Numerical Study on the Performance Of 2-Bladed and 3-Bladed Counter Rotating Wind Turbines

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In this research, the effect of number of blades (2 and 3) of counter rotating wind turbine (CRWT) were simulated in transient condition to be further analyzed the performance and the fluid flow characteristic formed. The simulations used finite volume method approach with additional turbulence model SST k-omega under transient condition to be analyzed the development of the fluid flow started from idling rotors until rotated on their own steady angular velocities. Results of this research show that 2-bladed CRWT had higher steady angular velocity characteristic than 3-bladed CRWT, both of the front and rear rotors, but 3-bladed CRWT had faster performance in term of time to achieve their steady angular velocities than 2-bladed CRWT during the transient process. In term of mechanical power produced, the 3-bladed CRWT performed better than 2-bladed CRWT, around 10.5% in their own steady angular velocities. This results were supported by velocity deficit flow visualizations and velocity profile in selected regions.

**Keywords:** blade element momentum, cfd, crwt, number of blades, transient simulation

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1. Introduction

Nowadays, researchers found concept of counter rotating wind turbines (CRWTs) that could harvest additional power compared with co-rotating wind turbines and single rotating wind turbine (SRWT) [1]. The concept of counter-rotating for DRWTs (rotors rotate in opposite direction) would give benefit for rear rotor because of additional kinetic energy related to swirling velocity of the wake flow behind the front rotor. Newman [2] studied multiorotor turbines by expanding theory of Rankine-Froud momentum used to calculate Betz limit, and showed that DRWT with same diameter would have $C_p$ up to 64%, while adding number of rotors more than 2, would decrease the performance.

Many experimental as well as numerical studies related to performance improvement of CRWTs compare with SRWT have been studied. Some of field experiments, conducted by Appa [3] with 6 kW of 2-bladed CRWTs and Jung [4] with 30 kW of 3-bladed CRWTs showed that the CRWTs harvested significant more power than conventional SRWT with the equal oncoming wind velocity. More recently, Ozbay [1] conducted wind tunnel experiment on wake characteristic and aeromechanic of small scaled DRWTs, and founded that DRWTs with counter-rotating rotors harvested more energy than co-rotating DRWTs and SRWT.

With an advanced of computational fluid dynamics, some numerical studies also have been studied comparing the performance of CRWTs to SRWT. Irawan et al [5] founded that CRWTs designed with close axial distance ranging 0.2 until 0.7 of the rotor diameter, produce higher mechanical power rather than longer axial distances. Buana et al [6] also founded that CRWTs with equal diameter size produce maximum mechanical power.

Furthermore, from the number of blades point of view, there were limited number of published paper which investigate the comparison on performance of number of blade for CRWTs comparably and comprehensively. Based on blade element momentum (BEM) theory, the different of number of blades would produce different airfoil chord length per section of blade, therefore generate different rotational speed, both front rotor and rear rotor, then result different wake characteristic formed as well as different mechanical power produced.

By using transient CFD simulation of ANSYS Fluent like work that has been published before [7], this paper aims to investigate more the torque generated both of front rotor and rear rotor when the transient condition occured, and then would also be calculated the mechanical power produced as well as the flow visualization and the velocity profile produced at the tip and root region of the blade.

2. Methodology

2.1 Rotor Design

In order to design a rotor blade, simple formulation to calculate blade setting angle $\beta(r)$ and chord length as function of radius $c(r)$ is presented in Eq. (1) and Eq. (2) respectively. Several variables need to be determined first, they are number of blades $(B)$, blade radius $(R)$, tip speed ratio at the design point $(\lambda_d)$, design lift coefficient of the airfoil $(C_{l_d})$, angle of attack of the airfoil lift $(\alpha)$. The present study uses NREL airfoil shape of S835 (root), S833 (main), and S833 (tip).

$$\beta(r) = \frac{2}{3} \tan^{-1} \left( \frac{R}{r \lambda_d} \right) - \alpha$$

(1)
At the design step, the oncoming wind velocity was assumed 4.5 m/s, with design of tip speed ratio at 5, blade radius 1.5 m (later scaled down with ratio 1/15 or r = 10 cm, in order to be validated in small wind tunnel) and angle of attacks corresponded with maximum lift coefficients of the three types airfoil at 50000 Reynolds number. With the difference of number of blade, which are 2-bladed and 3-bladed, different geometrical blade section produced are shown in Table 1.

