Vertical axis wind turbine with low turbulence Fluid-driven simulation

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Abstract. New blade was designed by combining the advantage of sweepback and characteristic of flight trajectory. Mass and rotational inertia of turbine were calculated before using UDF and SDOF to build up the condition of fluid-driven simulation and observing the behavior of VAWT with airfoil NACA0012-800, LJY-800 and NACA23012-800. Results showed the potential of new designed airfoil and blade with better aerodynamic stability. Fluid-driven simulation gave out further suggestion that VAWT with high lift-drag ratio coefficient and power coefficient should be validated for its feasibility by fluid-driven simulation.

1. Introduction

Wind power generation is the mainstream of renewable energy and can be widely used with appropriate technical support. Most of the wind turbine airfoil evolved from the traditional aviation airfoils [1]. To a large extent, it is difficult to keep up with the rapid development of wind turbines. They are gradually replaced. Therefore, the research on new airfoil structures has become an important direction of wind power development technology.

Wind turbine is a machine driven by airflow. The earliest to conduct CFD simulation for a whole VAWT impellor was Robert Howell et al [2]. A new performance prediction model based on CFD was proposed by Marco Raciti Castelli et al [3]. The feasibility and accuracy of three different CFD approaches were presented by Chao Li et al [4], with a focus on the capability of the 2.5D LES approach in CFD simulation of high angle of attack (AOA) flow.

We choose the most representative low-turbulence airfoil blades from the characteristics of turbulence. Calculate wind turbine mass and moment of inertia, design geometric model and generator anti-load parameters, simulate and compare three vertical axis winds with NACA0012-800, NACA23012-800, LJY-800 (low turbulence VAWT airfoil) turbulence performance of the machine. Verify the aerodynamic stability of the airfoil, so that the vertical axis wind turbine does not need to be shut down for long-term operation without affecting the wind energy utilization factor.

2. Low Turbulence Airfoil

A statistical theory of turbulence can be formulated where the velocity field is considered to be a random variable V(x, t) of the position x and the time t [5]. Using the ergodic hypothesis, in the limit N→∞, one can obtain the microcanonical probability calculate
\[
P_t\left(\{X_a\}\right) \sim \exp\left[-\left(\frac{\beta}{2} \sum X_a^2\right)\right]
\]  

(1)

Where \(X_a\) is a set of independent variables and "a" labels the spatial component and the wave vector.

Turbulence energy: To study the turbulence fluctuations in detail, we would have to learn how they get their energy (usually from the mean flow somehow), and what they ultimately do with it. The equation for the average kinetic energy per unit mass of the fluctuating motion can be written as

\[
[\frac{\partial}{\partial t} + \text{\(U_j\)} \frac{\partial}{\partial x_j}] K = \frac{\partial}{\partial x_j} \left\{-\frac{1}{\rho} \langle pu, \delta p \rangle - \frac{1}{2} \langle q^2 u_j \rangle + 2\nu \langle s_q, u_j \rangle \right\} - \langle u_i, u_j \rangle \frac{\partial U_i}{\partial x_j} - 2\nu \langle s_{iq}, s_{ij} \rangle
\]

(2)

Where \(K\) is the mean kinetic energy per unit mass, which is defined as

\[
K = \frac{1}{2} \langle u_i u_i \rangle = \frac{1}{2} \langle q^2 \rangle = \frac{1}{2} \left[\langle u_i^2 \rangle + \langle u_i^2 \rangle + \langle u_i^2 \rangle\right]
\]

(3)

In the meantime, there is the turbulence kinetic energy (TKE), defined as

\[
k = \frac{1}{2} \left(\langle u^2 \rangle + \langle v^2 \rangle + \langle w^2 \rangle\right)
\]

(4)

The sum of the mean kinetic energy \(K\) and the turbulence kinetic energy \(k\) then could be defined as the instantaneous kinetic energy \(k(t)\)

\[
k(t) = K + k
\]

(5)

Each item in the equation (2) for the kinetic energy of the turbulent flow has a distinct role to play in the overall kinetic energy balance. And it will provide the framework for understanding the dynamics of turbulent motion.

Turbulence dissipation rate: In equation(2), the rate of dissipation of the turbulence energy as

\[
\varepsilon = 2\nu \langle s_{iq}, s_{ij} \rangle
\]

(6)

The \(\varepsilon \geq 0\) always, and it occurs on the right-hand side of the kinetic energy equation for the fluctuating motions preceded by a minus sign, it can act only to reduce the kinetic energy of the flow.

