POWER PREDICTION OF DARRIEUS TYPE WIND TURBINE CONSIDERING REAL AIR VELOCITY ON THE WIND TURBINE BLADE

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Summary

The enhanced method for the performance prediction of Darrieus type vertical wind turbine is newly developed by applying relative air velocity instead of incoming air velocity in the calculation of lift and drag through the blade. The calculation is based on the performance prediction model by using multiple streamtubes. For the part of performance prediction calculation, the process is briefly divided into a few steps which are explained in detail in the paper, such as the separation of streamtubes, the performance prediction for each streamtube, the whole power prediction of the Darrieus wind turbine, and so on. Compared with test data and DART model predictions of two-meter-diameter wind turbine having a cross-sectional area of NACA0012, the new results show that the application of newly calculated local blade Reynolds number increases the accuracy of DWT performance prediction especially in the region of high tip speed ratio. The new calculation results show good match with test data, especially, in the region of high tip speed ratio.

It's important to predict the power in the off design point as well as in the design point when using Darrieus type wind turbine in the design of wind generating system. Therefore local blade Reynolds number application increasing the accuracy in the region of higher tip speed ratio can be applied widely in the wind power industry.

Nomenclature

A swept area [m^2]

A_S the area of the streamtube [m^2]

a interference factor

$B(y_B, z_B)$ the coordinates of point B

C_l lift coefficient

C_d drag coefficient

C_n normal force coefficients

C_t tangential force coefficient

C_p the rotor power coefficient

c chord length [m]

F_n normal force [N]

F_t tangential force [N]

F_x the average streamwise force [N]

H half height of the rotor [m]

h the height of streamtube [m]

L the total length of the blade [m]

l_1 the length of the straight part of the blade [m]

l_2 the length of the arc part of the blade [m]

N number of blades

N_S number of different vertical positions of streamtubes

N_t number of different azimuthal angles of streamtubes

P output power [W]

R the radius of the Darrieus turbine [m]

R_1 the radius of the arc [m]

Re blade Reynolds number

r local radius of darrieus turbine [m]

T the average rotor torque [$N \cdot m$]

T_S the torque produced by a rotor blade element [$N \cdot m$]

U velocity through the streamtube at the rotor [m/s]

U_R relative velocity [m/s]

U_∞ freestream velocity [m/s]

w rotational speed of Darrieus speed [deg/s]

ρ density of air [kg/m^3]

θ local azimuthal angle [deg]

$\Delta\theta$ the change of azimuthal angle [deg]

δ_1 the meridian angle [deg]

α the angle of attack [deg]

β the blade angle [deg]

λ tip speed ratio

μ_∞ viscosity

1. Introduction

Figure1. Darrieus Wind Turbine

Wind turbines can be classified into two categories according to the direction of rotational axes: vertical axis wind turbine (VAWT) and horizontal axis wind turbine (HAWT). The main advantage of VAWT is its single moving part (the rotor) where no yaw mechanisms are required, thus simplifying the design configurations significantly[1]. The Darrieus wind turbine is one kind of VAWT(Vertical Axis Wind Turbine). It's also a type of wind turbine used to generate electricity from the energy carried in the wind. The abbreviation for it is DWT. The turbine consists of a number of aerofoils vertically mounted on a rotating shaft or framework. The main composition of Darrieus wind turbine is shown in Figure 1.

VAWT uses straight or curved bladed rotors with rotating axes perpendicular to the wind stream. It is widely accepted that VAWT represents a suitable alternative for wind power extraction in many developing countries. This is mainly due to the advantages of this kind of machine over the horizontal axis type, such as their simple construction, the lack of necessity of overspeed control, the acceptance of wind from any direction without orientation, and the reduction of the mechanical design limitations due to the fact that the control systems and the electric generators are set up statically on the ground [2].

For the analysis of DWT, several power prediction models have been developed, such as single streamtube model, multiple streamtubes model, and double multiple sreamtube model, etc. The multiple streamtube model is simple and effective to power prediction, while it has been needed to be improved.

