# Aerodynamic Performance of the 1.5MW Darrieus Vertical-Axis Wind Turbine


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## Abstract

The study of aerodynamic performance of vertical axis wind turbine is the basis of the vertical axis wind turbine design. The double disk multiple stream-tube model, one of the important methods for predicting the aerodynamic performance of the vertical axis wind turbine, has been used wildly in the vertical axis wind turbine design. In the present work, the principle parameters of the 1.5MW vertical axis wind turbine designed for the offshore wind farm was optimized, and the aerodynamic performance of it was calculated by double disk multiple stream-tube model. The results show that the output of the wind turbine is 2.0MW at the rated wind speed. In terms of the model test data, the mechanism system will lose 22.9% wind power, as a result the real output power of the wind turbine is 1.542MW and it will meet the design requirement still after considering the mechanism lose.



**Keywords:** VAWT; aerodynamic performance; DDMT; principle parameters


## Nomenclature

$U$ = velocity vector
$V_a$ = wind speed
$W$ = Relative velocity vector
$\omega$ = rotational velocity in radian
$N$ = rotational velocity in rpm
$a$ = velocity induction factors
$F$ = Force
$C_t$ = tangential force coefficient
$Cn$ = Normal force coefficient
$\theta$ = azimuth angle
$A$ = stream-tube cross-sectional areas
$\alpha$ = angle of attack
$\lambda$ = tip-speed ratio
$P$ = output power
$C_P$ = power coefficient
$H$ = height of the rotor
$D$ = diameter of the rotor
$C$ = chord
$Z$ = number of blades
$x, y$ = cartesian co-ordinate system

**Subscripts**

$\infty$ = free stream
$u$ = upstream
$d$ = downstream
$x$ = tangential component
$y$ = axial component
$\xi$ = streamwise component
$\eta$ = normal to the streamwise direction

**Superscripts**

$*$ =dimensionless

## Introduction

In 1974, Single Stream-Tube Model[1] based on the momentum theorem with modification by Templin , used for aerodynamic character of the vertical-axis wind power turbine, and this model is the basis of each Stream-Tube model of momentum theorem subsequently. Sullivan and Leonard calculated the load of Darriues vertical-axis wind power turbine by this method. Result proved this method is feasible to predict the whole aerodynamic of wind turbine in low tip-speed ratio and low solidity[2].This model is comparatively simple, but it cannot reflect the changes of flow parameter in upstream and downstream and different position which is perpendicular to flow direction in the area of where rotor acts on the disk. So it is a relatively rough method

Since the 20th century 70's many compound stream-tube models have been developed in order to improve Templin's single stream-tube model. One of famous models is the


[1] Deepwater Offshore Specialty Symposium, 2009

Multiple Stream-Tube Model[3] raised by Strickland in 1975, based upon the calculation method of induced velocity for single stream-tube model, the method divides the rotor disk into many unattached infinitesimal stream tubes normal to the freestream direction and each stream-tube is parallel to the freestream velocity direction and the induced velocities in each cross-section of the infinitesimal stream tube is assumed to be uniformly distributed. Then momentum theorem can be applied for the solution of the induced velocity and flow hydrodynamic characters seperately for each stream-tube..This method is more reasonable than the single stream-tube model as it includes the effect causing by the difference of flow parameters normal to the freestream velocity. Double-Multiple Stream-Tube Model[4][5][6] raised by Paraschivoiu in 1982 used the same way of the division of the stream tubes and the difference is to split each tube into upstream and downstream. It assumed the outlet velocity from the upstream as the inflow velocity of the downstream. Then you can set momentum equation separately and calculate the induced velocities of each stream independently. It is more accurate because it includs the difference of flow parameters normal to the freestream velocity and the fluence of the upstream on the downstream. However, it doesn't include the difference of induced velocities in different streams and assumes them as the same. Another Double-Multiple Stream-Tube Model[7] is raised by Sharpe in 1990. The difference is that this method assumed different induced velocities in one infinitesimal tube in upstream and downstream and different velocities in different infinitesimal stream tube. At the same time, it corrected the stream tube expansion effect and the blade unsteady motion effect. So the model is more accurate.

In the present work, 1.5MW vertical axis wind turbine was designed for the offshore wind form and the double disk multiple stream-tube model was used for predicting the aerodynamic performances of it.

