Numerical Simulation of the Aerodynamic Performance of a H-type Wind Turbine during Self-Starting

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Abstract: The aerodynamic performance and the bypass flow field of a vertical axis wind turbine under self-starting are investigated using CFD simulations in this paper. The influence of pitch angle variations on the performance of the wind turbine during self-starting is presented. A two-dimensional model of the wind turbine with three blades is employed. A commercial software FlowVision is employed in this paper, which uses dynamic Cartesian grid. The SST turbulence model is used for turbulence modeling, which assumes the flow full turbulent. Based on the comparison between the computed time-dependent variations of the rotation speed with the experimental data, the time-dependent variations of the torque are presented. The characteristics of self-starting of the wind turbine are analyzed with the pitch angle of 0^o、-2^o and 2^o. The influence of pitch angle variations on two-dimensional unsteady viscous flow field through velocity contours is discussed in detail.

Introduction

In recent years, the vertical axis wind turbine gains more and more attention since the vertical axis wind turbine is applicable to any directions of wind without yaw device. The transmission device can be placed on the ground, it is convenient for operation and maintain. The manufacturing of the blade is also simpler comparing to horizontal axis wind turbines. And the cost and noise are also lower. However, the vertical axis wind turbine also has some shortcomings. For instance, the height of the rotor is low resulting in a low operational wind speed. The cyclic load of transmission device is fluctuated due to periodic torque. Moreover, for the lift-type (including H-type and Φ-type) vertical axis wind turbine, the torque during self-starting is low, sometimes auxiliary equipment is required to enhance the self-starting performance, which restricts the development of such kind of wind turbine [1, 2, 3].

The wind speed, number of blades and the initial position of each blade are major factors affecting the self-starting performance of the lift-type vertical axis wind turbine. Dominy et al. [4] studied the influence of initial position of each blade on the self-starting performance of a H-type wind turbine with one blade, two blades and three blades by experimental methods. Hill et al. [5] studied the process of self-starting of a H-type wind turbine with three blades experimentally in a wind tunnel. Four stages from starting to reaching the stable rotation are described in that paper, which provides a good validation case for CFD simulations. Untariou et al. [6] studied the two-dimensional and three-dimensional unsteady flow field during self-starting of a H-type wind turbine using CFD simulations. The computed time-dependent variations of the rotation speed are compared with the experimental data. Two-dimensional numerical simulation results have small differences to the three-dimensional numerical simulation results. However, the general variation trends are the same.

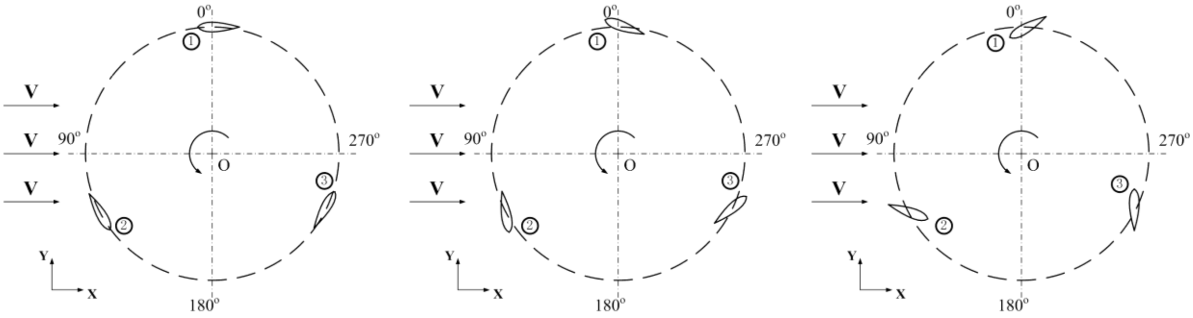
In order to improve the self-starting performance of the lift-type vertical axis wind turbine, Hwang et al. [7] combined the drag S-type wind turbine with lift-type wind turbine, which takes advantages of both wind turbines. At the starting stage, the wind turbine works as a drag-type wind turbine. At the operating stage, the wind turbine works as a lift-type wind turbine. However, the wind turbine generator is complex, and the cost is high. Chen et al. [8] studied the unsteady aerodynamic performance during self-starting of a two-dimensional H-type wind turbine with pitch angles of 0^o、10^o and -10^o using CFD simulations. The simulations results show that pitch angle variations have some influence on the rotation speed of the wind turbine during self-starting. In this case, the NACA4412 airfoil is used. However, a H-type wind turbine usually uses a symmetrical airfoil. Further research is needed to confirm if the conclusions drawn from that study are suitable for the symmetrical airfoil. In addition, according to literatures of [9, 10, 11], aerodynamic loads can be increased with different pitch angles.