Actually, the multiple streamtube model was developed by Strickland[3] for performance prediction last century. The calculation about DWT performance prediction was made by the corresponding computer code DART. In his study, the multiple streamtube model shows good agreement with test data only when a blade Reynolds number is similar to test Reynolds number as in Figure 2 (nearby 4 of tip speed ratio). At other points, it showed mismatch with test data because he used only one constant representative blade Reynolds number which actually changes along the blade of DWT with rotational speed and incoming air velocity in the analysis. So, it is very significant to do some research on the DWT performance prediction when substituting the local blade Reynolds number for a constant representative Reynolds number. This paper simply introduces the corresponding calculation process for DWT performance prediction with application of newly calculated local blade Reynolds number.

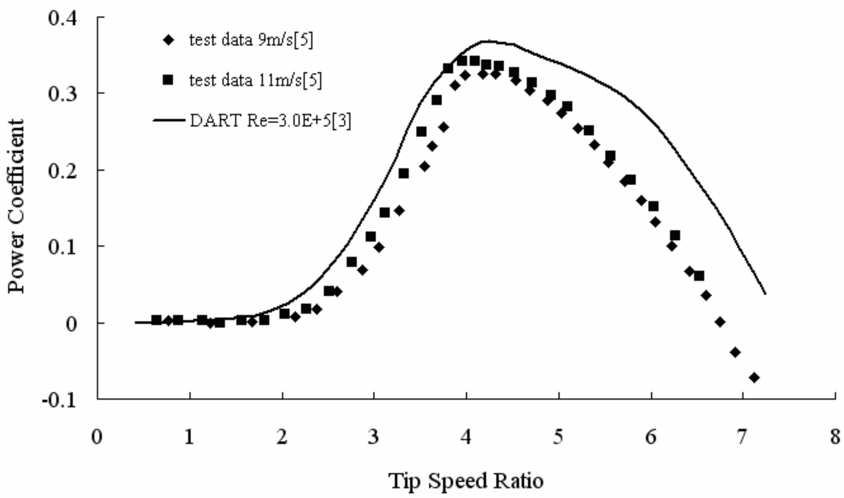

Figure 2. comparison between test and DART results

2. Equations and Calculations

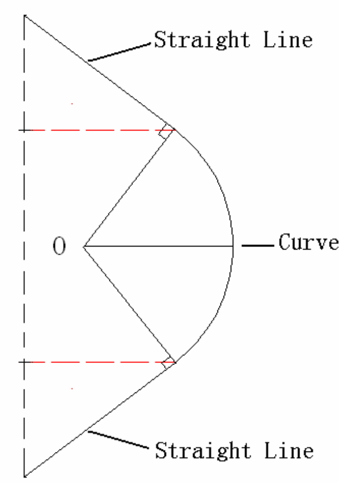

Figure3. blade of Sandia shape

2.1 Division of Swept Area

The type of the blade of Darrieus turbine introduced here is Sandia shape[4]. The blades of this kind of Darrieus turbine are designed as a straight-line at the top and bottom part with a circular-arc shape in the middle. It is represented in Figure 3.

According to the difference of the blade geometry, the height of the rotor, and the change of azimuthal angle, the swept area of the rotor was separated into many small areas (streamtubes).

In this paper, the model of performance prediction calculation is chosen from the reference [5]. So the size of DWT in detail should also be in accordance with the reference [5]. And it's shown in Table 1.

Table1 Size of DWT

Name	Value
solidity	0.27
blade number	3
cross-sectional shape	NACA0012
swept area of the rotor	2.595m^2
height of the rotor	2*m*
radius of the rotor	0.9798*m*
radius of the arc	0.6733*m*
horizontal coordinate of node	0.6721*m*
vertical coordinate of node	0.5654*m*

Here, node represents the connection between arc part and straight part of DWT blade in Figure 4 (a).