## 1 Numerical Model

Calculation of the streamtubes through the rotor is based on the principle of the two disks in tandem at each level of the rotor, as shown in Fig.1. Each streamtube is assumed to be straight as it crosses the turbine and kept consist with the freestream. The upwind and downwind components which traverse each streamtube are considered separately and the variations in the freestream velocity are incorporated into the model. Let the freestream velocity is $U_\infty$ , the equilibrium-induced velocity is $U_a$ . The upstream velocity of the up-disk part can be written as:

$$U_u = (1-a_u)U_\infty \tag{1}$$

The equilibrium-induced velocity

$$U_a = (1-2a_u)U_\infty \tag{2}$$

The momentum change in unit time for the upstream part of the streamtube is then

$$F_u = 2A_u \rho U_\infty^2 a_u (1-a_u) \tag{3}$$

The speed $U_a$ now becomes the upstream velocity (instead of $U_\infty$ ) for the downstream disk and hence

$$U_d = (1-a_d)U_a \tag{4}$$

And

$$U_w = (1-2a_d)U_a \tag{5}$$

So the rate of change of momentum for the downstream part of the streamtube is

$$F_d = 2A_d \rho U_a^2 a_d (1-a_d) \tag{6}$$

$A_u$ and $A_d$ are the stream-tube cross-sectional areas of the upstream and downstream disk respectively; $a_u$ and $a_d$ velocity induction factors in the upstream and downstream disk of the streamtube.

The rate of change of momentum for the upstream part and the downstream part of the streamtube are then

$$\begin{aligned} F_u^* &= a_u(1-a_u) \\ &= \frac{\sigma}{4}\frac{W_u^2}{U_\infty^2}\left|\sec\theta\right|\left(-C_n \sin\beta\cos\theta - C_t \sin\theta\right) \end{aligned} \tag{7}$$

$$\begin{aligned} F_d^* &= a_d(1-a_d) \\ &= \frac{\sigma}{4}\frac{W_d^2}{U_a^2}\left|\sec\theta\right|\left(-C_n \sin\beta\cos\theta - C_t \sin\theta\right) \end{aligned} \tag{8}$$

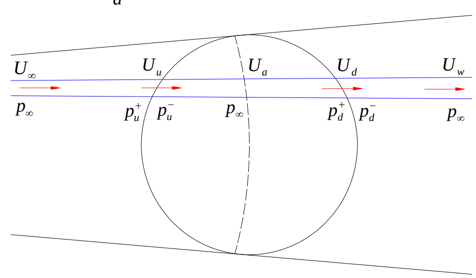

**Figure 1:** Sketch for Double Multiple Streamtube Method

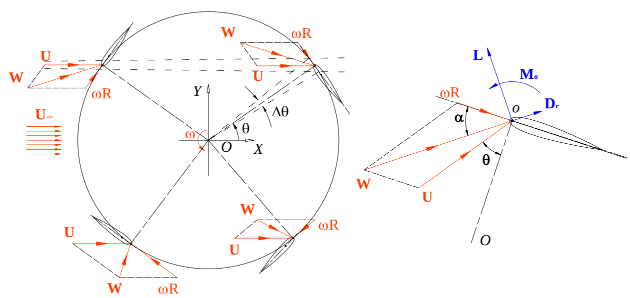

**Figure2:** Relative velocity and forces of blade

Relative velocities and forces on a blade element are showed in Fig.2, which are:

$$W_u^2 = [\omega R + U_\infty(1-a_u)\sin\theta]^2 + [U_\infty(1-a_u)\sin\beta\cos\theta]^2 \tag{9}$$

$$W_d^2 = [\omega R + U_a(1-a_d)\sin\theta]^2 + [U_a(1-a_d)\sin\beta\cos\theta]^2 \tag{10}$$

And the blade angle of attack can be written as bellow:

$$\tan\alpha_u = \frac{U_\infty(1-a_u)\sin\beta\cos\theta}{U_\infty(1-a_u)\sin\theta + R\omega} \tag{11}$$

$$\tan\alpha_d = \frac{U_a(1-a_d)\sin\beta\cos\theta}{U_a(1-a_d)\sin\theta + R\omega} \tag{12}$$

The solution of equation (11) and (12) are iterative process, and the particular process can be referred to references [1].

## 2 Results and discussion

The rotor blade is designed as a straight-line at the top and bottom part of the rotor, with two circular-arc-shape in the middle as shown in Fig.3. And the geometry parameters are shown in Table1.

