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Effect of Yaw Angle on Large Scale Three-blade Horizontal Axis Wind Turbines

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ABSTRACT

Offshore Horizontal Axis Wind Turbines (HAWT) are used globally as a source of clean and renewable energy. Turbine efficiency can be improved by optimizing the geometry of the turbine blades. Turbines are generally designed in a way that its orientation is adjustable to ensure the wind direction is aligned with the axis of the turbine shaft. The deflection angle from this position is defined as yaw angle of the turbine. Understanding the effects of the yaw angle on the wind turbine performance is important for the turbine safety and performance analysis. In this study, performance of a yawed HAWT is studied by computational fluid dynamics. The wind flow around the turbine is simulated by solving the Reynolds-Averaged Navier-Stokes equations using software ANSYS Fluent. The principal aim of this study is to quantify the yaw angle on the efficiency of the turbine and to check the accuracy of existing empirical formula. A three-bladed 100-m diameter prototype HAWT was analysed through comprehensive Computational Fluid Dynamics (CFD) simulations. The turbine efficiency reaches its maximum value of 33.9% at 0° yaw angle and decreases with the increase of yaw angle. It was proved that the cosine law can estimate the turbine efficiency with a yaw angle with an error less 10% when the yaw angle is between -30° and 30°. The relative error of the cosine law increase at larger yaw angles because of the power is reduced significantly.

1. Introduction

Offshore wind turbine farms provide large quantities of cheap energy whilst having a reduced impact on human environments when compared to onshore wind turbine farms. However, offshore wind farms are more expensive than onshore ones due to greater engineering requirements from storms, sea swells, and additional corrosion from salt

water. Analysis on the efficiency of wind turbines relative to the yaw is vital for the development of energy production facilities. Changes in the wind direction are inherent to the environment and thus large changes in this cannot always be matched by the turbines. By understanding the efficiency change as a turbine's yaw angle varies, the variations in energy production can be identified and attribut-

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ed to the related factors. Most offshore wind turbines used for energy harvesting are 3-bladed HAWT. These turbines utilise lift generated from the blades as the primary form of propulsion, as opposed to Vertical Axis Wind Turbines (VAWT) which utilise drag. Three bladed designs are chosen over two or four bladed designs for several reasons; most primarily is the cost to efficiency. Harvesting the maximum amount wind power is the key target of turbine design. Four bladed HAWT have a slightly better power coefficient, C_p , of approximately 0.505 compared to 0.500 for three bladed turbines. Four bladed HAWT also have a lower optimal tip speed ratio, TSR. However, the additional blade increases cost, weight, and the materials needed in manufacturing and maintenance. This increased cost is not justified by the increase in performance. For the purpose of offshore wind farms, two bladed designs are eliminated due to increased noise and manufacturing costs. Two bladed HAWT rotate at faster speeds at any given wind speed due to reduced drag. However, increased rotational speed results in faster TSR, thus increases noise and centrifugal forces. In addition, two bladed HAWT require a chord length 50% longer than equivalent three bladed HAWT [1]. This increase to the blade's size has dramatic impacts on cost, centrifugal forces, and noise.

When evaluating the performance of wind turbines, the International Electrotechnical Commission (IEC) recommends either annual energy production (AEP), Power Curve (Wind Speed vs Power), or power coefficient (C_p) as performance parameters [2]. Annual energy production is beyond the scope of the research conducted and thus only power curve and power coefficient will be utilized to evaluate performance. Power curves can be used to estimate the performance at relative positions on the power curve plot and relative productive efficiency.