The aerodynamic performance and the bypass flow field of a H-type vertical axis wind turbine with symmetrical airfoil during self-starting are investigated using CFD simulations in this paper. The influence of pitch angle variations on the performance of wind turbine during self-starting is also investigated. A two-dimensional model of the wind turbine with three blades is studied. A commercial software FlowVision is employed in this paper, which uses dynamic Cartesian grid. The SST turbulence model is used for turbulence modeling, which assumes the flow full turbulent. The variations of rotation speed and torque with time of self-starting are presented with pitch angle of 0^o、-2^o and 2^o. In addition, the influence of pitch angle variations on the unsteady flow details through velocity contours are also discussed in detail.

Research Model

The wind turbine model used in this paper is three-blade wind turbine with the radius of 0.375m. The symmetrical airfoil, NACA0018, is used. The length of the chord is 0.083m and the height of blade is 0.6m. The inertia moment is $0.018 kg \times m^2$. The wind speed is 6 m/s. Two pitch angles, -2^o and 2^o, are calculated, respectively.

The schematic orientations and the postures of each blade with different pitch angles (β=0、β<0 and β>0) are shown in Fig.1, *V* denotes the wind speed. For β=0, it is shown that the chord line is tangent to the locus circle of the aerodynamic center. For β<0, it is shown the leading edge of the blade on the cross section of the aerodynamic center rotated in clockwise for a certain angle. For β>0, it is shown the leading edge of blade on the cross section of the aerodynamic center rotated in anti-clockwise for a certain angle. The location of Blade ① is defined as the initial position of the self-starting.



（a） β=0 （b） β<0 （c） β>0

Fig.1 Schematic orientations and postures of each blade with different pitch angles

Numerical Methods

The commercial software named FlowVision HPC, which is based on the absolute coordinate system, is used in this paper. The velocity-pressure split-coupled algorithm is used to solve unsteady

Reynolds averaged Navier-Stokes equations, and the second-order implicit time discretization is used to solve unsteady calculations. FlowVision HPC has the ability to simulate six freedom degrees of a moving body. It can also set the inertia moment of the wind turbine directly to simulate the process of self-starting of wind turbine. Setting the physical time step in the FlowVision HPC software is different from that in some other CFD software. Since the physical time step changes with time, its value depends on the degree of velocity, pressure and other physical quantities. In addition, in the process of self-starting, the rotation speed increases, and the physical time step calculated by the software continues decreasing, so that the number of computation steps is the same in every circle. The total number of grids is about 360,000. Since the cartesian dynamic grid simulation method is used, the number of grids changes slightly for each time step. SST turbulence model is used, which assumes the flow full turbulent [12].

Computational Domain Settings. The two-dimensional computational domain with 12D×5D (D denotes the diameter of wind turbine) is shown in Fig.2. The distances from the inlet boundary, outlet boundary and both sides boundary to the rotation center of the wind turbine are 4D, 8D and 2.5D, respectively.

Refinement of Grids. The gird is refined according to the way used in the reference [13]. As shown in Fig.3, the refinement level of grids is up to level 4. The refinement level of grids in the far field is level 0, as showed in Fig.2. The refinement level in the circular area is level 2. The level of grids of partial encryption is level 3. The refinement level of dynamic grids around the blades is level 4.

