CFD Letters

Computational Fluid Dynamics (CFD) Evaluation of a Horizontal-axis Wind Turbine with a Bionic Blade

Russel Tapa Musa[1], Djamal Hissein Didane[2,3,*], Bukhari Manshoor[2], Norasikin Mat Isa[2], Mohammad Sukri Mustapa[2], Abdelazeem A. Amin[4]

[1] DOM Engineering Sdn Bhd, Kuching, Sarawak, Malaysia
[2] Center for Energy and Industrial Environment Studies, Universiti Tun Hussein Onn Malaysia, Malaysia
[3] National Institute of Sciences and Technology of Abeche, Abeche, Chad
[4] Renewable Energy Department, Delta Technological University, Quesna, Egypt

ARTICLE INFO	ABSTRACT
	With the world's energy supply becoming increasingly scarce, wind power is gaining popularity as a clean source of renewable energy which is good for the environment. Thus, it is an alternative to burning fossil fuels such as coal, which may have an environmental impact during operations due to the emissions of unwanted gases. Wind turbines are the devices used to produce power by moving a turbine's propeller-like blades around a rotor, which spins a generator that generates energy as air passes through them. However, existing wind turbines still suffer from low conversion efficiencies. Therefore, in this current study, the bionic blade design has been used to enhance the performance of a horizontal axis wind turbine utilizing a computational simulation approach while seeking to improve its efficiency. The blade profile of the model used was based on the NACA 0012 airfoil with the modified angle of attack. The hybrid shear stress transport (SST) k-omega was used as the turbulence model. The computational procedures involved the use of various inlet velocities while maintaining a constant rotational speed. The results show that the bionic design was found to improve the overall performance of the standard NACA0012 blade design. Moreover, both power and torque coefficient outputs increase as the tip speed ratio (TSR) increases. However, the torque decreases as the TSR increases. In terms of power coefficient, the highest conversion efficiency was about 28% and it was achieved at 3.7 TSR.

1. Introduction

The current source of electrical energy is the usage of fossil fuels, nuclear-powered reactors and coal. The problem with fossil fuels and the like is that they heavily impact the environment, especially our climate [1, 2]. Climate change may therefore be argued to be the effect of the electrical power generation using fossil fuels, nuclear-powered reactors and coals [3]. According to the Intergovernmental Panel on Climate Change (IPCC), to limit global warming to 1.5°C, quick, far-

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reaching, and unprecedented reforms in all parts of civilization would be required [4]. Our world requires energy to run the bulk of our devices and equipment, and having electricity in our daily lives and activities has become a necessity, and Malaysia has been fortunate to be blessed with a reasonable supply of both fossil and renewable energy sources and has thus far been effective in meeting the country's energy demands. It is apparent that Malaysia's energy environment has grown significantly in recent years. However, the moment has come to reconsider environmental concerns in every stage of economic growth in terms of the effects of emissions on the economy [5]. To respond to calls for more action in the fight against climate change and global warming, the world must reduce, if not eliminate, the use of fossil fuels, nuclear, and coal, which are currently used as the primary fuel to power the majority of heavy industrial machines such as gas turbines, diesel generators, and vehicles. As a result, the community must continue to develop and explore renewable energy solutions that can replace the usage of fossil fuels in the generation of power. Therefore, additional research is undertaken globally on the utilization of wind energy as a renewable energy source to replace the traditional usage of fossil fuels in power generation [6, 7].

Over the past decades, the rising scarcity of energy has caused wind power to gain popularity as a clean form of renewable energy, and the wind turbine is the typical instrument for harnessing wind energy. Several types of wind turbines exist in the world currently. They are characterized by their axis of rotation as horizontal axis wind turbine (HAWT) and vertical axis wind turbine (VAWT). The HAWT is widely spread due to its higher conversion efficiency compared to the VAWT. However, it comes with several disadvantages including the requirement of higher starting speed, yaw mechanism to direct the rotor to the prevailing wind direction and sensitivity to turbulence. On the other hand, although the VAWT appear to have low conversion efficiencies, it possesses many advantages including the ability to operate in low and turbulent wind zones such as urban environment, accommodation of wind from any direction and thus no yaw mechanism is required [8]. Apart from that there also emerges other types of wind turbines such the counter-rotating wind turbines (CRWTs). Although the application of CRWTs is not new in HAWTs, this concept is also being adopted currently to VAWTs and it showed a considerable improvement in the conversion capability of both types of turbines that can reach up to two folds in CRWT with vertical axis. However, the system requirements for both types of wind turbines are different [9-14]. In CRWT with a horizontal axis, the two counter-rotating rotors usually involve the use of two shafts and two alternators/generators, and the wind power is harnessed as it passes through both rotors. Since they are arranged one in front of the other, whatever wind escapes from the front rotor, the one in the rear will harness it. However, in the case of the new technique of CRWT with VAWT, the system requires only a single shaft and a single alternator/generator. Thus, one of the counter-rotating rotors is fixed in the shaft as usual turbines. However, the second counter-rotating rotor is fixed on the generator itself and moves it together as the rotor moves in opposite direction. Therefore, relatively more rotational speed is achieved which translates to more power output.