For optimal efficiency and power generation, a HAWT should be designed such that the rotor axis is aligned with the direction of wind. Any misalignment with wind flow is referred to as yaw angle, as shown Figure 1. Wind turbines are designed with mechanical systems to control yaw and correct for changes in the direction of wind. However, slightly misalignment may cause reduction in the power, increased off principal axis forces on the turbine structure, or increased noise levels. This paper examines the effect of a yaw angle on the performance of the turbine in an ideal condition. As a result, the turbine pole and other structures like the generator of the turbine are not considered. The efficiency of a wind turbine (C_p) is the power generated by the turbine (P_T) divided by the available fluid energy from wind (P_w), i.e.

$$C_p = P_T / P_w \quad (1)$$

where P_T and P_w can be calculated by

$$P_T = T\omega \quad (2)$$

$$P = \frac{1}{2} \rho A V_w^3 \quad (3)$$

where T and ω are the torque and angular frequency of the wind turbine shaft, respectively, ρ is the air density, $A = \pi D^2 / 4$ is the turbine blade swept area, D is the swept area of the turbine blades and V_w is the wind velocity. If the wind is in the form of boundary layer flow, the velocity at the level of turbine shaft axis can be used as the V_w . In most of applications, the turbine elevation is sufficiently high that the wind flow is nearly uniform. The torque T reduces with the increase of ω . The best design of turbine is that the product of T and ω reaches its maximum value.

Ideally the maximum mechanical efficiency a wind turbine can reach is $C_p = 0.593$ and this limitation is referred to as Betz limit [3]. This value cannot be achieved in physical application due to energy loss and the turbulence of the flow. The efficiency of electric power is even smaller than this value considering the energy loss when mechanical power is converted to electricity. Jamieson [4] stated that the maximum efficiency of a three-bladed HAWT is approximately $C_p = 0.50$. These maximum efficiencies consider rotor axis and wind direction to be perfectly aligned. If the wind approaches the turbine at a yaw angle θ , the turbine efficiency can be estimated by an empirical formula:

$$C_p = C_{p0} \cos^K(\theta) \quad (4)$$

where K is a constant that can be derived using experimental or numerical experiments and C_{p0} is the turbine efficiency at $\theta = 0^\circ$. Equation (4) is the simplified cosine law. Research conducted by Dahlberg and Montgomerie [5], Kragh and Hansen [6] found the parameter K in Equation (4) is about 3, but Kragh and Hansen [6] reported that K varies and its upper bound is 3. Madsen, Sofarsen [7] found $K = 3$ overestimates the reduction in power. Further tests conducted by Schreck and Schepers [8] reported a value of $K = 1.8$ for yaw angles between 0° and 25° . This study also found that the effect of yaw angle is dependent of wind velocity. Offset yaw angles have been studied to test potential increases to downstream wind turbines. It is interesting that for wind farms with an array of turbines, Miao, Li [9], Noura, Dobrev [10] and Xinghui Dong and Hui Wang [11] found purposely angling upstream wind turbines can increase the overall power yield. Tip speed ratio (λ), which is defined as the ratio of wind turbine blade tip velocity to the wind speed, is a crucial value when wind turbine design is considered. TSR is defined in Equation (4). Optimal TSR for 3-bladed wind turbines lay between 6 and 9 [12], and marginal increases in efficiency are observed beyond a TSR of 8 [13]. Many researchers reported different values of K . In addition, the accuracy of