To divide the streamtubes, firstly, according to the difference of the blade geometry: one part is straight line, the other is curve, so in Figure 4(a) the swept area can be separated into two parts (A and B) to make the calculation simple.

Then according to the height of the Darrieus turbine, we separate the A and B parts into a few layers respectively. The height of each layer is denoted by h (shown in Figure 4(b)).

At last, each layer is separated into 18 small streamtubes according to the change of azimuthal angle. The change of azimuthal angle is denoted by $\Delta\theta$=10 degrees. The Azimuthal angle is denoted by θ. The radius of each layer is denoted by r (shown in Figure 4(c)).

So, the area of the streamtube is

$$A_S = hr\Delta\theta\sin\theta \quad (1)$$

The cross section shape of blade used here is NACA0012 airfoil as shown in Figure 4(d).

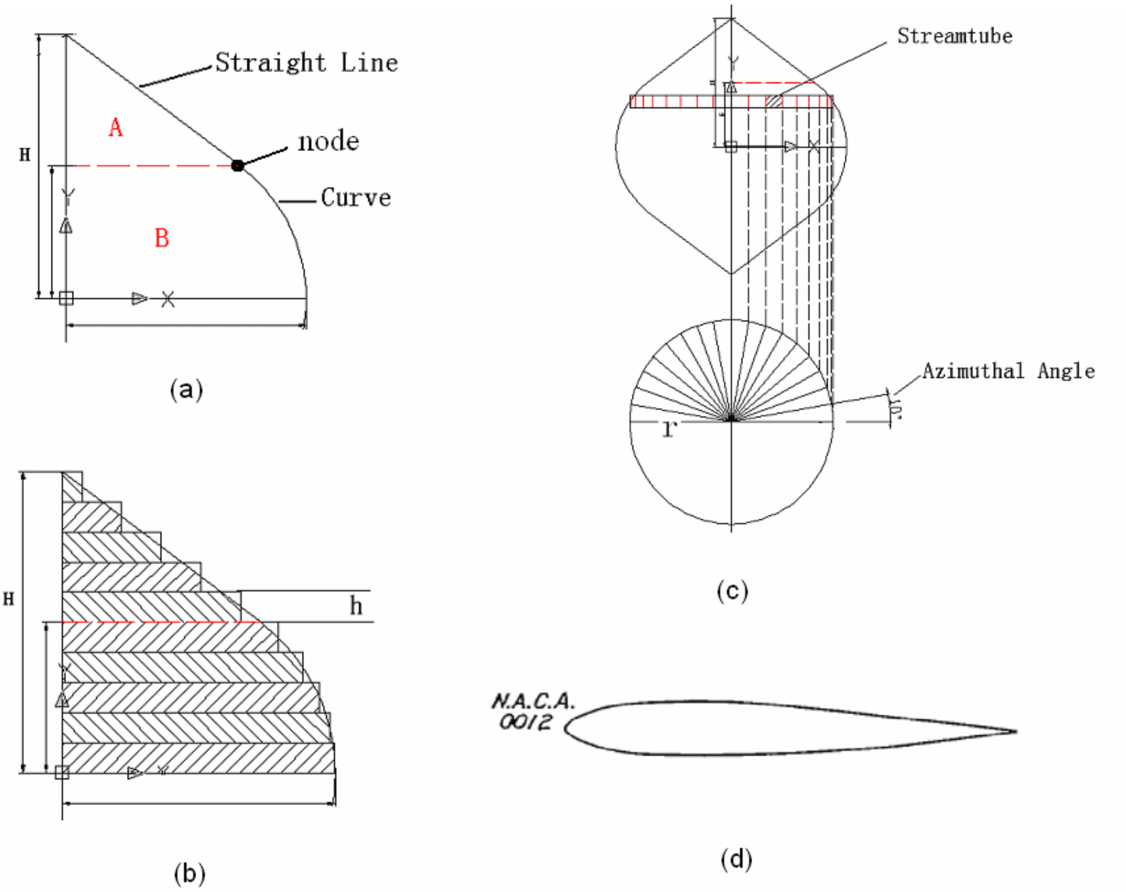

Figure4. division of swept area

2.2 Performance Prediction Calculation

This part mainly describes how to calculate and predict the performance of the Darrieus turbine. According to the previous research by the experts, it's apparent that the multiple streamtube performance prediction model for the Darrieus turbine is much more accurate than the single streamtube model. Here, the previous multiple streamtube performance prediction model was developed with taking the local Reynolds number into account. The following is the flow chart (see Figure 5) about the corresponding multiple streamtube performance model.