Therefore, with the wind turbine's rising popularity as an energy source, the issue of how to increase wind energy use is steadily becoming more prominent [15]. One of the most important components of the wind turbine is the blade, which is the component that is in direct contact with the wind, and the blade is overlaid with airfoils increasing in thickness along the spanwise, according to blade element momentum theory. Hence, the study emphasizes researching the probability of improving the wind turbine's blade efficiency and performance [16, 17]. In order to extract the maximum potential of a wind turbine, one must understand the physics of the interaction between airflow and wind turbine blades, since the optimal power output is definitely dependent on flawless contact between both the blade and the wind [18]. In general, the design of the blades should absorb as much wind energy as possible and transform it into spinning mechanical energy for electric

generation. To maximize the dependability of a wind turbine system, two key criteria must be considered: the aerodynamic performance of the wind turbine's blades and the structural behavior of the blades during normal and severe wind conditions [19].

Moreover, a vital parameter for power generation is comprised of the maximum acquisition of torque from wind power which is determined by the performance of the wind turbine's aerodynamic system. To ensure maximum torque is delivered to the generator, it is imperative to develop a wind turbine with the most advantageous blade design, which considers several essential attributes such as wind speed and density, surface area, and lift coefficient in order to generate lift to a greater extent as wind turbines grow in size. Furthermore, it is typically suggested that when a high air pressure is developed on the side of the blade with a lesser curve and a low air pressure is developed on the opposite side, a lifting force perpendicular to the direction of the airflow across the turbine blade is generated which increases the torque. In addition, the aspect ratio which is the ratio of blade length to rotor radius also affects the performance of the turbine. A computational study on the performance of an asymmetrical straight-bladed wind turbine has shown that the output was affected when the aspect ratios were varied. This numerical research demonstrated how the Reynolds number of the rotor blade has a significant impact on turbine performance. From a geometric standpoint, as the aspect ratio decreases, the Reynolds number increases, which improves wind turbine performance [20]. Apart from that the appropriate number of blades is important to match the generator performance curve for optimal overall performance and efficiency as the wind turbine design with a lesser number of blades has a higher flow speed, meanwhile a wind turbine design with a bigger number of blades provides larger torque, and the best power coefficient lies in between the two designs [21].

However, the airfoil is the hypothetical visual representation of each section from the root to the tip of the blade, and it must be considered while designing an airfoil for a wind turbine [22]. Meanwhile, in a recent study conducted by Zhang *et al.,* (2015) [23], the method of distributing the wind turbine blades' aerodynamic centers along the leading edge of the wings is known as configuration improved bionic blade where the typical blade's chord length and attack angle remain constant, and only the aerodynamic core of the seagull wings is in the front line [24, 25]. Furthermore, the tip speed ratio is also critical in the design of wind turbine turbines. If the wind turbine's rotor turns too slowly, the majority of the wind will flow through the space between the rotor blades unaffected. As a result, wind turbines are designed with the best possible tip speed ratio to be able to harness maximum power from wind energy, as the wind turbine blades will begin to consider the wind similar to a solid wall when the rotor rotates at a very high speed, disrupting the tip speed ratio [26]. Accordingly, Song *et al.,* (2007) [27] suggest that apart from the bionic blade design, the tip of a regular blade also could improve the perfromance. Similarly, Hua *et al.,* (2019) [16] indicated that the tip of a wind turbine blade has a significant impact on the aerodynamic performance of the blade and the improvement made on such blade results in a significant boost on the blade's aerodynamic performance.

As such, the present study concentrates on the selection of an optimal airfoil, with three variations of wind turbine blades chosen and analyzed using characteristics such as pressure contour analysis and torque coefficient.

2. Theoretical Formulations
2.1 Governing Equations

The Navier–Stokes equations are the governing equations of computational fluid dynamics (CFD) software which is based on the physical property conservation law of fluids. The change in properties

such as mass, momentum, and energy induced by a subject's input and output is the broad concept of conservation law. ANSYS Fluent, on the other hand, is a platform for solving mass and momentum conservation equations for all types of flows. The governing equations in terms of mass and momentum equations are presented as shown in Eq. (1) and Eq. (2), respectively. In terms of turbulence model, the k - omega hybrid shear stress transport (SST) model is better suited for this study of a system with close-to-the-wall forces as an investigation by Menter *et al.,* (1994) [28] ascertained that such model is appropriate for balancing the advantages of the k - omega with elements away from the wall.

$$\frac{D\rho}{Dt} + \rho \frac{\partial U_i}{\partial x_i} = 0 \tag{1}$$

$$\rho \frac{\partial U_j}{\partial t} + \rho U_i \frac{\partial U_j}{\partial x_i} = -\frac{\partial P}{\partial x_i} - \frac{\partial \tau_{ij}}{\partial x_i} + \rho g_j \tag{2}$$

