Application of computational fluid dynamics (CFD) simulation in a vertical axis wind turbine (VAWT) system

Jui-Hsiang Kao¹, and Po-Yuan Tseng¹
¹Department of Systems Engineering and Naval Architecture
National Taiwan Ocean University Keelung, Taiwan, R.O.C.

Abstract. The objective of this paper is to describe the application of CFD (Computational fluid dynamics) technology in the matching of turbine blades and generator to increase the efficiency of a vertical axis wind turbine (VAWT). A VAWT is treated as the study case here. The SST (Shear-Stress Transport) k-ω turbulence model with SIMPLE algorithm method in transient state is applied to solve the T (torque)–N (r/min) curves of the turbine blades at different wind speed. The T–N curves of the generator at different CV (constant voltage) model are measured. Thus, the T–N curves of the turbine blades at different wind speed can be matched by the T–N curves of the generator at different CV model to find the optimal CV model. As the optimal CV mode is selected, the characteristics of the operating points, such as tip speed ratio, revolutions per minute, blade torque, and efficiency, can be identified. The results show that, if the two systems are matched well, the final output power at a high wind speed of 9–10 m/s will be increased by 15%.

1. Introduction
VAWTs are usually good choices for urban areas because the radiated noise is lower as compared with horizontal wind turbines. However, the generated mechanical power of VAWTs is unstable due to the fluctuated inflow around the rotor blades and the variation of inflow attack angles at different azimuth. The published researches generally centered on the hydrodynamic simulation of turbine blades and the logic setting of the controller; matching the two systems, the turbine blades and the generator, is rarely discussed. Accordingly, a matching process in which CFD technology is applied will be described to improve the efficiency of VAWTs.

CFD technology has been widely applied in turbine design. Hirsch (1990) [1] applied CFD in blade simulation. Bardina et al. (1997) [2] commented that the SST k-ω turbulence model derived by the Menter (1994) [3] was suitable for predicting the flows with separation under adverse pressure gradients. Since the 2000s, much attention has been paid to achieving higher efficiency for wind turbines. Eftichios et al. (2006) [4] applied the Perturb and Observe Algorithm to track the maximum power of the turbine system by the controller. Adam et al. (2007) [5] set Fuzzy Logic in the controller to obtain maximum power. Qing'an et al. (2015) [6] tested the effect of blade number on aerodynamic forces of a straight-bladed VAWT, and it was clarified that the power coefficient decreases with the increase of numbers of blades. Kosasih, and Hudin (2016) [7] improved the performance of the turbine system by detecting turbulence intensity. Yin et al. (2016) [8] analyzed the system design, basic dynamic characteristics, thermal losses and management aspects; hydro-viscous transmission was applied to enhance the overall efficiency. Natapol and Thananchai (2016) [9] presented a wind booster to enhance performance of the VAWT at both low and high wind speeds. In Jian et al. (2016) [10], an airfoil family was specified by a coupled approach. This airfoil family achieved higher efficiency than traditional NACA 0015 by 15.5%. Besides, it was verified that the thickness-chord ratio had the biggest effect on the blade efficiency. Abdolrahim et al. (2017) [11] simulated a VAWT by 2D...
unsteady Reynolds-averaged Navier-Stokes. It was verified the 3D tip effects are negligible as the aspect ratio of the turbine is high. Ghulam, and Uzma (2017) [12] applied magnetic levitation method to the axial flux permanent magnet generator of a VAWT for increasing the efficiency. Under the inspiration of migrating geese flying in a V or I formation to save energy, Baoshou et al. (2017) [13] presented a novel wake energy reuse method to optimize the Savonius-type VAWT. Qing’an et al. (2017) [14] investigated the effect of rotor aspect ratio and solidity on a straight-bladed VAWT by 3D Panel Method. It was concluded the peak of power coefficient increases with the increase of the ratio of the blade span length and diameter at the fixed solidity.

In this paper, the efficiency of the VAWT is improved by matching the turbine blades and the generator. The performance of the blades is predicted by CFD technology first. Then the predicted results are matched with the selected generator by the T-N curves to determine the optimal operating point at different wind speed. Both matched and unmatched results will be compared to prove the improvement in the system efficiency.

