Cascade Theory for Design & Development of Darrieus Wind Turbine

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Abstract— Since ancient past humans have attempted to harness the wind energy through diversified means including horizontal wind turbines and vertical axis wind turbines (VAWTs). In this modern time, there is resurgence of interests in VAWTs as wide range of research is being conducted using several aerodynamic computational models. These models are crucial for deducing optimum design parameters and also for predicting the performance before manufacturing the blades of turbines. It has been found that at present some of the most widely used models are Double multiple stream tube model, Vortex model, Cascade model, etc. In this project, Cascade model is implemented for design and optimization of parameters of Darrieus wind turbine. Then, a three bladed wind turbine is proposed as candidate for further prototype testing after evaluating the effect of several parameters like turbine power, torque and efficiency.

Keywords: VAWT, Darrieus wind turbine, Cascade model, Efficiency

I. Introduction

Generally, there are 2 categories of wind turbine which produces electricity from wind; they are horizontal-axis and vertical-axis wind turbines (VAWTs). Straight-bladed VAWTs have simplified geometry, without yaw mechanism as well as no tapered or twisted blades. By the very nature of design, the blades of such turbines rotate essentially perpendicular to the direction of oncoming wind. It can handle the wind from any direction regardless of its orientation and less expensive as compared to horizontal wind turbines. It can operate during unstable wind speed thereby making it suitable in urban as well as rural areas. Even during high wind turbulence VAWTs can produce energy because of its axial symmetrical design. Hence, these features of VAWTs have attracted academicians to investigate every aspect of turbine by applying different computational and numerical models.

II. Working of DARRIEUS VAWTS

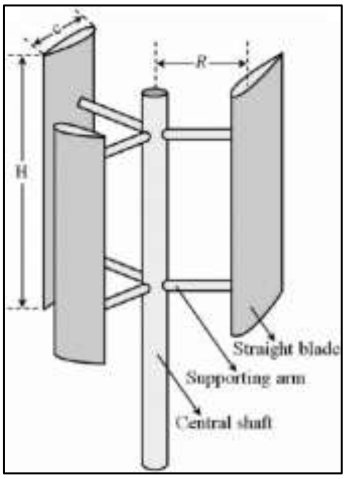

Fig. 1.1: Straight blade Wind Turbine

Darrieus-type VAWTS are basically lift force driven turbines. It comprises of two or more airfoil-shaped blades which are attached to a rotating vertical shaft. The wind blowing over the airfoil contours of the blades creates aerodynamic lift and actually pulls the blades along thereby causing turbine to rotate vertically. The H-Rotor are usually self-regulating in all wind speeds, reaching its optimal rotational speed shortly after its cut-in wind speed.

III. Design Procedure

For the innovation in the VAWT design, the key aspect that plays a crucial role is 'blade geometry'. To optimize the turbine performance at variable wind speed, the airfoil must be properly designed and configured. The correlation between the lift and drag coefficients as well as aspect ratio are very important for the selection of airfoil for VAWTs. The optimum operating conditions of this turbine depends on rotor solidity and tip speed ratio (TSR). Often, these parameters are chosen empirically based on user experience instead of scientific considerations. This project aims to find the optimum value of coefficient of power as well as to optimize various parameters of Darrieus VAWTs using Cascade theory.

Following are the parameters which needs to be considered while designing VAWTs:

- Swept Area
- Tip Speed Ratio
- Blade Chord
- Number of blades
- Rotor Solidity (σ)
- Initial angle of attack (α)

With all possible considerations, keeping in mind that a prototype must be built in order to validate the algorithm results & make further refinements, the candidate for a prototype is presented in the table 1.

Cut-in wind speed	4 m/s
Rated wind speed	10 m/s
Cut-out wind speed	20 m/s
Rotor radius (R)	0.3m
Blade profile	NACA0012
Blade chord length (C)	0.2m
Blade height (h)	0.6m
Number of blades (N)	3
Initial angle of attack	0°
Turbine speed (n)	60RPM

Table I: Prototype data

Though the straight-bladed Darrieus-type VAWT is the simplest type of wind turbine, its aerodynamic analysis is quite complex. Before comparative analysis of the main aerodynamic models, the general mathematical expressions, which are common to most of the aerodynamic models, are described in this section.