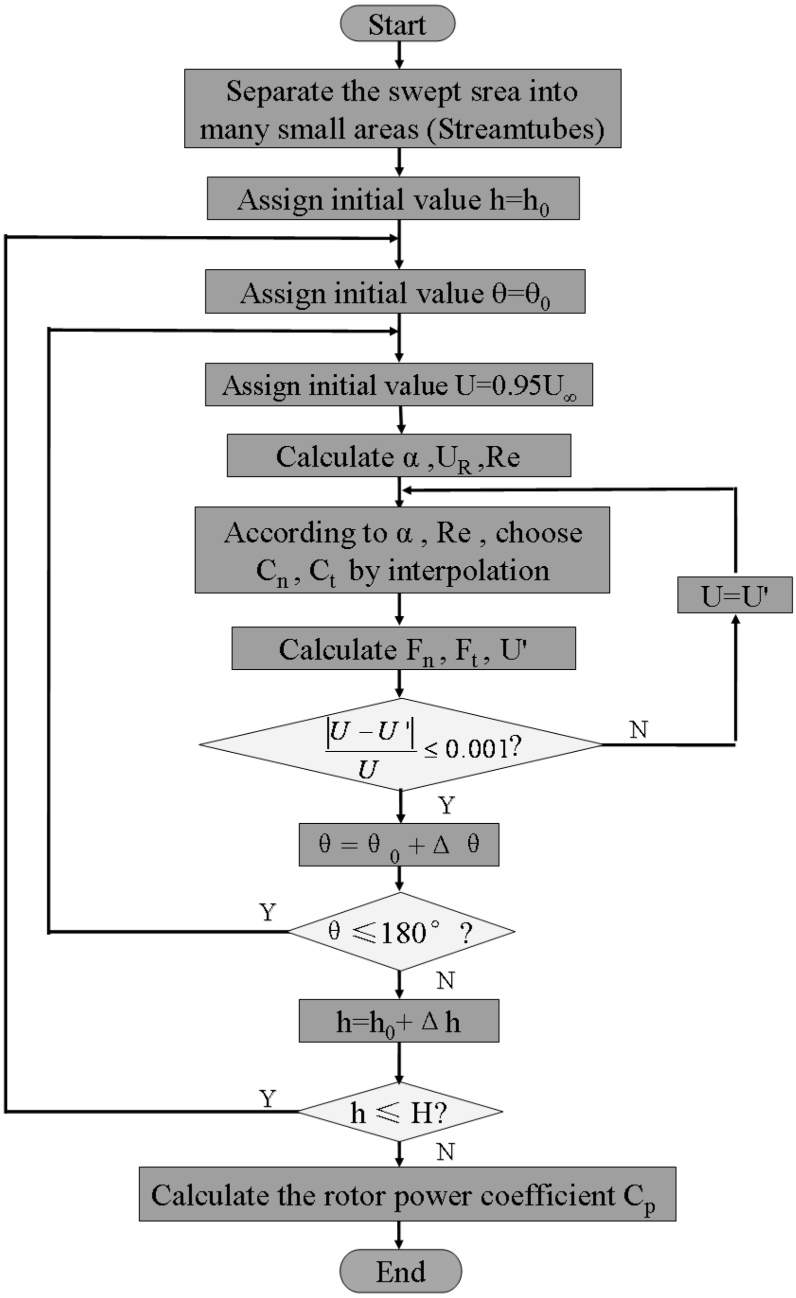

Figure 5. flow chart of the multiple streamtube model

Some of the explanations about the above flow chart are illustrated in detail below.

