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Analysis of Vertical Axis Wind Turbine Using Pitching Mechanism

Tushar R. Mali[1], Avinash P. Dhale[2], Harsh A. More[3], Prachi R. Kavade[4], Prof. Ramesh K Kavade[5], Dr.P.M.Ghanegaonkar[6]

[1,2,3,4]*(Department of Mechanical Engineering, Dr. D. Y. Patil, Institute of Technology, Pimpri,Pune-18)*
[5] *Associate Professor(Department of Mechanical Engineering, Dr. D.Y. Patil, Institute of Technology, Pimpri, Pune-18)*
[6]*Professor(Department of Mechanical Engineering, Siddhant College of Engineering, Pune)*

Abstract: *Vertical Axis Wind Turbines (VAWT) have been valued in recent years for their low manufacturing cost, structural simplicity and convenience of applications in urban settings. In this study, a small-scale H-darrieus VAWT using four NACA-0018airfoils with a cord length of 0.095 m and a wind turbine radius of 0.6 m is designed. During each rotation, the angle of attack depends on the wind velocity, angular velocity and current azimuth angle for each turbine blade. Negative torqueses at certain angles are attributed to the inherent unsteady aerodynamic behaviour at high angles of attack. The unfavourable negative torques are eliminated using an optimal pitch control strategy, which maximizes the tangential force coefficients and thus the torque coefficients by iterations of all possible relative angles of attack for various tip speed ratios. As a result, the power coefficient is significantly improved especially at low tip speed ratios in the range of zero to two. Blade pitch control can also solve the self-starting problem and reduce the vibration of vertical axis wind turbines*

Keywords: *VAWT, Pitching Mechanism, H-Darrieus, NACA0018.*

1. INTRODUCTION

Whenever the flowing medium velocity is changing with respect to a propeller, that propeller needs a pitch control mechanism to operate as desired. The wind speed always fluctuates up and down around this optimum wind speed. To generate the optimum power, the turbine blades should adjust, up and down, according to the wind speed. This adjustment comes from turning the blades around their longitudinal axis (to pitch). When the wind speed is decreased the blade pitch is such that it exposes more surface area to the wind and vice versa.

There are two kinds of pitch control mechanism. The first is called "Active Pitch Control" or "Force pitch control'', where the rotor blades turn around their longitudinal axis (to pitch) by a computer controlled mechanism. This type of pitch control requires expensive equipment however provides good pitch control. Active pitch controls are used in one third of the large turbines currently installed. The second pitch control mechanism is called "Passive" or "Stall Pitch Control" or "Self-acting Pitch control". In this type of design the blade does not rotate around its longitudinal axis, but is designed such that it naturally creates a stall and lower rotation speed. This type blade requires precise blade design and structurally strong towers.

To extract the more power output from VAWT a blade angle with respect to its axis is change.

2. LITERATURE REVIEW

In Research paper named as "Analysis of Lift and Drag Forces at Different Azimuth Angle of Innovative Vertical Axis Wind Turbine [1]" which is published by author Abhijeet M. Malge and Prashant M. Pawar. From these papers we concluded that the coefficient of power developed by the turbine depends upon lift force, drag force and pressure acting on the turbine blades and flaps at different azimuth positions at different tip speed ratio. Pressure on the upstream side of the turbine is maximum as compared to the downstream side of the turbine. This pressure difference between upstream side and downstream side causes lift force in the turbine which makes it to rotate. Velocity aggravates from centre to its periphery of the turbine.

The Research Paper "Limitations of fixed pitch Darrieus hydrokinetic turbines and the challenge of variable pitch[2]", made by "B.K. Kirke, L.Lazauskas". From paper we concluded that Variable pitch can generate high starting torque, high efficiency and reduced shaking but active pitch control systems add considerably to complexity and cost, while passive systems must have effective pitch control to achieve higher efficiency than fixed pitch systems.