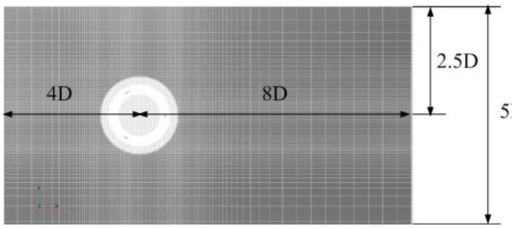


Fig.2 Computational domain and grid

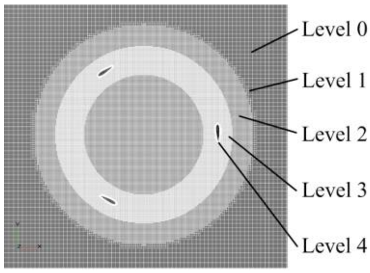


Fig.3 Refinement of the grid

Boundary and Initial Conditions. At the inlet of the computational domain, uniform atmospheric temperature and velocity are given. The turbulence intensity is set to 0.05. At the outlet, standard atmospheric pressure is given. The surfaces of the airfoils are non-slip solid walls. Other boundaries are defined as symmetric boundaries.

The initial velocity in the whole domain is equal to the velocity at the inlet.

Convergence Criteria. When the rotation speed reaches stability, the unsteady calculation can be considered as converged.

Numerical Results and Analysis

Rotation Speed and Physical Time Step. The variations of the rotation speed with time during self-starting are compared with the experimental data for $\beta=0^{o}$, which has been shown in Fig.4. There are four stages in the self-starting process in experiments. The first stage is a linear acceleration section, in which the wind turbine starts to rotate from halt, and absorbs wind energy to increase the rotation speed. The resistance also increases in this stage [14]. When the resistance increases to a certain extent, which is equal to the lift, the process of self-starting reaches the second stage, a balanced section. In this stage, the resistance and lift are equal, thus the rotation speed of wind turbine increases slightly. Then the process of self-starting comes to the third stage, a rapid acceleration section. In this stage, the wind turbine overcomes the resistance to operate in the disturbance of the inertia moment and flow field. The last stage is a stable section. The rotation speed is stable in this stage, and the wind turbine operates steadily at this rotation speed.

The connection rod between blades and the spindle has some mechanical frictions in experiments [5]. Since the effect of mechanical friction is not considered in this simulation, the resistance is smaller than that in experiments. There is no second balance stage, and the gradient of the rapid acceleration section is smaller [6]. In three dimensional flows, the span-wise movement of the flow may cause tip vortex, which is not considered in the two-dimensional CFD simulations, so the numerical results have some differences to the experimental results. But the overall trend of the numerical results is the same to the experimental results. It is seen from both the simulation results and experimental results, the H-type wind turbine can complete the process of self-starting from the halt to the stable rotation speed without any external stimulation, but this process is slow.

It is worth to recall that the numerical time step changes with the increase of the rotation speed. Fig.5 shows variations of the time-step length with time for β=0°. It is seen that the time step continues decreasing with the increase of the self-starting time and the rotation speed. When the rotation speed is getting stable, the time step reaches to constant.

The variations of the rotation speed with time for β=-2° and 2° are compared with the numerical results for β=0° as shown in Fig.6. The wind turbine takes about 192s to finish the self-starting process for β=0°. The wind turbine takes a shorter time, which is about 170s, to finish the same process for β=-2°. While, the wind turbine takes extremely long time, which is about 440s, to finish the process of self-starting for β=2°. At the beginning, the rotation speed is not stable, which increases then slightly decreases for some time and increases again. There even exists a short period of reverse rotation. After about 100s, the rotation speed of wind turbine increases gradually, as the wind turbine absorbs wind energy into mechanical energy for β=2°. When the wind turbine finishes the self-starting process, the rotation speed calculated for β=2° is smaller than that for β=0°. According to the above research results, adjusting the blade pitch angle in a clockwise direction can improve the self-starting of a H-type vertical axis wind turbine, thus the wind turbine reaches the stable rotation in a short time.