The normal and tangential forces on a blade element are estimated by lift and drag. The lift and drag can be expressed as a function of Reynolds number and attack angle. Here, the Normal and Tangential Coefficients are defined as a two-dimensional array respectively. The first dimension of the arrays is denoted by blade Reynolds number, and the second one is denoted by angle of attack. The blade Reynolds number is obtained with relative velocity on the blade rather than incoming air velocity of the test Reynolds number as in Equation (2).

$$\mathrm{Re} = \frac{\rho U_R c}{\mu_\infty} \quad (2)$$

The force can be converted into torque and power in a given rotational speed, or tip speed ratio. By the way, the relative velocity is related with air velocity after blade, force and torque of the blade, again. Therefore iteration loop of try and error is adopted to find solutions in the algorithm. If the calculation is finished in one streamtube, it is marched to the next steamtube until the last element is reached. After all of calculation is performed, the total of power and other data including power coefficient will be calculated under the given DWT conditions.

The flow chart for the power prediction can be described as following few steps:

1. Start from the first position, the corresponding azimuthal angle and height are $\theta=\theta_0$, $h= h_0$ respectively.
2. Assign a value of the induced velocity $U(\theta_0 , h_0)$ at this position, and the corresponding interference factor (Equation (13) in Table 2).
3. Calculate the values of angle of attack, α (Equation(3)), relative velocity, U_R (Equation(4)), and local blade Reynolds number, Re (Equation (2)), according to previous data.
4. According to the values of angle of attack and local blade Reynolds number, find out the values of normal coefficients, C_n (Equaition (5)), and tangential coefficient, C_t (Equaition (6)), by applying the mathematical interpolation method with lift and drag coefficients.
5. Calculate the values of normal force, F_n (Equation(7)), and tangential force, F_t (Equation(8)), and new generated induced velocity, U' (Equation(9)).
6. Compare the values of induced velocity U and U'. If the deviation between is smaller than iteration citeria, then go on to next step. If not, replace the initial value of induced velocity U as U', and go back to the step 2.
7. Continue to calculate the value of the torque produced by this element for the preparation of output power and power coefficient calculation.
8. Move to a new position for calculation: first on the same height but different azimuthal angles, $\theta=\theta_0 +\Delta\theta$, here $\Delta\theta=10°$, until $\theta=180°$. After that, move to a another height, $h=h_0+\Delta h$, until h equal to height.
9. Calculate the rotor output power and power coefficient since the calculations at all positions are finished.

Table2 equations

Name	Equation	
the angle of attack α	$Tan\alpha = \frac{U\sin\theta\sin\beta}{U\cos\theta + U_t}$	(3)
	$U_R\sin\alpha = U\sin\theta\sin\beta$	(4)
coefficients of C_n and C_t	$C_n = C_l\cos\alpha + C_d\sin\alpha$	(5)
	$C_t = C_l\sin\alpha - C_d\cos\alpha$	(6)
normal force and tangential force	$F_n = -0.5C_n\rho\frac{\Delta hc}{\sin\beta}U_R^{\ 2}$	(7)
	$F_t = 0.5C_t\rho\frac{\Delta hc}{\sin\beta}U_R^{\ 2}$	(8)
the streamwise force	$F_x = \frac{U'}{U_\infty}(1-\frac{U'}{U_\infty})\frac{2\pi\rho r\Delta h\cdot\sin\theta\cdot U_\infty^{\ 2}}{N} = -(F_n\sin\beta\cdot\sin\theta + F_t\cos\theta)$	(9)
the torque produced by a rotor blade element	$T_s = 0.5\rho rC_t\frac{c\Delta h}{\sin\beta}U_R^{\ 2}$	(10)
the average rotor torque	$T = \frac{N}{N_t}\sum_1^{N_t}\sum_1^{N_s}T_s$	(11)
the rotor power coefficient	$C_p = \frac{\sum_1^{N_t}\sum_1^{N_s}[\frac{Nc}{2R\sin\beta}\frac{U_t}{U_\infty}(\frac{U_R}{U_\infty})^2C_t]}{N_t\sum_1^{N_s}\frac{r}{R}}$	(12)
interference factor	$a = 1-\frac{U}{U_\infty}$	(13)
solidity	$\sigma = \frac{Nc}{R}$	(14)