2. Mathematical model

The aerodynamics of the present study case is investigated by using the commercial CFD software, ANSYS FLUENT. The SST (Shear-Stress Transport) k-ω turbulence model of the second-order upwind scheme with the SIMPLE algorithm method is applied to solve the Reynolds-averaged Navier Stokes (RANS) equations. The time averaging approach for a time dependent and irregular motion splits all the time varying terms into mean and fluctuating values. ANSYS Fluent solves the RANS equations by finite volume discretization. The SST k-ω model introduced by Menter (1992) [15] is applied in this paper. To measure adverse pressure gradients, aerofoils and transonic shock waves, the SST k-ω model has been strongly recommended by Menter (1992) [16]. The SIMPLE algorithm derived by Patankar & Spalding (1972) [17] was used to solve the incompressible flow. The main idea of this scheme is to update the pressure and velocities by corrected terms.

3. The governing equations

Yuwei et al. (2012) [18] mentioned that the flow in wind turbines is still essentially incompressible with Mach numbers based on a blade tip speed rarely exceeding 0.25. The Mach numbers based on the blade tip speed of in this present study did not exceed 0.25; thus, it was reasonable to consider the flow as incompressible in this paper. With the assumptions of incompressible and turbulent-steady flow, mass and momentum conservation equations can be written respectively as below:

\[
\frac{\partial \bar{u}_j}{\partial x_j} = 0
\]

\[
\rho \frac{\partial \bar{u}_j}{\partial t} + \rho \bar{u}_j \frac{\partial \bar{u}_j}{\partial x_j} = -\frac{\partial P}{\partial x_j} + \frac{\partial}{\partial x_j} \left( \mu \frac{\partial \bar{u}_j}{\partial x_j} \right) + \frac{\partial R_{ij}}{\partial x_j}
\]

\( \bar{u}_j \) is the average velocity along the \( x_j \) direction, \( \rho \) the fluid density, \( \bar{P} \) average pressure, \( R_{ij} \) the Reynonlds stress.

\[
R_{ij} = -\rho \bar{u}_i \bar{u}_j
\]

3.1 The applied turbulent model

The two equations of SST k-ω model are as followings.

Turbulence Kinetic:

\[
\frac{\partial (\rho k)}{\partial t} + \frac{d(\rho ku_i)}{dx_i} = \frac{\partial}{\partial x_j} \left( \Gamma_k \frac{dk}{dx_j} \right) + G_k - Y_k + S_k
\]

Specific Dissipation Rate:
\[
\frac{\partial (\rho \omega)}{\partial t} + \frac{d (\rho \omega u_i)}{dx_i} = \frac{\partial}{\partial x_j} \left( \Gamma_\omega \frac{d \omega}{dx_j} \right) + G_\omega - Y_\omega + D_\omega + S_\omega
\]  

(5)

Here \( \overline{G_k} \) is the turbulence kinetic energy caused by the mean velocity gradients, \( G_\omega \) the generation of \( \omega \), \( \Gamma_\omega \) and \( \Gamma_\omega \) the effective diffusivity of \( k \) and \( \omega \), \( Y_k \) and \( Y_\omega \) the dissipation of \( k \) and \( \omega \) due to turbulence, \( S_k \) and \( S_\omega \) source terms, and \( D_\omega \) the cross-diffusion term.

### 4. SIMPLE algorithm method

The SIMPLE algorithm is often used to solve the incompressible flow. The main ideal of this scheme is to update the pressure and velocities by corrected terms. In this scheme, the momentum equation is replaced by following discrete form.

\[
a_n u'_n = \sum_{nb} a_{nb} u'_{nb} + A_n \left( P'_p - P'_N \right)
\]

(6)

\( a_{nb} \) is the coefficient of the convective and diffusive terms summed by the nearby grid points.

\( A_n \left( P'_p - P'_N \right) \) presents the pressure force on the control volume. The corrections in velocity from the nearby grid points are assumed to be ignorable.

\[
\sum_{nb} a_{nb} u'_{nb} = 0
\]

(7)

The corrected terms in velocities can be reformed.

\[
u'_n = d_n \left[ P'_p - P'_N \right] = \left( \frac{A_n}{a_n} \right) \left[ P'_p - P'_N \right]
\]

(8)

\[
v'_e = d_e \left[ P'_p - P'_E \right] = \left( \frac{A_e}{a_e} \right) \left[ P'_p - P'_E \right]
\]

\[
w'_u = d_u \left[ P'_p - P'_U \right] = \left( \frac{A_u}{a_u} \right) \left[ P'_p - P'_U \right]
\]

The corrected term in pressure can be calculated by following.

\[
aP = \sum_{nb} a_{nb} P'_{nb}
\]

(9)

Thus, the updated pressure and velocities are as below.

\[
P = P^* + \Delta P^*
\]

\[
u = u^* + d_n \left( \Delta P^* \right)
\]