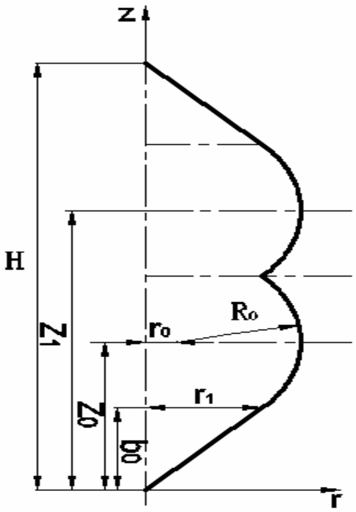


**Figure3:** Rotor geometry

| *D* [m] | *H* [m] | *C* [m] | *Z* [-] | Airfoil section [-] |
|---|---|---|---|---|
| 55 | 105 | 1.4 | 3 | NACA0018 |

**Table 1:** Rotor Geometry Parameters

Fig.4 illustrates the power coefficient at various tip-speed ratios at rated wind speed (Va=13m/s). The maximum power coefficient is about 0.44 at the tip-speed ratio of $\lambda \approx 4.9$ .

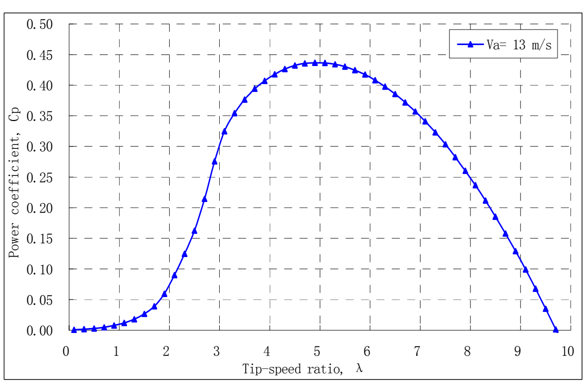


**Figure4:** Power coefficient as a function of the tip-speed ratio

The Fig.5 shows the variation of the P, Cp with Va at various rotational speeds. And the main (left) coordinate is the curve of P vs. Va, while the secondary (right) one is about Cp vs. Va. As shown in Fig.4, the output power is 2.0MW at the rated wind speed (Va=13.0m/s). According to the model test data, the mechanism system will lose 22.9% wind power, so the real output power is 1.542MW and it meets the design requirement still.

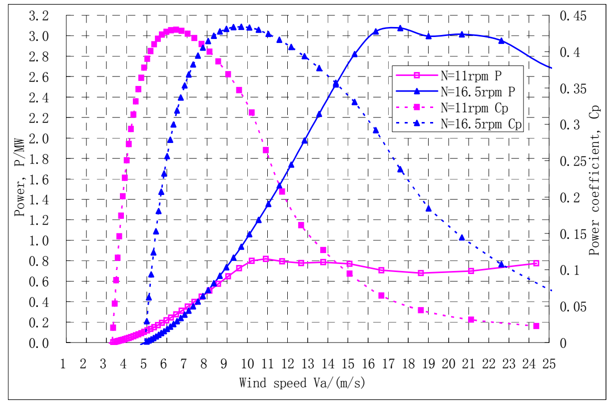


**Figure5:** Power and power coefficient as a function of the wind speed

## 3 Conclusion

In the present work, 1.5MW vertical axis wind turbine was designed for a offshore wind form and the double disk multiple stream-tube model was used for predicting the aerodynamic performances of it. The results show that the output of the wind turbine is 2.0MW at the rated wind speed. In terms of the model test data, the mechanism system will lose 22.9% wind power, as a result the real output power of the wind turbine is 1.542MW and it will meet the design requirement still after considering the mechanism lose.

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## References


[1] R.J. Templin. Aerodynamic performance theory for the NRC vertical axis wind turbine, NRC of Canada TR, LTR-LA-160, 1974

[2] W.N. Sullivan and T.M. Leonard. A Computer Subroutine for Estimating Aerodynamic Blade Loads on Darrieus Vertical Axis Wind Turbines. Sandia Laboratory Rept. SAND 80-2407.Albuquerque, New Mexico: Sandia National Laboratories. Nov. 1980

[3] J.H. Strickland. The Darrieus Turbine: A Performance Prediction model Using Multiple Stream-tubes. Sandia Laboratory Rept. SAND 75-0431.Albuquerque, New Mexico: Sandia National Laboratories. 1975

[4] Ion Paraschivoiu. Aerodynamic Loads and Performance of the Darrieus Rotor. J. Energy,

1981,6(6):406-412P
［5］ I. Paraschiviou. Double-multiple stream-tube model for studying vertical- axis wind turbines. Journal of Propulsion 1988:4P.
［6］ I. Paraschiviou and P. Desy. Aerodynamics of small-scale vertical axis wind turbines. Journal of Propulsion, 1986:2-3P.
［7］ D.J. Sharpe. Wind Turbine Aerodynamics. London Freris (Ed.)，Prentice Hall. Wind energy conversion system，1990，54-118P