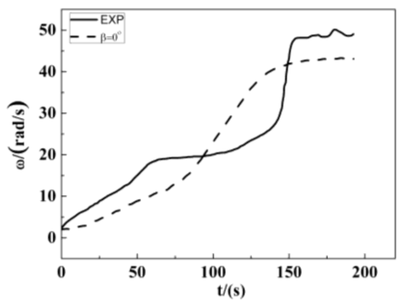


Fig.4 The variations of the rotation speed compared with experimental data for β=0°

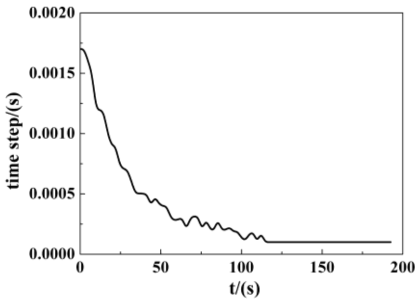


Fig.5 The variations of the time-step length for β=0°

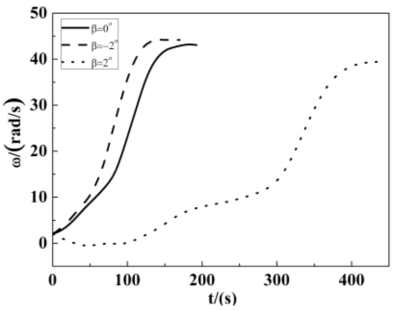
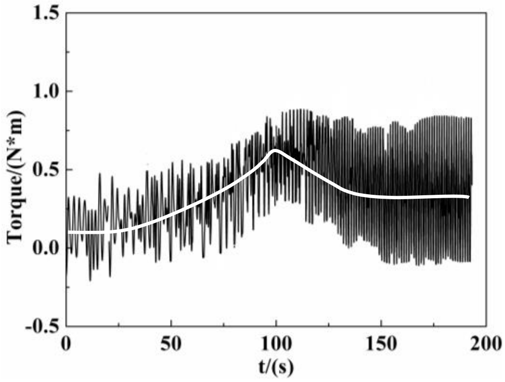


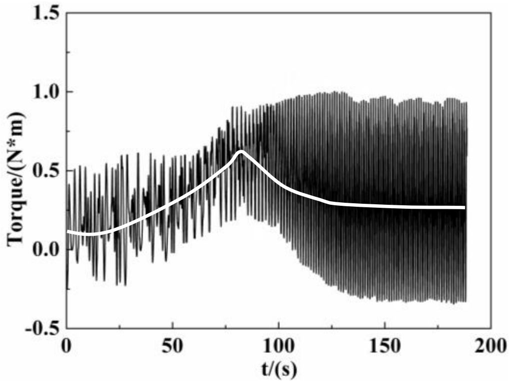
Fig.6 The variations of the rotation speed with time

Aerodynamic Load. The variations of the torque and its averaged values with time for β=0°、-2°、2° are shown in Fig.7. When the wind turbine starts to rotate from halt to the stable operation point, the torque increases firstly, then decreases to constant finally. At the beginning, the torque of wind turbine increases with the increase of the rotation speed and the wind energy is absorbs. The maximum torque is at the time of self-starting about 110s, 80s and 340s for β=0° (Fig.7 (a)), β=-2° (Fig.7 (b)) and β=2° (Fig.7 (c)), respectively. When the torque reaches the maximum value, the rotation speed increases slowly (Fig.6). While the resistance still increases fast, then the torque decreases again. Finally, when the rotation speed is stable and the resistance will not change any more. The torque will also be a constant value. Moreover, the torque is not equal if the pitch angle is different. For β=-2°, the torque is the maximum, while the torque is the minimum for β=2°. Furthermore, the torque with time is in the sharp shock, even the minimum torque is negative after the rotation speed is stable.