Turbulence intensity (TI): Instability of wind speed manifests an increased prevalence of turbulence, which has been shown to affect turbine performance both positively and negatively when calculated using the Turbulence Intensity metric.

\[
TI = \sigma_u / \langle u \rangle = \lim_{N \to \infty} \frac{1}{N} \sum_{i=1}^{N} (u^{(i)} - \langle u \rangle)^2
\]

(7)

Where \(u^{(i)}\) is the \(i^{th}\) random variable of random velocity variable \(\langle u \rangle\).

Turbulence viscosity: Turbulent viscosity refers to strong eddy diffusion and cascade hash caused by random impulse when the fluid flows in the turbulent state, making the fluid having great viscosity. A Newtonian type closure for the Reynolds stresses, often referred to as turbulent viscosity model, as

\[
- \rho \langle uu_j \rangle + \frac{1}{3} \langle uu, u_j \rangle = \mu_t \left[ S_{ij} - \frac{1}{3} S_{kk} \delta_{ij} \right]
\]

(8)

Where \(\mu_t\) is the turbulence viscosity, and \(S_{ij}\) is the mean strain rate.

Applying dimensional analysis, we can specify the eddy viscosity as follows:

\[
\mu_t = \rho C_{\mu} \frac{k^3}{\varepsilon}
\]

(9)

Where \(C_{\mu}\) is a constant. Turbulent viscosity depends entirely on motion and has nothing to do with fluid properties. It can be used to evaluate the flow characteristics in airfoil numerical simulation.

It is demonstrated [6] that camber line is a streamline of the flow based on the fundamental equation of thin airfoil theory, the airfoil can be simulated by a vortex sheet placed along the camber line. An object following the streamline has the least resistance and the most prominent stability. Then if every
point of the camber line follows the flight path of a blade, perturbation on around airflow must be the least, which means the turbulence is the lowest.

The Joukowski transformation can directly obtain the airfoil by solving the equation, the Trefftz graphical construction is suitable for constructing airfoils with definite leading edge. A low turbulence airfoil is generated by combining the Joukowski transformation of the curved plate with the Trefftz graphical construction of the radial airfoil as shown in Figure 1 [7].

Figure 1. Vertical axis wind turbine airfoil two-dimensional geometry with low turbulence

3. Calculation Model and Conditional Design of Vertical Axis Wind Turbine

3.1. Geometric Model Parameter Design of the Whole Machine

Increasing blade aspect ratio and the average height of impellor can harness more wind energy, meanwhile, requiring material has high hardness. The solidity selection is between 0.01 and 0.75 [8]. But manufacturers tend to select one much higher than this range so that their products exhibit low start-up wind speed and higher average of power output. We determine to compute $\sigma$ of 1.2.

Figure 2. Impellor as an entirety, including blades, supporting arms and main shaft

3.2. Design of mass and rotational inertia with resisting load from generator

Since the impellor will be driven by fluid, the mass and rotational inertia must be determined before computation [9]. Suppose blade is fabricated by Fiber Reinforced Plastics and the other parts by steel. Mass and rotational inertia can be written as

$$m_{bi} = N_{bi} \rho_{FRP} \delta c^2 \frac{d}{c} H$$

(10)

$$SI_{bi} = m_{bi} R^2$$

(11)

Where $\delta$ is a factor dividing sectional shell area by total sectional area considering the blade contains hollow zone, set as 0.3.

One blade is accompanied by two supporting arms whose sectional areas are $w \cdot h$. Total written as

$$m_{ar} = N_{ar} \rho_{st} \delta whR$$

(12)

$$SI_{ar} = N_{ar} \int_0^R \rho_{ar} \delta whr^2 dr$$

(13)

Electric appliance is always connected to electric generator so that mechanical energy can be transferred into electric energy. CFD simulation will not allow the existence of generator and appliance. But the torque is allowed. Resisting torque to pose on impellor shaft. The power of impellor is given as

$$P_{in} = \frac{1}{2} \rho_{ar} DHV^3 C_p$$

(14)
3.3. Fluid-driven simulation

3.3.1. Mesh
Flow domain was divided into two parts. Impellor was enclosed in a domain called inflow and the inflow zone was placed in an outflow domain which resembled to the geometry of a wind tunnel. Since the three airfoils were placed periodically, the inflow domain can be divided into three identical parts. Three steps were essential to build a periodic mesh: setting periodic properties, creating periodic point pairs, and copying block in axial symmetry. Copying block should be done right after the preliminary block was created and associated to the outer edges of the model. Then each block was further divided into pieces to cater with the detailed geometry of the model.

3.3.2. Solver settings
Since fluid-driven simulation is about time, the solver is transient one. Using a very efficient low Reynolds number turbulence model, it not only handles complex flows, but also has low memory and CPU requirements. The inlet wind speed of the flow field is imported through UDF module, and the flow field speed is set by setting and initializing the simulation parameters.