3. Results

From the report[3], for the 9 meter per second wind speed, blade Reynolds numbers on the rotor tip range from about 0.10×10^6 to 0.36×10^6 for tip to wind speed ratios of 2 and 7 respectively. Data used in the DART model were selected from reference [6] for the NACA airfoil for a blade Reynolds number of 0.30×10^6.

On the right hand side of the curve (see Figure 6), the DART prediction is somewhat high which may be in part due to the constant blade Reynolds numbers toward the rotor hub which are less than that used in the analysis.

It's apparent that there exists big difference when the high tip speed ratio is over 5. The differences of some points are even over 50%. But in this paper, the local blade Reynolds number is applied to each small area according to the division of the streamtubes. Through calculating under given conditions (see Table 3), it's definite that the gap between calculation result and test data[4] is largely reduced at the high tip speed field from Figure 6. The differences at high tip speed ratio between them are even reduced to below 15%.

Table3 given conditions

Condition	Value
air density	1.204 kg/m^3
wind speed	9 m/s
tip speed ratio	2.5~ 7

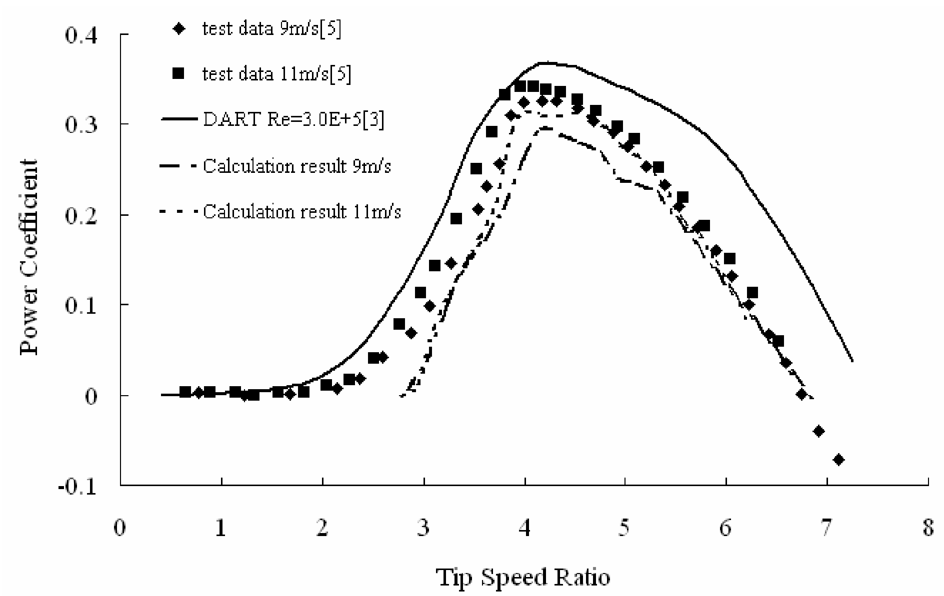

Figure 6. comparison between test and calculation results

4. Conclusions

It is shown that the multiple streamtubes method with local blade Reynolds number can predict performance of DWT well in the region of higher tip speed ratio. Calculation algorithm for the DWT power prediction is developed, and the local blade Reynolds number based on the blade velocity instead of Reynolds used on the incoming air velocity is applied for the calculation of lift and drag of Darrieus wind turbine. The calculation results showed good match with test data. And it is verified that the multiple streamtubes method with local blade Reynolds number can predict performance of DWT well in the region of higher tip speed ratio.

5. Acknowledgement

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