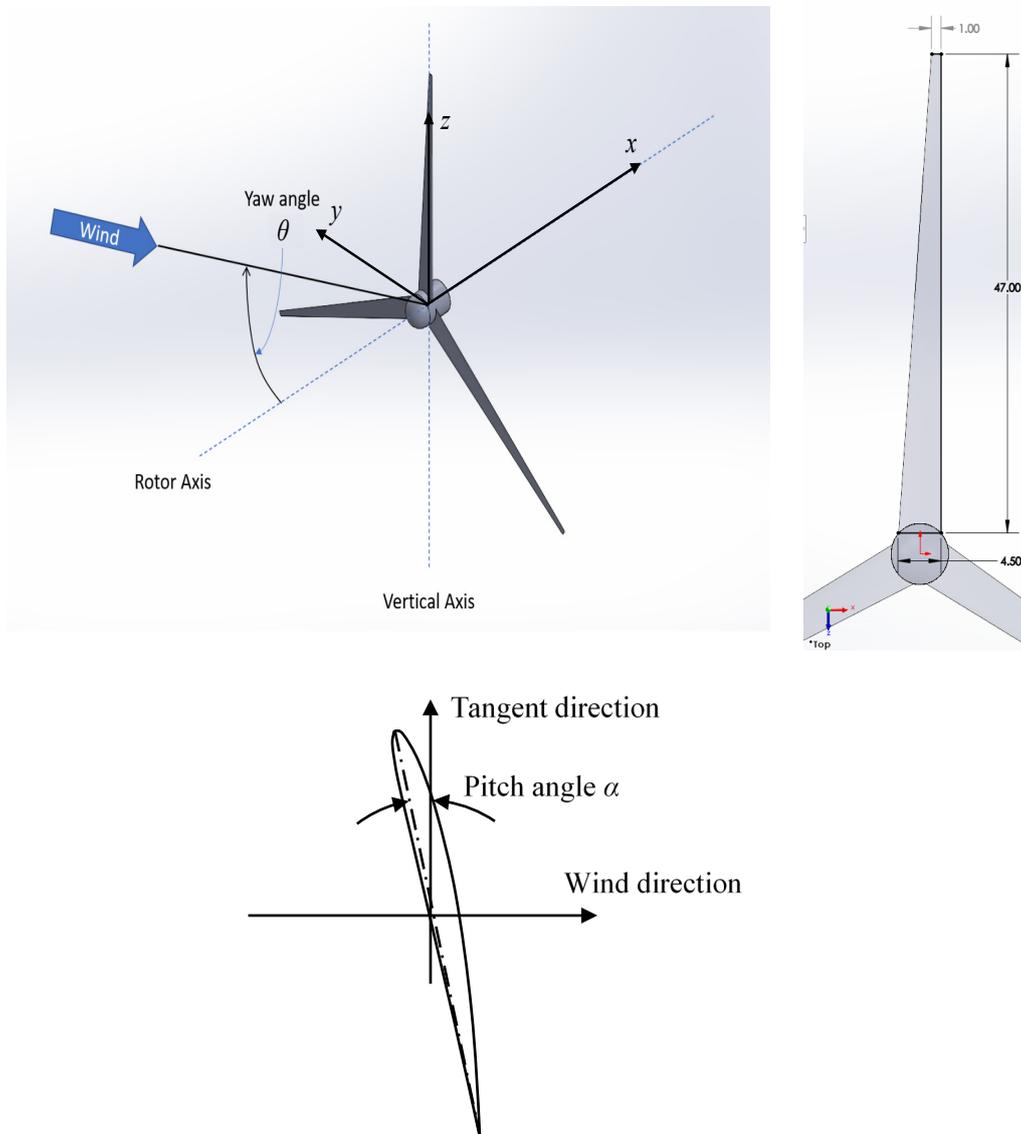


Figure 1. Design of a yawed wind turbine. Top left: isometric view; Top right: turbine blade design with a constant pitch angle; Bottom: definition of pitch angle α .

Equation (4) for predicting the turbine power at a yaw angle has not been considered in these papers. A systematic study is necessary to find out how accurate Equation (4) is. It is also expected that the applicability of Equation (4) also depends on the yaw angle. There might be a range of yaw angle where Equation (4) is accurate.

Mainstream utilization of yaw control systems in wind turbines has led to significant increases in power generation. The accuracy of these systems is crucial to reducing the cost of energy and maintaining functioning wind turbines. The analysis of a 2.3 MW three-bladed wind turbine found that the identified yaw error distribution resulted in a 0.2% loss in efficiency over a year of operation^[6]. This is a small percentage, however when considering the number of wind turbines in use and the amount of power

generated, any loss is considerable. This demonstrates how accurate current systems are and the importance of yaw angle. Yaw control is also used to improve the overall power generation of a wind farm as the wake effect from upstream turbines affects power generation of downstream turbines.

