbine", Alternative Energies, pp. 93 - 112, 2013.

[8] Mazharul Islam, David S.-K. Ting, and A. Fartaj, "Aerodynamic models for Darrieus-type straight-bladed vertical axis wind turbines", Renewable and Sustainable Energy Reviews. pp. 1087-1109, 2008.

[9] Akiyoshi Iida, Akisato Mizuno, and K. Fukudome, "Numerical simulation of aerodynamic noise radiated form vertical axis wind turbines", Proceedings of 18th international Congress on Acoustics, 2004.

[10] H. Dumitrescu and V. Cardos, "A free wake method for vertical-axis wind turbine performance prediction", Rev. Roum. Sci. Techn. – Méc. Appl., pp. 87–100, 2009.

[11] Carlos Simão Ferreira and F. Scheurich, "Demonstrating that power and instantaneous loads are decoupled in a vertical-axis wind turbine", Wind Energy. pp. 385-396, 2014.

[12] Alessandro Zanon, Pietro Giannattasio, and C.J.S. Ferreira, "Wake modelling of a VAWT in dynamic stall: impact on the prediction of flow and induction fields", Wind Energy, pp. 1855–1874, 2014.

[13] C Simao Ferreira, et al., "Comparison of aerodynamic models for vertical axis wind turbines", Journal of Physics, pp. 10-11, 2014.

[14] [Jonathan C. Murray and M. Barone, "The Development of CACTUS, a Wind and Marine Turbine Performance Simulation Code", AIAA, pp. 18-19, 2011.

[15] Crastto, G., Numerical Simulations of the Atmospheric Boundary Layer, UniversitÃ di Cagliari, 2007.

[16] S Chandramouli, TP Premsai, P Prithviraj, Vivek Mugundhan, Ratna Kishore Velamati, "Numerical analysis of effect of pitch angle on a small scale vertical axis wind turbine", International Journal of Renewable Energy Research (IJRER), pp.929-935, 2014.

[17] S. Brusca , R. Lanzafame , M. Messina, "Design of a vertical-axis wind turbine: how the aspect ratio affects the turbine’s performance", Int. J. Energy Environ. Eng., pp. 333-340, 2014.