CFD analysis of number of blades on the performance of counter rotating wind turbine designed using blade element momentum theory under transient condition

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Abstract. Unsteady CFD simulations on the effects of number of blades on counter rotating wind turbine (CRWT) were carried out in order to investigate the performance and the flow characteristics. In this paper, 2-bladed and 3-bladed CRWT were designed using Blade Element Momentum Theory (BEMT) which comprised of S833, S834, and S835 airfoils. As a comparison baseline, a SRWT model which have similar design with front rotor of the 3-bladed CRWT would be also investigated. It was found that the SRWT had the same rotational speed with the front rotor of the 3-bladed CRWT. There was about 10.24 % and 11.79 % rotational speed reduction of the rear rotor from the front rotor of 2-bladed CRWTs and 3-bladed CRWTs, respectively. Both of 2-bladed CRWT and 3-bladed CRWT have higher total power than SRWT, thereby generating more larger velocity deficits in the wake flow.

1 Introduction

Recently, horizontal axis wind-turbine (HAWT) is the leading type of wind electric power generation because of its easiness, reliableness, and durableness. By using single rotating wind turbine (SRWT), a mainstream design of HAWT have been used widely, a maximum coefficient of performance, C_p , that could be reached are 59% (well known as Betz limit) with assumptions no viscous losses or wake swirl, and infinite number of blade [1]. The value would be less than 50% when these assumption are considered [2, 3]. It shows that the energy available from the oncoming wind flow are could not be harvested by more than 50% [4].

Nowadays, researchers found concept of dual rotating wind turbines (DRWTs) that could harness additional power, therefore increase overall power production. Newman [5] studied multirotor turbines by expanding theory of Rankine-Froude 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. Furthermore, a 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 [4].

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 [6] with 6 kW of 2-bladed CRWTs and Jung [7] 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 [4] 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 [8] 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 [9] also founded that CRWTs with equal diameter size produce maximum mechanical power.

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, this paper aims to investigate the correlation of rotational speed generated both of front rotor and rear rotor from the velocity inlet specified, and then would also be calculated the mechanical power produced as well as the wake characteristic formed using steady simulation.

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2 Methodology

2.1 Rotor design using blade element momentum method

In order to design a blade of rotor using the blade element momentum (BEM) method, a 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 [10, 11]. Several variables need to be determined first, they are number of blades (B), blade radius (R), tip speed ratio at the design point (λ_D), design lift coefficient of the airfoil (C_{LD}), angle of attack of the airfoil lift (α) [10]. The present study uses NREL airfoil shape of S835 (root), S833 (main), and S833 (tip) [12].

$$\beta(r) = 2/3 \arctan(R/r \lambda_D) - \alpha \quad (1)$$

$$c(r) = (16\pi/BC_{LD}) \sin^2[1/3 \arctan(R/r \lambda_D)] \quad (2)$$

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, in order to be validated in small wind tunnel) and angle of attacks corresponded with maximum lift coefficients of the three types airfoil were gotten from airfoil tools [13] at 50000 reynolds number. With the difference of number of blade, which are 2-bladed and 3-bladed, would produce different geometrical blade section as shown in **Table 1**.

Table 1. Optimized design geometry based BEM.

Optimized Geometry		S835 (root)	S833 (main)	S834 (tip)	
r/R		0.2	0.4	0.85	1
$\beta(r)$		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.

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 Computational fluid dynamic of wind turbine

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) $k-\omega$ turbulent modelling type that can be written respectively in Eq. (3), Eq (4), and Eq (5) [14].

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = Sm \quad (3)$$

$$\frac{\partial}{\partial t} (\rho \vec{v}) + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \nabla \cdot (\bar{\tau}) + \rho \vec{g} + \vec{F} \quad (4)$$

$$\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_i} (\rho k u_i) = \frac{\partial}{\partial x_j} \left(\Gamma_k \frac{\partial k}{\partial x_j} \right) + G_k - Y_k + S_k \quad (5)$$

$$\frac{\partial}{\partial t} (\rho \omega) + \frac{\partial}{\partial x_i} (\rho \omega u_i) = \frac{\partial}{\partial x_j} \left(\Gamma_\omega \frac{\partial \omega}{\partial x_j} \right) + G_\omega - Y_\omega + S_\omega$$

Where Sm is the mass source, p is static pressure, $\bar{\tau}$ is stress tensor, $\rho \vec{g}$ is the gravity force, and $\vec{F}$ is other external body force. In the $k-\omega$ turbulence models, k is the turbulent kinetic energy and ω 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 [14].