Although yaw control method has been used in wind turbine design, it is still necessary to understand the effects of yaw angle on power generation. Equation (4) make it possible to accurately predict the efficiency of a yawed wind turbine. However, many existing studies of wind turbines have been conducted using small scale models. The validity of Equation (4) in large scale wind turbine needs to be analysed further. In this study, a detailed numerical study is performed to investigate the yaw

angle on the efficiency of a prototype scale three-blade wind turbine with a turbine blade swept area of 100 m. Instead of conducting study at small scale, the simulations are conducted at prototype scale to make sure the research outcomes are applicable for real turbines. In addition, we conducted simulations at a variety of yaw angles to fully understand the effect of yaw angle on the turbine efficiency. The numerical simulation is performed using ANSYS software. The numerical results show turbine blade pitch angle of 5° generate the maximum power and Equation (4) with $K=3$ can predict efficiency of yawed turbine with satisfactory accuracy.

The rest of the paper is organized as follows. The numerical method is explained in Section 2. Section 3 includes three parts, the best performance of the rotation speed of the turbine with a right wind approaching angle and the best pitch angle of the blades are found in part 1 and 2, respectively. In part 3, the effects of the yaw angle on the efficiency of the turbine are studied and the accuracy of the empirical method is evaluated. Finally, the research conclusions are summarized in Section 4.

2. Numerical Method

A larger scale wind turbine shown in Figure 1 is analyzed numerically using computational fluid dynamics (CFD). The advantage of CFD simulations over laboratory experiments is that they can be performed at the scale intended for manufacture, mitigating the need for scaled models, and thus scaled conditions as well as making it possible to test singular components. The turbine is created in Solidworks with 5 components, the nacelle, nose, and 3 blades. The nacelle and nose are simple bodies that have undergone limited aerodynamic improvement as these elements are not the focus of analysis. The nacelle is the centre body of a wind turbine that houses the gearbox, driveshafts, and operational componentry. For the turbine designed for this project, the nacelle is connected to the nose and blades as the cylindrical shape does not impact the results when rotated. This simplifies the assembly and reduces the meshing complexity in ANSYS. The nacelle is comprised of a 6 m diameter cylinder, and 6 m in length. The nose of the turbine is a 6 m diameter hemisphere attached to the forward-facing end of the nacelle. This geometry improves air flow around the body of the nacelle as well as redirected flow towards the blades. Each blade of the turbine is a tapered airfoil with the shaft and tip ends having chord lengths of 4.5 m and 1 m, respectively, as seen in the top right picture of Figure 1.

A coordinate system is defined with its origin located at the centre of the turbine shaft. The x -, y - and z -axes are in the shaft direction, normal direction of the hub on the hor-

izontal plane and the vertical direction, respectively. The wind approaches the turbine at a yawed angle θ . $\theta=0^\circ$ corresponds to the case where the wind direction aligned with the shaft axis direction perfectly. ANSYS Fluent is used to simulate wind and the mechanical energy generated by the turbine. This study mainly conducts fundamental study of the effect of the wind direction on the energy harvesting and the wind turbine supporting pole is not considered. The wind turbine is designed using Solidworks software. It consists of a 6 m diameter hub with curved nose connected to 3 blades. The total diameter of the wind turbine blade swept area is $D=100$ m and the chord length of the blades decreases from 4.5 m at the hub to 1 m at the tip. A NACA 4412 aerofoil profile is implemented along the entire length on the blade. Analysis performed by Hossain, Raiyan^[14] found the NACA 4412 aerofoil to be a suitable design for low speed applications such as HAWT. The pitch angle does not vary along the length of the blades. This paper will prove the validity of the empirical formula Equation (4) and derive the coefficient K in this equation for prototype large scale turbines under a wind velocity of 12 m/s (43.2 km/h), which is within the range of wind speed in typical offshore environments.

Wind past a turbine with a shaft speed and yaw angle is simulated using ANSYS Fluent software 2020 version. Fluent has been proven to be accurate software for simulating aerodynamics problems. The size of the rectangular computational domain is 400 m in the wind direction, 400 m in the vertical direction and 500 m in the crossflow direction. The computational domain includes two zones, a spherical rotating zone at the centre and an outer zone. The 150-m diameter spherical central zone is allowed to rotate along the x -axis with the same speed of the turbine rotation speed (see Figure 1 for the coordinate system). Using rotating inner zone avoid remeshing, which reduces the calculating speed. In addition, the mesh quality of the rotating zone remains high without remeshing.