According to phenomenology of aerodynamic turbulence mentioned previously, quantified calculations of turbulence can be calculated. Using the built-in surface integrals calculator of ANSYS FLUENT, the five turbulence results of one simulation. Based on the understanding of turbulence, the output includes: TKE, Intensity, Dissipation, Production, Viscosity and wind turbine torque (Cm). Specific analysis of TKE. The vertical axis wind turbine rotates around the central spindle, the remaining five degrees of freedom need to be limited. The six degrees of freedom (SDOF) solver in fluent software is used to calculate the wind turbine torque.

Define the inflow zone and the marked zone as rigid body which could be recognized as an entirety. Build and load UDF before the motion of rigid body can be set up. For a transient solver, the wrong setting of time step size will lead to a series of problems. When it is over large, the computation will not converge. When it is over small, the computation cost is large, size is referenced to

\[ \Delta t = \frac{\Delta x}{v} \]  

(15)

Where \( \Delta x \) is local mesh size and \( v \) characterized fluid velocity. In this case, \( \Delta x \) is 0.05 and \( v \) is
80m/s in maximum. The step size is set as 0.001.

4. Numerical simulation results and analysis

The following three types of airfoil, NACA0012-800, NACA23012-800, and low turbulence airfoil, simulate the operating conditions of the wind turbine. A specific rotation speed will be given at one time and the torque will be calculated. By repeating the same procedure with different speed, the characteristic line can be drawn, known as the power coefficient curve.

Figure 4 and Figure 5 showed the behavior of VAWT with NACA0012-800mm, as a reference. Before 60s, turbine started without load. This phase can be divided into three parts: linear starting, rapid acceleration, and speed saturation. The slope at linear starting revealed the starting ability of the turbine. Rapid acceleration is a symbolic phase of VAWT because our group have already observed such phenomenon at experiment. At this phase, speed, cm and power will experience rapid increase. Speed saturation is the only phase when load can be put on or electricity be output to the power grid. Putting load before this phase will lead to total stop. After 60s, load was put on and speed decreased by 25%. It eventually came into balance.

![Figure 4. NACA0012-800mm without load](image1)

![Figure 5. NACA0012-800mm with load](image2)

![Figure 6. Low turbulence airfoil without load](image3)

![Figure 7. Low turbulence airfoil with load](image4)
Figure 8. NACA23012-800mm without load at start

Figure 6 and Figure 7 showed the behavior of VAWT with low turbulence airfoil. As can be seen, TKE and viscosity were lower than the ones of NACA0012-800mm, meaning disruption of airflow is lower than NACA0012-800mm. Although production was higher, dissipation will also be higher.

Figure 8 showed the behavior of VAWT with NACA23012-800mm. It didn’t experience the rapid acceleration and speed saturation phase. It was vulnerable because after load was put on, speed dropped to zero. This type of airfoil was designed for aviation with high lift-drag coefficient but didn’t work for VAWT. So it brings up the question about whether other airfoils designed for high lift-drag coefficient and power coefficient will work on VAWT. All of them should be calculated in fluid-driven simulation.

We built up the environment of fluid-driven simulation with UDF and SDOF. Turbine first started without load. When it came into full speed, load was put on. Airfoil that works properly will experience three phases: linear starting, rapid acceleration, and speed saturation. Low turbulence airfoil can work properly. But NACA23012 can’t work properly and when load was put on, it led to full stop. New designed airfoil low turbulence airfoil had lower turbulence value and can go to higher speed and gain higher C\text{power} than NACA0012-800.

5. Conclusion and prospect

The main results are as follows:(1) Static forces will exert influence of the part and assembly of turbine. Turbulence exhibit difference between airfoils. TKE and intensity have the same trend, so as production and dissipation rate. Viscosity is another parameter which can show difference;(2) Fluid-driven simulation will show transient characteristic of wind turbine. A typical VAWT will experience three phases: linear starting, rapid acceleration and speed saturation. New designed airfoil has lower turbulence value than referenced airfoil. Turbine with lower solidity will have slower linear starting but higher full speed and output C\text{power}. So designer can choose solidity according to the wind condition and electric facility;(3) Airfoil with high lift-drag coefficient should be paid more attention before being applied on VAWT. It may lead to failure operation.

The next work is as follows:(1) In order to simulate the real wind conditions, the wind speed must also be set to a specific mode to observe the fan response characteristics, and to study the operating characteristics of the VAWT wind turbine with low turbulence under different wind conditions; (2) More high lift-drag coefficient airfoils should be conducted on fluid-driven simulation to verify viability.

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