Table 1. Rotor design geometry [7]

| Optimized Geometry | S835 (root) | S833 (main) | S834 (tip) |
|--------------------|-------------|-------------|------------|
| r/R                | 0.2         | 0.4         | 0.85       | 1          |
| β(r)               | 19          | 8.21        | 0.38       | -0.96      |
| 2-bladed c(r)/R    | 0.347       | 0.253       | 0.139      | 0.119      |
| 3-bladed c(r)/R    | 0.232       | 0.168       | 0.092      | 0.079      |

For the CRWT model, design of front rotor and rear rotor are identical, but the rear rotor were made by mirroring the airfoil configuration of the front rotor. As a result, the front rotor rotate in counter-clockwise direction while the rear rotor rotate in clockwise direction. The properties of the front rotor and rear rotor of both 2-bladed and 3-bladed CRWT are presented in Table 2.

Table 2. Properties of CRWT [7]

| Specification       | Front Rotor | Rear Rotor |
|---------------------|-------------|------------|
| Diameter (mm)       | 200         | 200        |
| Position            | Upwind      | Downwind   |
| Blade material      | PLA         | PLA        |
| Rotation direction  | Counter-Clockwise | Clockwise |

Furthermore, as a comparison baseline, a SRWT model which have similar design with front rotor of the 3-bladed CRWT was also investigated.

2.2 Wind turbine computational fluid dynamic

CFD is a set of numerical solution for studying fluid dynamic problems based on the fundamental mass, momentum, and energy conservation principles. In the present study, CFD analysis of the CRWT only based on the conservation of mass and momentum principles with addition of shear-stress transport (SST) k-ω turbulent modelling type that can be written respectively in Eq. (3), Eq (4), and Eq (5).

\[
\frac{∂ρ}{∂t} + \nabla . (ρ \vec{v}) = Sm
\]  \hspace{1cm} (3)

\[
\frac{∂}{∂t} (ρ \vec{v}) + \nabla . (ρ \vec{v} \vec{v}) = -\nabla p + \nabla . (\vec{τ}) + ρ \vec{g} + \vec{F}
\]  \hspace{1cm} (4)

\[
\frac{∂}{∂t} (ρk) + \frac{∂}{∂x_i} (ρ k u_i) = \frac{∂}{∂x_j} \left( \Gamma_k \frac{∂k}{∂x_j} \right) + G_k - Y_k + S_k
\]  \hspace{1cm} (5)

where Sm is the mass source, p is static pressure, \( \vec{τ} \) is stress tensor, \( ρ \vec{g} \) is the gravity force, and \( \vec{F} \) is other external body force. In the k-ω turbulence models, k is the turbulent kinetic energy and \( \omega \) is the dissipation rate of the turbulent kinetic energy.

This study use pressure-based solver approach in Fluent which mean the pressure field is obtained by solving pressure correction equation, results from combining conservation of mass and momentum equation. Velocity vector are corrected by the pressure to satisfy the continuity, and solve the turbulent model using the current value. The solution process involves iterations, wherein the entire set of governing equations are solved repeatedly until reach convergence.

This numerical study was done using Ansys Fluent to simulate transient condition by activating dynamic mesh and one-degree of freedom rotation codes was performed for knowing the correlation of rotational speed both of front and rear rotor due to specified oncoming wind velocity (i.e \( v = 4.5 \text{ m/s} \)).
The boundary condition and volume mesh generated in this study are depicted in Fig.1. The comparison of the volume mesh generated from the SRWT (as a comparison baseline), 2-bladed CRWT, and 3-bladed CRWT are presented in Table 3.