To simulate the wind interaction with such a large turbine, an efficient numerical method with acceptable accuracy is important. Predicting very small scale turbulence using refined CFD model like Direct Numerical Simulation (DNS) or Large Eddy Simulation (LES) is practically not achievable. In this study, the flow is simulated by the three-dimensional Reynolds Averaged Navier-Stokes equations (RANS):

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} (\rho u_i) = 0 \quad (5)$$

$$\frac{\partial}{\partial t} (\rho u_i) + \frac{\partial}{\partial x_j} (\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[\mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] + \frac{\partial}{\partial x_j} (-\overline{\rho u_i u_j}) \quad (6)$$

where t is time, x_i ($i=1,2$ and 3) are the Cartesian coor-

dinates, ρ is the air density, u_i is the fluid velocity in the x_i -direction, p is the fluid pressure, μ is the molecular viscosity. On the right-hand side of Equation (6), represents the Reynolds stresses of turbulence. The RANS equations are time-averaged fluid flow equations that only calculate the time-average flow field while the effect of turbulence on the mean flow is captured by the so-called Reynolds stress.

The Shear Stress Transport (SST) $k-\omega$ turbulence model is used to calculate the Reynolds stress of turbulence. The SST $k-\omega$ turbulence has been proved to be able to simulate strong turbulent flow problems with adverse pressure gradient in aerodynamics^[15-17]. In this study, the turbine is assumed to be placed well above the boundary layer above the ground, as a result, uniform velocity is given at the inlet boundary, the continuity of mass and momentum is ensured at the interface between the inner and outer zones of the computational domain. Non-slip boundary condition is used on the surface of turbine blades, i.e. the velocity of fluid is the same as the motion of the blade. On the outgoing boundary, the gradient of pressure and velocity in the streamwise direction is zero. On the side boundaries (top, bottom, front and back boundaries), free-

slip boundary condition is used.

The whole computational domain is divided into about 1.1 million tetrahedron elements. Mesh refinement test were conducted to make the computational mesh is sufficiently dense for converged results of the turbine power. The use of the RANS equations allows the flow to be simulated at affordable time without compromising the accuracy of main flow characteristics. The computational time step is 0.2 s. Figure 2 shows the computational mesh near turbine blades. Denser mesh is implemented near the blade surfaces to ensure complex flow features can be captured. On the interface between the rotating inner zone and the outer zone, mesh is also dense to make sure the effects of the interface on the accuracy are small.

After the flow around the turbine is simulated, the torque is calculated by integrating the pressure and shear stress over the blade surface and the power and efficiency of the turbine are calculated by Equation (2) and Equation (1), respectively. Fluent can calculate the torque automatically. When a turbine with a yawed angle is generated, the whole coordinate system and the turbine is rotated at an angle same as the yaw angle, but the outer zone does not change.