Zhenzhou Zhao, Siyuan Qian, Wenzhong Shen, Tongguang Wang, Bofeng Xu, Yuan Zheng, and Ruixin

Wangpublished a paper entitled “Study on variable pitch strategy in H-type wind turbine considering effect of small angle of attack[3]” is about Variable-pitch (VP) technology is an effective approach to upgrade the aerodynamics of the blade of an H-type vertical-axis wind turbine (VAWT). At present, most of the research efforts are focused on the performance improvement of the azimuth angle owing to the large angle of attack (AoA). The purpose of this novel approach is to widen the band of azimuth positions with high performance and eventually enhance the power efficiency of the overall VAWT. Compared with the fixed-pitch (FP) blade, the VP-blade has a wider zone of the max AoA and tangential force in the upwind half-circle and yields the two new larger max values in the downwind half-circle.

The Research Paper “Aerodynamic models for Darrieus-type straight-bladed vertical axis wind turbines”, made by “Mazharul Islam, David S.-K. Ting, Amir Fartaj [4]”.Several aerodynamic models have been analyzed in this paper which are applied for better performance prediction and design analysis of straight-bladed Darrieus-type VAWT. At present the most widely used models are the double-multiple stream tube model, free-Vortex model and the Cascade model. It has been found that, each of these three models has their strengths and weaknesses. Though among these three models, the Vortex models are considered to be the most accurate models according to several researchers, but they are computationally very expensive and in some cases they suffer from convergence problem. It has also been found that the double-multiple stream tube model is not suitable for high tip speed ratios and high-solidity VAWT. On the other hand, the Cascade model gives smooth convergence even in high tip speed ratios and high solidity VAWT with quite reasonable accuracy.

3. PROBLEM STATEMENT

Despite the advantages, VAWTs have several drawbacks including low power coefficient, poor self-starting ability, negative torque and the associated cyclic stress at certain azimuth angles.

To overcome this, we have developed the mechanism to change the pitch angle of airfoil blade for this turbine at the best lift of airfoil blade to improve the power coefficient and its performance and also developed an individual active aerofoil blade pitching control mechanism for H-Darrieus turbine to improve its performance and power coefficient.

4. DESIGN OF BLADE PITCHING MECHANISM

In the blade pitching turbine, the rotating blades pitch around an axis that is parallel to axis of rotation of turbine. The pitching schedule and amplitude or pitching angle is controlled by Cam and follower mechanism. In individual blade pitching, blade angle is changed with respect to its axis to extract more power output from VAWT.

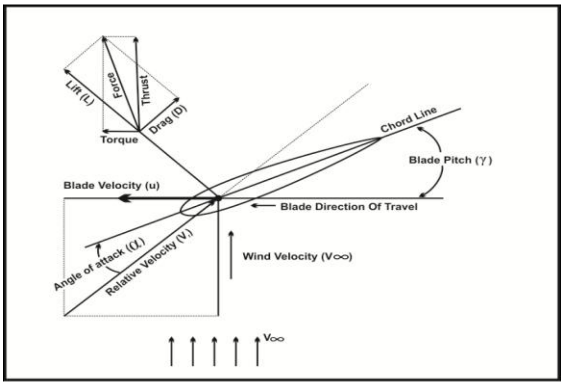

Figure 1: *Velocity triangle and various forces acting on variable blade pitch angle.*

Pitch angle is the angle made by chord line of airfoil blade with tangential blade velocity.

Angle of attack is the angle made by vector of relative velocity with chord line of airfoil blade. It is calculated by following equation.

$$\alpha = \tan^{-1}\left(\frac{\sin(\theta)}{\cos(\theta)+\lambda}\right) - \gamma$$

Individual blade pitching can be done using Cam and follower mechanism where individual blades are actuated by linkages of four bar mechanism. It is possible to make maximum tangential force by all blades to generate maximum power output.

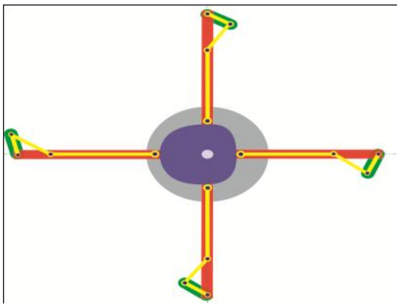

Figure 2: *Pitching Mechanism*

Design Parameters:

1. ρ =Density of air
2. c= Blade chord length

3. h = Height of blade
4. S= Area of blade= h ×c
5. B = Number of blades
6. C_p =Power coefficient
7. C_t =Torque coefficient
8. $A = Swept area = H \times D$
9. F_N =Normal force on blade
10. F_T= Tangential force on blade
11. R = Turbine radius
12. V_∞= Free Stream velocity
13. V_r= Relativevelocity
14. P_∞= Free Stream Pressure
15. a = velocity Induction factor= $\frac{V1-V2}{V1}$
16. F_L= Lift
17. F_D= Drag
18. C_D =Blade drag coefficient
19. C_L= Blade lift coefficient
20. θ=Azimuth Angle
21. γ= Blade pitch angle
22. α=Angle of attack
23. u=Blade velocity = Rω
24. ⋋**=**Tip speed ratio = $\frac{u}{V_\infty}$
25. ω= Angular speed
26. T = Instantaneous Torque
27. P = Power = Tω
28. C_n= Normal force coefficient
29. C_t=Tangential coefficient
30. μ=Dynamic viscosity

Required Formulae:

The tangential force (F_T) and Normal Force (F_N) are given by,

$$F_T = \frac{1}{2}\rho V_r^2 (hc) C_t$$

$$F_N = \frac{1}{2}\rho V_r^2 (hc) C_n$$

Chord wise tangential force coefficient (C_t) and Normal force (C_n) are calculated as,

$$C_t = C_L \sin(\alpha+\gamma) - C_D \cos(\alpha+\gamma)$$

$$C_n = C_L \cos(\alpha+\gamma) + C_D \sin(\alpha+\gamma)$$

The tangential force (F_T) and Normal Force (F_N) are also calculated as,

$$F_T = \frac{1}{2}\rho V_r^2 (hc)[C_L \sin(\alpha+\gamma) - C_D \cos(\alpha+\gamma)]$$

$$F_N = \frac{1}{2}\rho V_r^2 (hc)[C_L \cos(\alpha+\gamma) + C_D \sin(\alpha+\gamma)]$$

For turbine with B blades Torque becomes,

$$T = \frac{\rho hcBR}{4\pi}\int_0^{2\pi} V_r^2 C_t \, d\theta$$

Power generated by turbine,

$$P_t = T.\omega = \frac{\rho hcBR\omega}{4\pi}\int_0^{2\pi} V_r^2 C_t \, d\theta$$

Max power generated by turbine,

$$P_w = P_{max} = \frac{1}{2}\rho A V_\infty^3$$

Power Coefficient C_p,

$$C_p = \frac{P_t}{P_w} = \frac{P_t}{\frac{1}{2}\rho A V_\infty^3}$$

5. DESIGN OF TURBINE

The design of turbine is shown in below fig.

Figure 3: *Layout of Turbine*

6. Determination of Best Position 0f Blade at Various Azimuth Angles for Different Tip Speed Ratio

Best position of each blade in the rotation of turbine is been calculated at various tip speed ratio of the turbine by using the aerodynamic equations. Best position of the blade is fixed at pitch angle to produce the maximum tangential force to rotate the turbine and produce the maximum power output to improve the power coefficient of the turbine. The various operating and design parameters for best position of blades at various tip speed ratio is presented in the following tables and figures.

Table 1: *Best position of blade at various azimuth angles for different tip speed ratio, λ:*

Sr. No.	Azimuth angle, θ	Pitch angle, γ at λ=0.5	Pitch angle, γ at λ=1.0	Pitch angle, γ at λ=1.5	Pitch angle, γ at λ=2
1	0	0	0	0	0
2	30	15	10	9	7
3	60	25	20	12	10
4	90	35	30	20	15
5	120	45	40	30	25
6	150	40	35	25	20
7	180	0	0	0	0
8	210	-40	-35	-25	-20
9	240	-45	-40	-30	-25
10	270	-35	-30	-20	-15
11	300	-25	-20	-12	-10
12	330	-15	-10	-9	-7
13	360	0	0	0	0

Input Data:

1. ρ =Density of air =1.25 $^{Kg}/_{m^3}$
2. c= Blade chord length=0.095 m
3. h = Height of blade= 0.6 m
4. R_e Reynolds Number =$\frac{\rho uc}{\mu}$= 98884
5. V_∞ = Free Stream velocity = 5$^{m}/_{s}$