The flow velocities in the upstream and downstream sides of the Darrieus-type VAWTs are not constant as seen in fig. 1.2. From this figure one can observe that the flow is considered to occur in the axial direction.

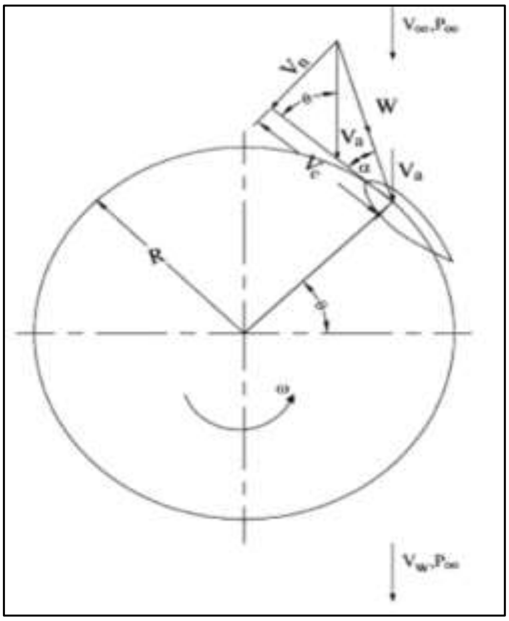

Fig. 1.2: Flow velocities of straight-bladed Darrieus VAWT

The chordal velocity component (*Vc)* and the normal velocity component (*Vn)* are, respectively, obtained from the following expressions:

$$Vc = R\omega + Va.\cos\theta, \quad (1.1)$$

$$Vn = Va \sin\theta, \quad (1.2)$$

where *Va* = Induced velocity

ω = Angular velocity of turbine

θ = Azimuth angle

Referring to fig 1.1, the angle of attack (α) can be expressed as

$$\alpha = \tan^{-1}(Vn/Vc) \quad (1.3)$$

The relative flow velocity (W) can be obtained as (fig 1.1),

$$W = \sqrt{V_C^2 + V_n^2} \quad (1.4)$$

The directions of the lift and drag forces and their normal and tangential components are shown in fig. 1.3. The tangential force coefficient (*Ct*) is basically the difference between the tangential components of lift and drag forces. Similarly, the normal force coefficient (*Cn*) is the difference between the normal components of lift and drag forces. The expressions of *Ct* and *Cn* can be written as

$$Ct = Cl \sin\alpha - Cd \cos\alpha, \quad (1.5)$$

$$Cn = Cl \cos\alpha + Cd \sin\alpha. \quad (1.6)$$

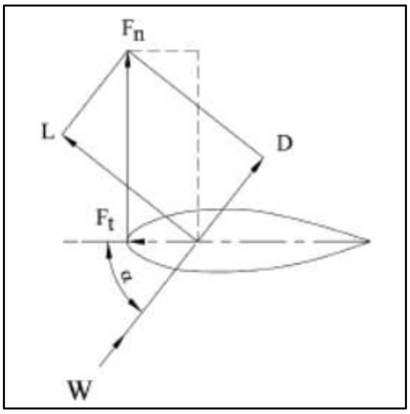

Fig. 1.3: Force diagram of an airfoil

The net tangential force (*Ft)* and normal force (*Fn)* can be defined as

$$Ft = 0.5*Ct\, \rho ChW^2, \quad (1.7)$$

$$Fn = 0.5*Cn\, \rho ChW^2. \quad (1.8)$$

Since, the above tangential and normal forces represented are for any azimuthal position, so, they are considered as a function of azimuth angle *θ*. Average tangential force (*Fta*) on one blade can be expressed as