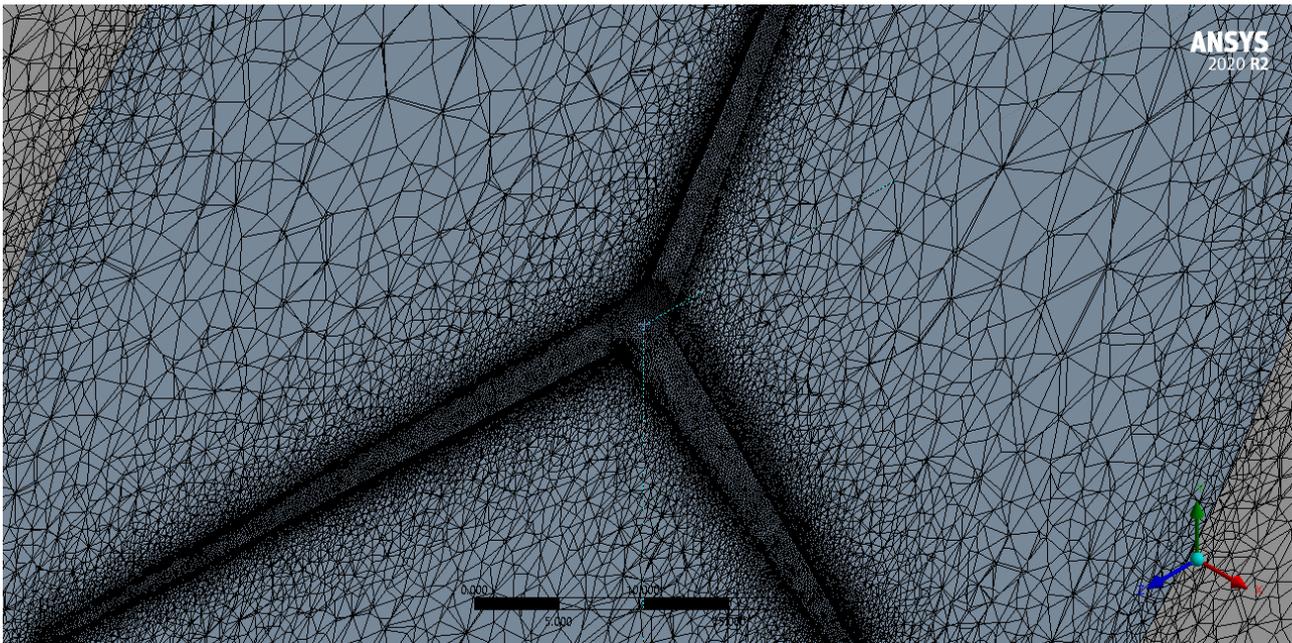


Figure 2. Computational mesh near the turbine blades. Dense grids are used near the blades to make sure the complex blade-flow interaction is well predicted.

3. Numerical Results

A constant wind velocity of $V_w=12$ m/s is used in the present study. The first step of the study is to find the best performance condition of the turbine, i.e. the pitch angle of the turbine blades, the rotation speed of the turbine

shaft where the turbine's performance reaches the maximum. The effects of the yaw angle under this condition is examined. Pradeep and Harikumar^[18] found the maximum drag to lift coefficient ratio of an airfoil can be achieved at 5° angle of pitch angle (blade angle for a turbine, defined

in Figure 1). In this study the pitch angle of the blade is 5° . We want to do the study at the rotation speed of the turbine where the best performance is achieved. To find out the best rotation speed, turbine performance at zero yaw angle $\theta=0^\circ$ and various turbine rotational speed is simulated first, and Figure 3 shows the variation of the turbine power with the turbine rotational speed, i.e., the performance curve of the turbine. The variation of the power with the angular speed ω has characteristics of typical performance of wind turbines. The power is zero at $\omega=0$ rad/s and increases with the increase of ω until it reaches its maximum value, after which the power decreases very quickly. The turbine power reaches its maximum of 2.818 MW at $\omega=2$ rad/s and this best performance shaft speed is used in the study of the effects of yaw angle. In practice, turbine should be designed to allow it to rotate at the best performance speed.

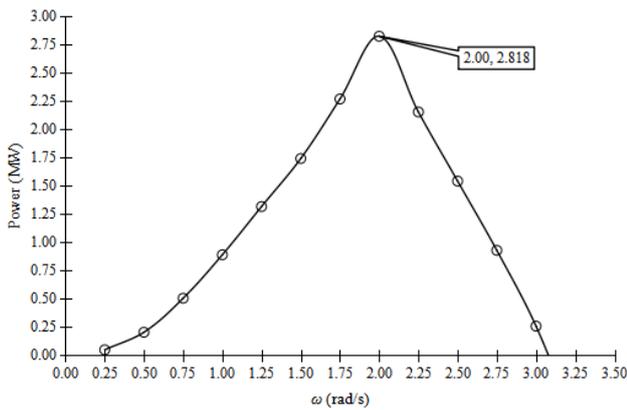


Figure 3. Variation of the efficiency with the angular velocity of the turbine shaft at $\theta=0^\circ$ and $\alpha=5^\circ$.