(10)

\[
v = v^* + d_e \left( \Delta P^* \right)
\]

\[
w = w^* + d_u \left( \Delta P^* \right)
\]

### 5. Meshing arrangement and boundary conditions

A straight-bladed VAWT with 3 blades shown in Figure 1 is discussed in this paper. The rotor diameter \( (D) \) is 2.6 M, and blade length \( (H) \) is 2.6 M. The matching problem is emphasized here. Thus, the 3D tip effects are negligible, and 2D CFD simulation is carried out in this paper. According to Steffen et al. (2001) [19], in order to correctly analyze the relative velocity of a rotating turbine, two computing domains are necessary; one encloses the calculated structures, and the other one includes the whole computing domain. Thus, the inner and outer domains are both developed in the present computation. Please refer to Figure 2 for the computing domains and the arrangement.
The applied meshes including 130000 mixed cells are shown in Figure 3. Figure 3 shows the meshes near the blade surface intensive. The mesh size increases from the blade toward the downstream and upstream directions.

**Figure 1.** The outline of the discussed wind turbine

**Figure 2.** The computing domains and applied boundary conditions

**Figure 3.** The arranged meshes for the present case
The boundary conditions for the present simulation are indicated in Figure 2. On the outer-domain inlet, a steady uniform velocity, \( V \), is imposed and the outer-domain outlet is set as a pressure outlet. The outer-domain walls are considered as stationary with no slip. Rotational moving and no slip walls are applied in the inner domain.

6. Results and discussion

The selected generator, to be matched with the turbine blades, is a direct-drive type with a 3-phase permanent NdFeB magnet. The measured T-N curves of this generator with every CV model are plotted in Figure 4 and the corresponding efficiencies are shown in Figure 5. According to Figure 5, for any CV mode the maximal efficiency is larger than 80%; the slope varies rapidly before reaching the maximal efficiency point. For attaining high efficiency, the location of the operating point should not be in the steep-slope region.

![Figure 4. The T-N curves of this generator measured by different CV mode](image)

![Figure 5. The efficiency of this generator at different CV model](image)

6.1 The matched case

In this paper, the considered wind speeds are 5m/s, 6m/s, 7m/s, 8m/s, 9m/s and 10m/s. The T (torque)-N (RPM) curves of the turbine blades, according to the CFD simulation, are plotted in Figures 6 & 7. It is also evident in Figures 6 & 7 that when the inflow attack angle exceeds the stall angle, the blade torque will be reduced. The \( C_p \)-TSR curve is shown in Figure 8. \( C_p \) is the blade efficiency. TSR, tip speed ratio, is the ratio of the tip speed to the wind speed.

\[
C_p = \frac{2 \cdot \pi \cdot N \cdot T}{\frac{1}{2} \cdot \rho \cdot V^3 \cdot (D \cdot H)} \quad (11)
\]

\[
TSR = \frac{2 \cdot \pi \cdot N \cdot R}{V} \quad (12)
\]
Figure 6. The T (torque)-N (RPM) curve of the blades at different wind speed

Figure 7. The T (torque)-N (RPM) curve of the blades at different wind speed

Figure 8. The Cp- TSR curve of the turbine blades

Figure 8 shows that when the TSR of the operating point for this wind turbine is located at 1.6~2.0, the blades will operate more efficiently.

For a wind turbine system, the torque generated by the blades is used to overcome the torque of the generator. In this way, the mechanical energy can be transferred to electronic energy by the generator. Thus the data shown in Figures 6 & 7 should be matched with those shown in Figure 4. Figure 9 is obtained by combining Figures 6 and 4, and Figure 10 is obtained by combining Figures 7 and 4. From Figures 9 & 10, the operating point (i.e. the matched point) at every wind speed can be determined. At the optimal operating point, both the efficiencies of turbine blades and the generator should be kept high. The efficiency of the turbine blades varies with the dimensionless factor, as shown in Equation (12), TSR. As shown in Figure 8, when the TSR of the operating point for this wind turbine is located at 1.6~2.0, the blades will become more efficient. Besides, it should be noted that the operating speed, RPM, cannot be in the steep-slope region of the selected CV mode, as shown in Figure 3. In this steep-slope region, the efficiency of the generator will obviously be reduced. Thus, the criteria for the choice are operating points are the TSR-C_p curve as shown in Figure 8, the efficiency curves of the
generator at every CV mode as shown in Figure 2, the determined operating speed, RPM, and the selected CV mode of the generator. It is expected that the TSR value calculated by the determined RPM will be located in the high-efficiency region of Figure 8, and not in the steep-slope region of the selected CV mode in Figure 3.