Table 3. Volume mesh characteristic of the SRWT and CRWT

| Variables               | SRWT     | 2-bladed | 3-bladed |
|-------------------------|----------|----------|----------|
| Meshing type            | Tetrahedral | Tetrahedral | Tetrahedral |
| Element number          | 1,675,532 | 1,474,734 | 1,789,499 |
| First layer thickness   | 4 x 10^{-5} m y+=0.8 | 4 x 10^{-5} m y+=0.8 | 4 x 10^{-5} m y+=0.8 |
| Average skewness        | 0.237    | 0.247    | 0.255    |
| Average orthogonal quality | 0.846 | 0.838    | 0.831    |

This simulation was done using a second order implicit transient formulation with 0.01 time step size and total time step up to 4000 times. By activating SIX DOF solver and dynamic mesh, the change of rotor’s angle (\(\Delta\theta\)) every time step (\(\Delta t\)) would be recorded in motion history of the rotor then could be calculated the rotor rotational speed using formula in Eq. (6).

\[
N (RPM) = \frac{\Delta \theta}{\Delta t} \times \frac{60}{\pi}
\]  

(6)

Beside calculate angular velocity, the simulation also produced mechanical torque by inputing the inertia moment both of front and rear rotor (i.e resulted from SolidWork calculation using PLA material properties). Finally, the mechanical power (P) could be counted by multiplying torque (T) with angular velocity in rad/s unit as stated in Eq. (7).

\[
P = T \times \omega
\]  

(7)

3. Result

3.1 Rotor rotational speed

The main result of this study are characteristic of the rotor rotational speed, as given in Fig. 2. The SRWT, designed equally with the front rotor of 3-bladed CRWT, has similar rotational speed, as depicted by blue line (SRWT) which overlap the black line (front rotor of 3-bladed CRWT). They reach steady rotational speed after 30 seconds in approximately 2154 rpm. While the rear rotor of the 3-bladed CRWT achieve the steady rotational speed in 1900 rpm.

Furthermore, there were also founded a rotational speed drop of the rear rotor from the front rotor of 2-bladed CRWT. In this 2-bladed CRWTs, the front rotor achieve steady rotational speed in approximately 2436.9 rpm, while the rear rotor reaches 2188.32 rpm, which is higher than the back rotor of the 3-bladed CRWTs.

3.2 Torque and mechanical power

After obtaining the characteristic of rotational speed from the transient simulation both of SRWT and CRWTs, then transient torque as function of time also can be resulted, as shown in Fig 3, and finally mechanical power can be calculated by multiplying the rotational speed and the torque, as shown in Fig 4.

During the transient process, the torque and mechanical power fluctuate as time function. Both of torque and mechanical power will reach their steady value on a time when the flow driven rotor rotational speed (Fig.2) reach their steady. The front rotor has higher torque as well as mechanical power than the rear rotor, both of 2-bladed CRWT and 3-bladed CRWT. By comparing the total mechanical power resulted in Fig 4, it is known that 3-bladed CRWT can produce higher mechanical power than 2-bladed CRWT during the transient process until their own steady state condition. Based on total mechanical power produced at their own steady state condition, 3-bladed CRWT can produce around 10.5% higher than 2-bladed CRWT.
3.3 Wake flow characteristic

Mathew [8] said that when the fluid applies torque to the rotor, as a reaction, rotational wake is generated behind the rotor. This will cause energy loss and reduce the peak power coefficient. Based on [9], there were some factors which greatly affected the characteristics of the near wake flow, like the presence of the rotor (i.e., the number of blades, blade aerodynamics, and tip vortices), and the interactions between the turbine rotors, tower and nacelles. In this study, the oncoming airflow drive the rotor to rotate and convert a portion of the kinetic energy of them into torque. This phenomena cause deceleration of the airflow streams as they pass through the rotation disk-like of the rotor.