To further confirm that 5° blade angle is the best angle, turbine efficiencies at $\alpha=0^\circ, 5^\circ, 10^\circ$ and 15° are calculated and Figure 4 shows the variation of the efficiency of the turbine with the blade pitch angle at $\omega=2$ rad/s. Further increase the blade angle to beyond 15° could cause negative efficiencies. It can be seen that blade angle of 5° generates the maximum turbine efficiency compared with other blade angles. For a two-dimensional NACA 4412 aerofoil, the maximum lift coefficient occurs at an attack angle between 10° and 15° . The best performance pitch angle is smaller than the best lift angle of a two-dimensional aerofoil because the rotation of the turbine changes the effective attack angle. In addition, the variation of the motion speed of the blade in the radial direction makes different section of the turbine blades works on different effective attack angles. Because of this, the best performance pitch angle can only be determined by either CFD simulations or experiments.

The maximum efficiency of 33.9% is 43% smaller than

the ideal solution of 59.3% [3]. The focus of this study is to quantify the effects of yaw angle on the performance of the turbine. We did not make further efforts to optimize the design of the turbine blade to achieve the maximum power. It is expected that the yaw angle effects for different turbine blade design should be the same.

With the blade pitch angle (α) and the rotational speed of the shaft (θ) determined, simulations for $\alpha=5^\circ, \omega=2$ rad/s and $(V_w)=12$ m/s and yaw angle θ varying from -70° to 70° with a 10° increment to examine the effect of yaw angle on the performance. It was found that angles beyond $\pm 80^\circ$ resulted in negative power, and we did not include the results of these cases in the discussion. Turbine cannot have such large yaw angles in reality. At $\theta=0^\circ$ a power of 2.82 MW was generated, resulting an efficiency of 33.9%. Figure 5 shows the variation of the turbine efficiency with the yaw angle. Both negative and positive yaw angles reduce the efficiency and the reduction rate increase with the increase of the yaw angle magnitude. The component of the wind in the axial direction of the turbine contributes the power generation. If the turbine is yawed either in the negative or positive direction, the component of the wind in the turbine axial direction reduces and as a result the power of the turbine reduces. The power curve in Figure 5 is symmetric because positive and negative yaw angles with same magnitude have same effects on the reduction of the wind velocity in the turbine axial direction. The predicted efficiencies using the efficiency at $\theta=0^\circ$ and Equation (4) with $K=3$ are also shown in the figure for comparison. The CFD results of the efficiency follow cosine law of Equation (4) very well. The efficiency changes with increase/decrease of θ at very small rate as is very small, especially near $\theta=0^\circ$. The maximum change rate of C_p with the change of θ occurs at $\theta = -45^\circ$ or 45° . The efficiency is negligibly small as approaches 90° . In addition, it is found that positive and negative yaw angles of the turbine generate the same effect on the turbine efficiency.

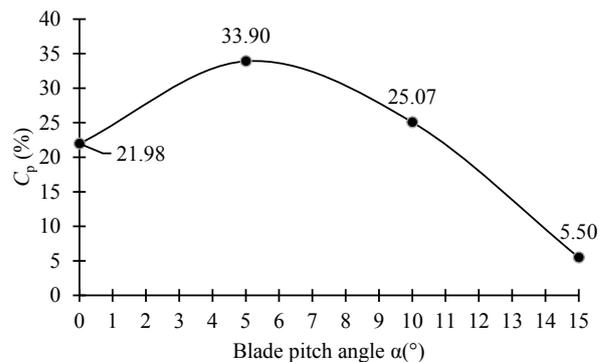


Figure 4. Variation of Efficiency with the blade angle at $\theta=0^\circ$.