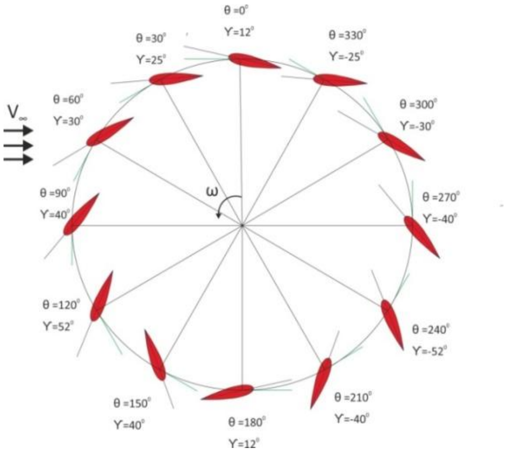

Figure 4: *Best position of blades at different azimuth for λ=0.5*

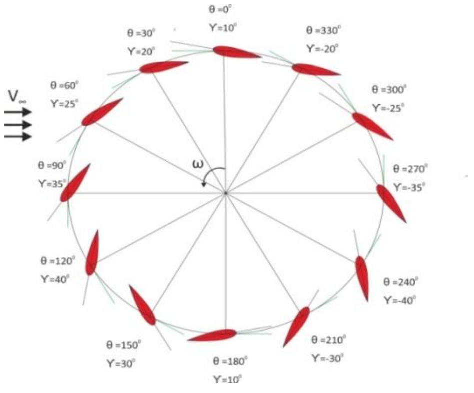

Figure 5: *Best position of blades at different azimuth for λ =1*

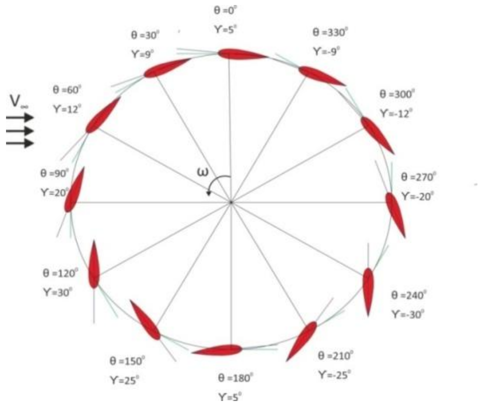

Figure 6: *Best position of blades at different azimuth for λ =1.5*

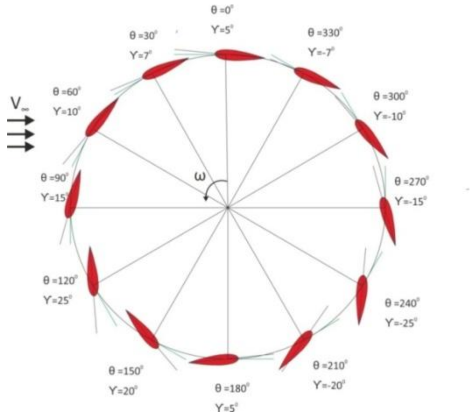

Figure 7: *Best position of blades at different azimuth for λ =2*

7. RESULTS AND DISCUSSION

Tangential force (Ft) at best position of blade at various azimuth angles for different tip speed ratio, λ:

Table 2: *Best position blade pitching at tip speed ratio, λ=2*

Sr. No.	Azimuth angle, θ	Relative velocity (Vr)	Lift coefficient (Cl)	Drag coefficient (Cd)	Tangential force (Ft)
1	0	15	0	0.0170	-0.1310
2	30	14.5	0.2748	0.0180	0.2630
3	60	13.2	0.5917	0.0271	0.9980
4	90	11.15	0.4706	0.0756	0.5901
5	120	8.66	0.3527	0.0242	0.3998
6	150	6.19	0.2004	0.0247	0.0730
7	180	5.00	0	0.0265	-0.0227
8	210	6.19	-0.2004	0.0247	0.0730
9	240	8.66	-0.3527	0.0242	0.3948
10	270	11.15	-0.4706	0.0756	0.5901
11	300	13.2	-0.5917	0.0271	0.9980
12	330	14.5	-0.2748	0.0180	0.2163
13	360	15	0	0.0170	-0.1310
				Ftavg.	0.3667
				Cp	0.532