Fig. 5 gives velocity deficit or deceleration of the airflow streams in the wake behind the SRWT and CRWT models at their own steady rotational speed, stated by non-dimensional parameter \( \frac{(U - U_{in})}{U_{in}} \), where \( U \) is velocity at the analyzed region and \( U_{in} \) is oncoming velocity. Because a portion of the kinetic energy carried by the oncoming airflow was harvested by the model wind turbines, the oncoming airflow streams were found to decelerate greatly as they passed through the rotation disks of the turbine blades. As a result, significant velocity deficits were found to exist in the wakes behind the turbine models, stated by X/D region where X is distance in X coordinate and D is diameter of the rotor (i.e D = 10 cm).

By comparing the velocity deficit, both 2-bladed and 3-bladed CRWT faced more velocity deficit than the SRWT which can be attributed by the presence of the rear rotor. From the mechanical power output, both CRWTs could harvest more power than SRWT from the same oncoming wind velocity, thereby generating more larger velocity deficits in the wake flow. It also can be seen that, the velocity deficits of the 3-bladed CRWT in comparison with 2-bladed CRWT were higher, so that 3-bladed CRWT could generate more mechanical power.
With the two rotors in a counter-rotating configuration, the downwind rotor could benefit from the disturbed wake flow of the upwind rotor (i.e., with a significant tangential velocity component or swirling velocity component in the upwind rotor wake). As a result, the downwind rotor could harvest the additional kinetic energy associated with the swirling velocity of the wake flow [1]. Furthermore, the pressure difference between the lower surface (high pressure region) and the upper surface (low-pressure region) drives the fluid at the rotor tips upward while the fluid is swept toward the back because of the relative motion between the fluid and the wing [10]. This results in a swirling motion that spirals along the flow, called the tip vortex.

Fig. 6 and Fig. 7 represent fluid velocity profile in regions upwind the rotors, between the rotors, and downwind the rotors at y/D = 0.1 (in-line with blade root) and y/D = 0.425 (in-line with blade tip) respectively. In the beginning, the fluid velocity are 4.5 m/s then decrease when approach the front rotor, after that the fluid velocity fluctuate between the rotors. Interactions between front rotor wake and the rotation of the rear rotor in near axial distance (i.e. x/D = 0.5) cause the fluid velocity fluctuation there. Based on [1], the rear rotors will get additional kinetic energy related to the swirling velocity occurred.

There is a difference phenomena in the wake of the rear rotors at the two regions selected. The fluid velocity decline continuously at region in-line with blade root, as theoretically mentioned in 1-dimensional momentum theory. On the other hand, there is fluid velocity increase at the wake in-line with the tip. This is because tip vortex or swirling velocity created as mentioned by [10]. Overall, the results presented in Fig.6 and Fig.7, support the velocity deficit contour in Fig.5 and agree with the result of Ozbay et al [1] that counter rotating wind turbine can produce more power than single rotating wind turbine, as indicated by their velocity deficit. This research also found that 3-bladed CRWT could produce around 10.5% more power than 2-bladed CRWT as mentioned before.

4. Conclusion

A numerical study based on CFD analysis was carried out to investigate the performance and wake characteristics of 2-bladed CRWT and 3-bladed CRWT in comparison to those of a conventional SRWT. In term of rotational speed, 2-bladed CRWT has higher steady state rotational speed than 3-bladed CRWT, around 13.01 % for the front rotor and 15.12 % for the rear rotor. In term of time to reach steady state rotational speed, the design 3-bladed CRWT has faster around 10 seconds than design 2-bladed CRWT in this research.

Furthermore, 3-bladed CRWT has better performance in term of total mechanical power produced (i.e. from front rotor and rear rotor), around 10.5 % higher than 2-bladed CRWT. This result are supported by fluid flow visualization using velocity deficit contour that in the wake of 3-bladed CRWT, there is higher velocity deficit than 2-bladed CRWT wake region.

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