2.3 Simulation step and computational domain

Actually, this simulation consist of two steps. In the beginning, transient simulation 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. Then, steady simulations were conducted to know the torque from both rotor, therefore the mechanical power could be obtained by multiplying torque with rotational speed.

Blade rotor designed using BEM in the previous step played important role, because of the aerodynamic characteristic and inertia moments generated would affect the rotor rotational speed as well as the torque resulted.

In this study, the computational domain only consist of the rotor, with addition of rotating domain and far-filed domain, without including tower and ground. The overview of the volume grid generation are presented in **Fig. 1**.

Fig. 1. Overview of the mesh (a) full domain, (b) side view, (c) zoom of side view, (d) mesh around airfoil.

The volume mesh generated was categorized as unstructured mesh by inserting layers on the surface of the rotor to accommodate boundary layer phenomena. The comparison of the volume mesh generated from the SRWT, 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	$4e^{-5}$ m $y^{+}=0.8$	$4e^{-5}$ m $y^{+}=0.8$	$4e^{-5}$ m $y^{+}=0.8$
Average skewness	0,237	0.247	0.255
Average orthogonal quality	0,846	0.838	0.831

3 Results and discussion

3.1 Rotational speed driven from transient simulation

The main result of the transient simulation in 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.

Fig. 2. Flow driven rotor rotational speed.

Those steady state rotational speed resulted in the transient simulation played important role for the next torque calculation in steady multiple rotating frames simulation. Mostly in the previous CRWT numerical study, researcher only use steady simulation method by assuming the rotational speed both of front and rear rotor, but this transient simulation give advantage in the prediction of the characteristic of front and rear rotor rotational speed which approach the real phenomena of the CRWTs rotational speed.

3.2 Torque and mechanical power results

After obtaining the characteristic of rotational speed from the transient simulation both of SRWT and CRWT, then torque can be resulted in the multiple rotating frames steady simulation, and finally mechanical power can be calculated by multiplying the rotational speed and the torque. **Fig. 3** gives the comparison results of the SRWT and CRWTs performance at the steady rotational speed and some rotational speed reductions as loading-like. Both of 2-bladed CRWT and 3-bladed CRWT have higher total power (i.e the addition of front rotor and rear rotor) than SRWT. Furthermore, in the higher rotational speed reduction (i.e after 80 rpm rotational speed reduction), 2-bladed CRWT performs better than 3-bladed CRWT.

Fig. 3. Comparison of the SRWT and CRWTs performance.

3.3 Wake-flow characteristics behind the SRWT and CRWT

Fig. 4. Contour of velocity deficits of (a) SRWT, (b) 2-bladed CRWTs, (c) 3-bladed CRWTs.

Based on [15], 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. 4 gives velocity deficit in the wake behind the SRWT and CRWT models at their optimum power output (i.e. SRWT at 50 rad/s reduction, 2-bladed CRWTs at 70 rad/s reduction, and 3-bladed CRWTs at 50 rad/s reduction, from their steady rotational speed). 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.

4 Conclusions

A numerical study based on CFD analysis was carried out to investigate the performance and wake characteristics of 2-bladed CRWTs and 3-bladed CRWTs in comparison to those of a conventional SRWT. The transient simulation to drive rotational speed of the rotor was performed, followed by steady simulation to generate the torque, then finally could be calculated the mechanical power resulted.

By using multiple reference frames (MRF) simulation and assuming there are loading-like represented by rotational speed reduction from their steady rotational speed, it can be known that total mechanical power resulted from both CRWTs were higher than SRWT baseline. In more detail, after 70 rad/s rotational speed reduction, it can be shown that 2-bladed CRWTs could produce more total mechanical power than 3-bladed CRWTs. Later, the results can be used as consideration in choosing the suitable generator specification in term of torque and rotational speed requirements.

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