(For the values of pitch angle and angle of attack refer above figures 5, 6, 7, and 8: take their values w.r.t azimuth angle **θ**)

Table 3: *Best position blade pitching at tip speed ratio, λ=1.5*

Sr. No.	Azimuth angle, θ	Relative velocity (Vr)	Lift coefficient (Cl)	Drag coefficient (Cd)	Tangential force (Ft)
1	0	12.5	0	0.0179	-0.0959
2	30	12.09	0.1799	0.01869	0.0801
3	60	10.89	0.4568	0.0766	0.4393
4	90	9.01	0.2693	0.1405	0.0803
5	120	6.67	0.2830	0.0634	0.2035
6	150	4.03	-0.00692	0.1405	-0.0640
7	180	2.5	0	0.0354	-0.0075
8	210	4.03	-0.00692	0.1405	-0.0593
9	240	6.61	-0.2830	0.0634	0.2035
10	270	9.01	-0.2693	0.1405	0.0803
11	300	10.89	-0.4568	0.0766	0.4393
12	330	12.09	-0.1799	0.01869	0.0801
13	360	12.5	0	0.0179	-00959
				Ftavg.	0.1149
				Cp	0.1251

Table 4: *Best position blade pitching at tip speed ratio, λ=1*

Sr. No.	Azimuth angle, θ	Relative velocity (Vr)	Lift coefficient (Cl)	Drag coefficient (Cd)	Tangential force (Ft)
1	0	10	0	0.0200	-0.0686
2	30	9.65	0.3719	0.0233	0.2356
3	60	8.66	0.3793	0.0504	0.3758
4	90	7.07	0.1229	0.1770	-0.0656
5	120	5	0.2288	0.2820	0.0490
6	150	2.5	1.0350	0.9200	0.1633
7	180	0	0	0	0
8	210	2.5	-1.0350	0.9200	0.1633
9	240	5	-0.2280	0.2820	0.0490
10	270	7.07	-0.1229	0.1770	-0.0656
11	300	8.66	-0.3793	0.0504	0.3758
12	330	9.65	-0.3719	0.0233	0.2356
13	360	10	0	0.0200	-0.0686
				Ftavg.	0.1206
				Cp	0.0875

Table 5: *Best position blade pitching at tip speed ratio, λ=0.5*

Sr. No.	Azimuth angle, θ	Relative velocity (Vr)	Lift coefficient (Cl)	Drag coefficient (Cd)	Tangential force (Ft)
1	0	7.5	0	0.0241	-0.0465
2	30	7.25	0.3254	0.0272	0.1546
3	60	6.61	0.1013	0.1770	-0.0917
4	90	5.59	0.6653	0.4875	0.3982
5	120	4.33	0.8550	0.5700	0.4363
6	150	3.09	1.0350	0.9200	0.2815
7	180	2.5	0	0.0354	-0.0075
8	210	3.09	-1.0350	0.9200	0.2815
9	240	4.33	-0.8550	0.5700	0.4363
10	270	5.59	-0.6653	0.4875	0.3982
11	300	6.61	-0.1013	0.1770	-0.0917
12	330	7.25	-0.3254	0.0272	0.1546
13	360	7.5	0	0.0241	-0.0465
				Ftavg.	0.1919
				Cp	0.069

Table 6: *Resultant value Of $C_{p\ w.r.t}$ TSR (λ)*

TSR(λ)	Cp
0.5	0.069
1	0.0875
1.5	0.1251
2	0.532

8. CONCLUSION

1. The NACA0018 aerofoil profile gives maximum power coefficient at tip speed ratio 2 compared to other profile.
2. The best position pitching blade variation in the amplitude allows for the maximum power extraction for wide range of tip speed ratios.
3. For this turbine analysis, maximum power coefficient greater than 0.532 can be achieved at 2.0 tip speed ratio with pitching curve.
4. Best position of blade with higher pitch amplitudes are preferred at lower tip speed ratios, while best position of blade with lower pitch amplitude produces better performance at higher tip speed ratios.
5. Four blades give more stability by reducing fluctuation of net forces acting on blades.

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