Table 1 shows the associated information of each matched operating point for every wind speed. Take 5 m/s wind speed for example. A CV 40V mode of generator is selected as the electronic control model. According to Figure 9, the matched point of 5m/s corresponds to 72 RPM and 21.7 Nm. From Figure 3 we can see that the generator efficiency, eff-g, of CV 40V at 72RPM is 79%. The electronic efficiency, eff-e, is usually 90–93%, and is assumed to be 90% here. The blade efficiency is about 37.9% as calculated by Equation (11). 

\[
P_{\text{blade}} = 2 \cdot \pi \cdot N \cdot T
\]

\[
P_{\text{out}} = P_{\text{blade}} \cdot \text{eff}_g \cdot \text{eff}_e
\]

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\]

\[
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\]

Figure 9. The matching results of turbine blades and generator

Figure 10. The matching results of turbine blades and generator

| V(m/s) | 5 | 6 | 7 | 8 | 9 | 10 |
|-------|---|---|---|---|---|----|
| CV    | 40| 40| 40| 40| 50| 50 |
| RPM   | 72| 80| 88.5| 98| 120| 132|
| Torque (Nm) | 21.7| 33.9| 48.3| 64.8| 76.3| 95.0|
| eff-g | 0.79| 0.74| 0.66| 0.58| 0.61| 0.55|
| eff-e | 0.90| 0.9| 0.9| 0.9| 0.9| 0.9|
| Cp    | 0.379| 0.376| 0.374| 0.374| 0.376| 0.376|
| P-blade | 163.6| 284.0| 447.6| 665.0| 958.8| 1313.2|
| P-out | 116.3| 189.1| 265.9| 347.1| 526.4| 650.0|
| TSR   | 1.96| 1.81| 1.72| 1.67| 1.81| 1.80|

6.2 The unmatched case
When the two systems: blade and generator, are unmatched, the generator will operate at the same CV mode for all wind speeds. In the case where these two systems are not matched, an overall CV mode should be selected first. Here the 40V mode is chosen in the unmatched case because the T-N curves of the turbine blades at every wind speed can form an intersection point with that of the 40V mode, as shown in Figure 11. At the intersection point, the torque needed by the generator is equal to that generated by the turbine blades. The final outputted powers are listed in Table 2. By comparing the P-out listed in Tables 1 and 2, it can be seen that the final outputted power of the unmatched case at high wind speeds, 9–10 m/s, will be decreased by 15%.

![Figure 11. The selection of the CV mode for the unmatched case](image)

| V(m/s) | 5    | 6    | 7    | 8    | 9    | 10   |
|--------|------|------|------|------|------|------|
| CV     | 40   | 40   | 40   | 40   | 40   | 40   |
| RPM    | 72   | 80   | 88.5 | 98   | 108  | 120  |
| Torque (Nm) | 21.7 | 33.9 | 48.3 | 64.8 | 83.2 | 102.7 |
| eff-g  | 0.79 | 0.74 | 0.66 | 0.58 | 0.53 | 0.49 |
| eff-e  | 0.90 | 0.90 | 0.90 | 0.90 | 0.90 | 0.90 |
| Cp     | 0.379| 0.376| 0.374| 0.374| 0.371| 0.371|
| P-blade| 62.0 | 106.8| 167.4| 248.7| 941.0| 1290.6|
| P-out  | 44.1 | 71.1 | 99.4 | 129.8| 448.8| 569.1|
| TSR    | 1.96 | 1.814222 | 1.720271 | 1.666817 | 1.63 | 1.63 |

7. Conclusions
The main purpose of this paper was to develop a matching process for vertical axis wind turbines to improve the efficiency. Several points can be concluded, as follows:
1. The basis for choosing the operating points are: the TSR-Cp curve of the turbine blades, the efficiency curves of the generator at every CV mode, the determined operating speed, RPM, and the selected CV mode of the generator. It is suggested that the determined RPM be located in the high-efficiency region of the TSR-Cp curve of the turbine blades, not in the steep-slope region of selected CV mode.
2. By comparing the final outputted power of the matched condition with these of the unmatched condition, it is known that the final outputted power of the matched condition at high wind speed, 9–10m/s, will be increased by 15%.
3. The proposed method of achieving an optimal balance of turbine and generator is still in the developmental stage. Over-speed protection and noise abatement during the matching process are suggested for future study. The expectation should be that the matched rotating speed is under control as the wind turbine experiences gusts, and does not cause unacceptable noise.

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