$$Fta = (1/2\pi)\int_0^{2\pi} Ft\,(\theta)d\theta \quad (1.9)$$

The total torque (*T*) for the number of blades (*N*) is obtained as

$$T = \rho R^2 h\int_0^{2\pi}(W_2^2 \sin\alpha_2 \cos\alpha_2 - W_1^2 \sin\alpha_1 \cos\alpha_1)d\theta \quad (1.10)$$

where W_1 & W_2 = relative velocities in the cascade inlet and outlet,

ρ = density of air

The total power (P) can be obtained as

$$P = T.\omega \quad (1.11)$$

The Coefficient of power is equal to

$$Cp = P/(0.5\rho ChN\boldsymbol{V}_\infty{}^2) \quad (1.12)$$

IV. MATLAB ALGORITHM RESULTS

By using the Cascade theory and solving the algorithm in MATLAB following results are obtained;

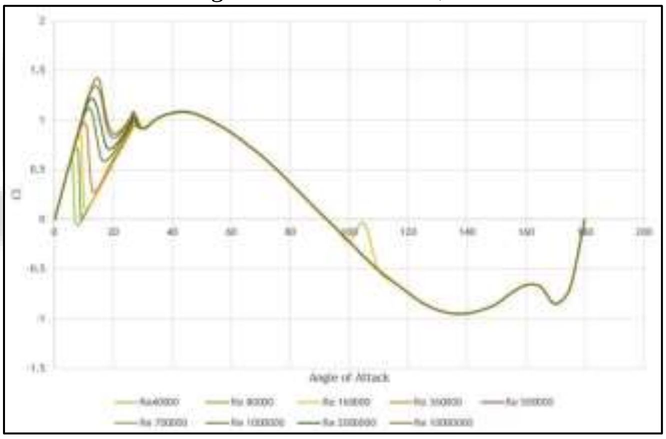

Fig. 1.4: Relation between Blade lift coefficient *(Cl),* Reynold Number (*Re*) & Angle of Attack

From fig. 1.4, it is evident that maximum lift coefficient of a blade is obtained when the angle of attack is nearly around 10 to 15 degree. As the lift coefficient will increase, then tangential force and torque will increase which in turn will increase the power coefficient. As the angle of attack will further increase from 20 degree then lift coefficient will start decreasing and thus power produced by turbine will decrease.

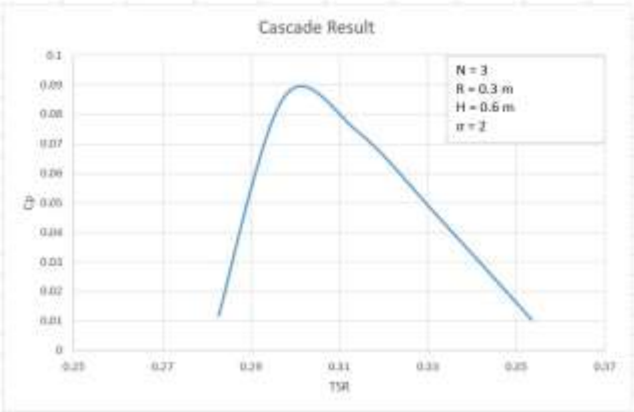

Fig. 1.5: Relation between Coefficient of power (*Cp*) and Tip speed Ratio (TSR)

The maximum power coefficient obtained is approximately 0.09 at an optimum tip speed ratio of approximately 0.30 for small scale vertical axis wind turbine model.

V. CONCLUSION

Measurements of tangential force and aerodynamic torque at the turbine shaft were used to determine the power produced by VAWT as a function of angle of rotation for a certain range of tip speed ratios.

At a low tip speed ratio, the power coefficient behaves as a hyperbolic curve and after reaching to the peak, it starts decreasing at high tip speed ratio and this pattern is particularly for small scale vertical axis wind turbine.

By comparing the results of MATLAB algorithm with experimental results, it is found that although the code does a good job of predicting the power over a specific range of tip speed ratios, it does not accurately predict the rotationally resolved torque at lower tip speed ratios. It may be due to the fact that the inclusions of dynamic stall effect in the calculation is not considered.

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