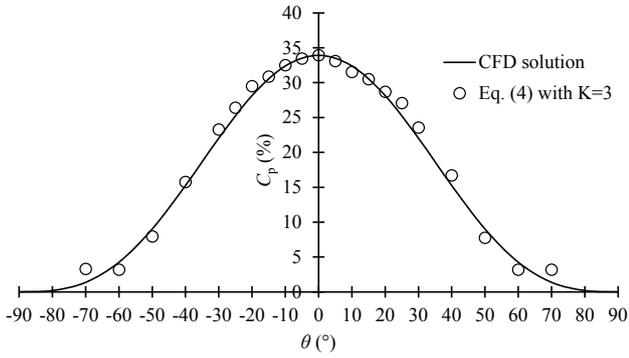


Figure 5. Variation of the efficiency of the turbine with $\alpha=5^\circ$, $\omega=2$ rad/s and $(V_w)=12$ m/s

To quantify the accuracy of the cosine law (Equation (4)), Figure 6 compared the CFD solution of the turbine power with that predicted by the cosine law. The difference between the two sets of results is defined as

$$err = \frac{|P_{T,CFD} - P_{T,cosine\ law}|}{P_{T,CFD}} \times 100\% \quad (7)$$

where and are the power calculated by CFD and cosine law, respectively. The error of the cosine law is less than 10% when the yaw angle is in the range between -30° and 30° . The error *err* is large at large yaw angles $|\alpha| > 40^\circ$ because the error is amplified by the small value of the power value. In practice, only small yaw angles are allowed because large yaw angles do not generate power.

The proved the validity of the cosine law Equation (4) is very useful. It provides a simplified method for estimating the power of a turbine at a yawed angle quickly before refined study is required in the early stage of design. To use Equation (4), the turbine efficiency at $\theta=0^\circ$ must be predicted using either experimental or numerical model and the prediction accuracy is important.

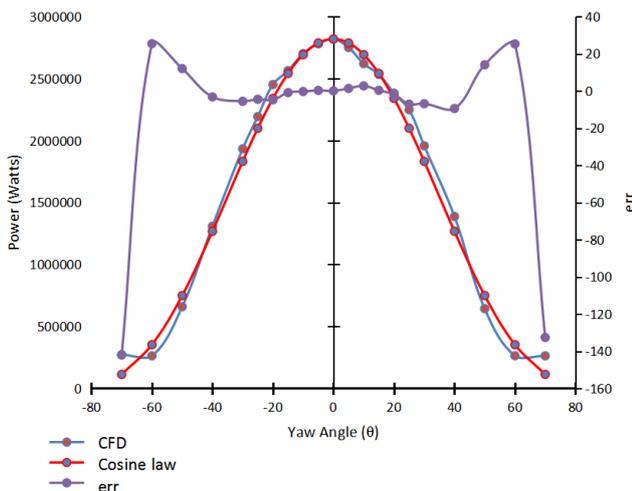


Figure 6. Comparison between the CFD results of turbine power and the power predicted by the cosine law.

4. Conclusions

The efficiency of a prototype three-blade HAWT is investigated through numerical simulation and the focus of this study is the effect of the yaw angle on the turbine performance. The maximum efficiency at $\theta=0^\circ$ is 33.9%. The cosine law Equation (4) with $K=3$ can be used to predict turbine efficiency with satisfactory accuracy. If the effect of the yaw angle on the turbine efficiency follows cosine law, very small value of yaw angle does not affect the power much. The maximum change rate of the power with the yaw angle occurs at $\alpha=45^\circ$. It can be concluded that this form of computational fluid dynamics is viable when comparing predicted efficiency values to that of simulation analysis. In terms of yaw control and the application of this methodology to large-scale wind turbines, the cosine law stands as an accurate method of determining the behaviour of efficiency loss over a range of yaw values. However, CFD simulation on the flow behaviour and efficiency are a more advanced and design specific method to confirm these predictions and investigate the effect of wind turbines in proximity to each other. This paper only studied the case where the turbine is placed in a uniform flow. If the turbine is in a boundary layer flow with strong variation of the velocity in the vertical direction, more study is required to testify the cosine law. In addition, the effect of yaw angles on the total generated power by an array of multiple turbines in a wind farm need to be studied further in future.

Author Contributions

Thomas Posenauer: Investigation, Methodology, Formal analysis, Writing-original draft;

Ming Zhao: Supervision, Conceptualization, Methodology, Validation, Formal analysis, Writing-review & editing;

Ee Long Tan: Writing-review & editing.

Conflict of Interest

The authors declare not conflict of interest.

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