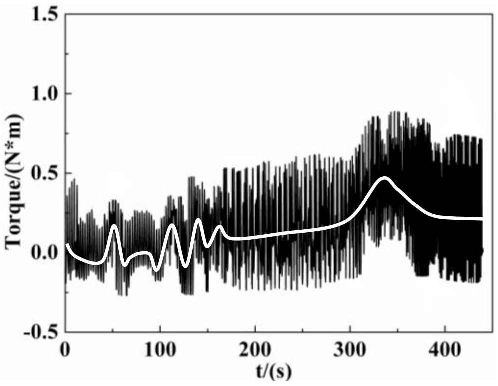
The variations of the torque with the phase angle (ωt) in one circle when the rotation speed is stable for β=0° has been shown in Fig.8. As can be seen, variations of the torque show obvious periodicity. The torque reaches the maximum value when phase angles are 80°、200°、320°. On the contrary, when phase angles are 30°、150°、270° the torque reaches the minimum value.



(a) β=0°



(b) β=-2°



(c) β=2°

Fig.7 The variations of the torque and its averaged values

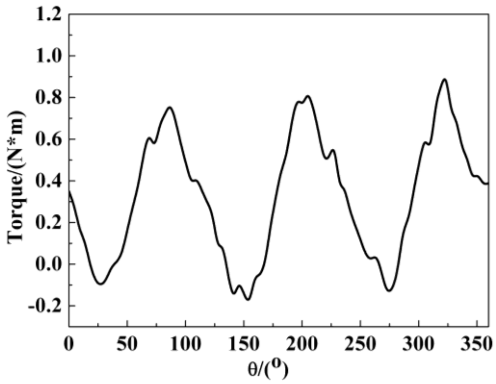


Fig.8 The variations of the torque with the phase angle in one circle (β=0°)

Velocity Contours

Fig.9 to Fig.12 show the velocity contours of the flow field for β=0°、-2°、2° at different time, respectively. When the self-starting time is at 20s (Fig.9), the velocity contour has a large rang of low-speed area in the wind wheel for β=0° and β=-2°. Wind turbines absorbs more wind energy than that for β=2°. With the operating time increases to 60s (Fig.10), the low-speed fluid in the wind wheel extends downstream near wake region for β=0° and β=-2°. With the operating time increases to 100s (Fig.11), the velocity contours with different pitch angles are different obviously. The low-speed region, which is near the wake region, is getting larger for β=0°. The low-speed region develops towards the far wake region for β=-2°. The low-speed region near the wake region is smaller for β=2°. With the operating time increases to 140s (Fig. 12), the differences among the velocity contours for different pitch angles are more remarkable. The rotation speeds for β=0° and β=-2° are gradually getting stable (Fig.6), the wind wheel and the wake region are all in the low-speed region, a lot of wind energy are absorbed and the flow field around the blade has more obvious regularity. The flow field for β=2° does not form with a certain regularity. This variation indicates that adjusting the pitch angle of the blade in the clockwise direction (i.e. β<0) can improve the ability of the wind turbine to capture more wind energy, so that the rotation speed increases rapidly and completes the self-starting process in a short time.

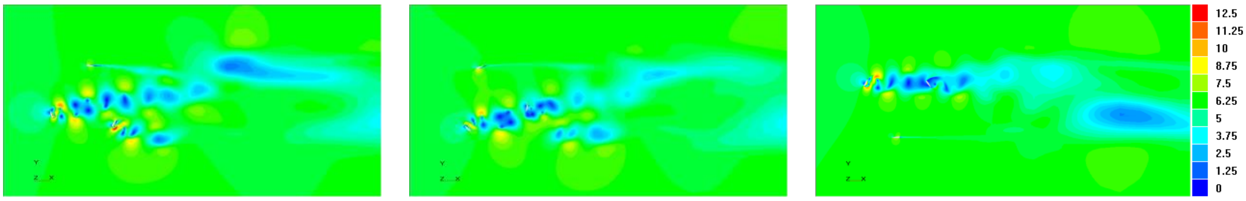
Conclusions

The aerodynamic performance during self-starting of a H-type vertical axial wind turbine with three blades was investigated using CFD simulations in this paper. The influence of pitch angles variations on the self-starting performance of the wind turbine was also investigated. The following conclusions can be drawn:

(1)The variations of the rotation speed are compared with the experimental data during self-starting. The overall trend of the numerical results is the same to the experimental results. Since the effect of mechanical friction is not considered in this simulation, two linear accelerations are calculated and there is no second balance stage, the gradient of the rapid acceleration section is smaller.

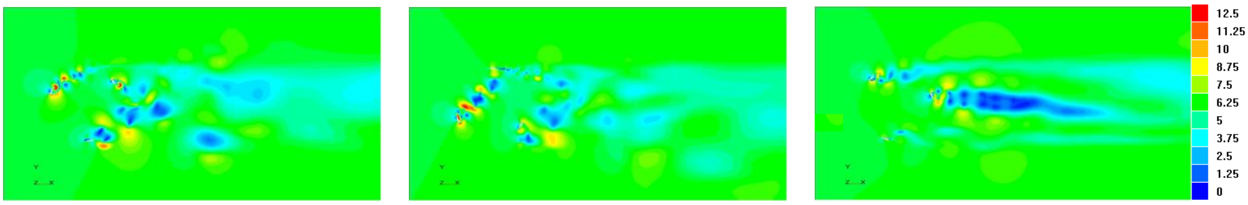
(2) When the wind turbine starts to rotate from halt to the stable operation point, the torque increases firstly, then decreases to constant finally with different pitch angles.

(3)Adjusting the pitch angle of the blade in the clockwise direction can improve the ability of the wind turbine to capture more wind energy, so that the rotation increases rapidly and completes the self-starting process in a short time.



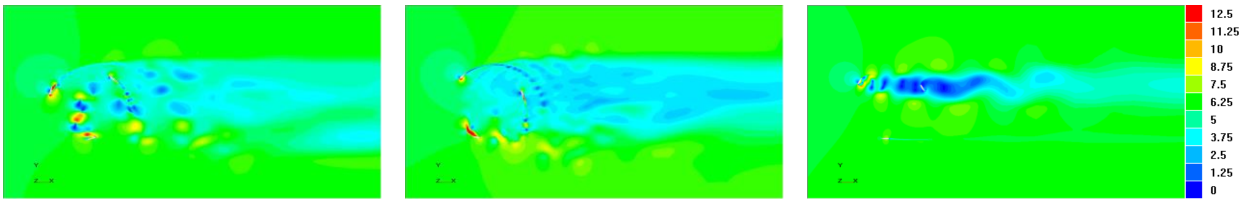
（a） β=0° （b） β=-2° （c） β=2°

Fig.9 Velocity contours for β=0°、-2°、2° (t=20s)



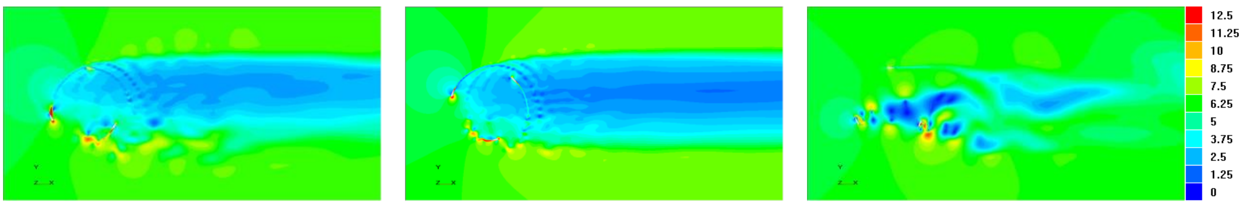
（a） β=0° （b） β=-2° （c） β=2°

Fig.10 Velocity contours for β=0°、-2°、2° (t=60s)



（a） β=0° （b） β=-2° （c） β=2°

Fig.11 Velocity contours for β=0°、-2°、2° (t=100s)



（a） β=0° （b） β=-2° （c） β=2°

Fig.12 Velocity contours for β=0°、-2°、2° (t=140s)

Acknowledgments

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