3. Materials and Methods

3.1 Blade Design

The present wind turbine blade was modeled based on the standard NACA 0012 airfoil. The design of the model is selected from the bionic blade of a totally improved airfoil the standard NACA 0012 airfoil. The bionic blade design of the total improved airfoil is a modified version of the NACA 0012 airfoil which changes being made to the angle of attacks, while the blade length is maintained the same as the standard NACA 0012 airfoil blade length, as shown in Figure 1. Meanwhile, for the bionic blade of the partially improved airfoil, the modifications altered on the blade are the angle of attacks and the chord length of the blade is varied from the standard wind turbine blade of the NACA 0012 airfoil. With two designs to be selected from, the study will evaluate and analyze the performances of the bionic blade of a totally improved airfoil, as shown in Figure 2.
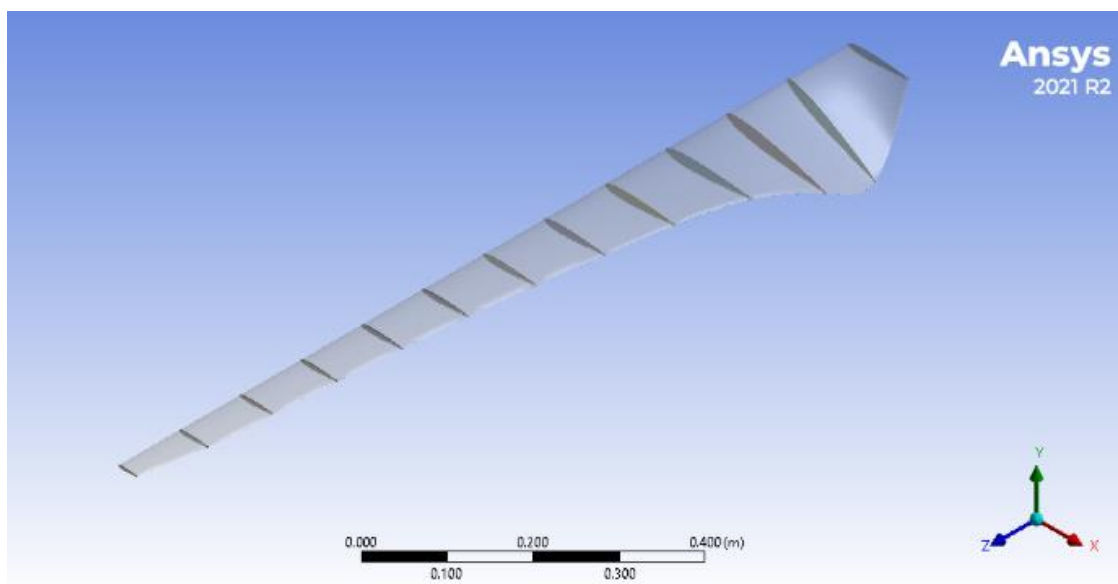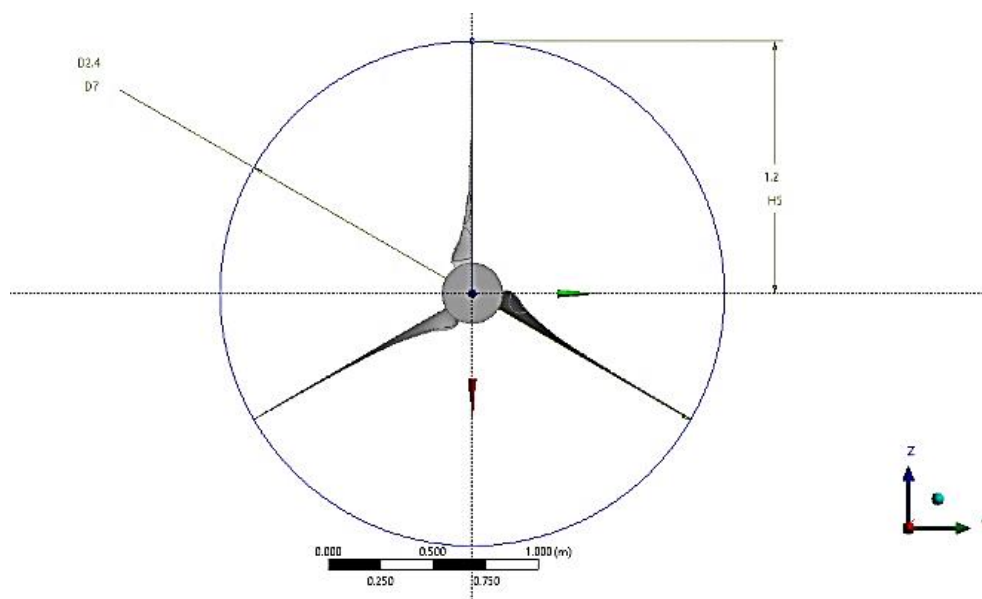

Fig. 1. Improved bionic blade

Fig. 2. 3-blade bionic wind turbine blade design

3.2 Spatial Domain Discretization and Boundary Conditions

In the study, the computational domain is divided into two distinct regions known as the fixed region and the rotating region. The fixed region is a rectangular shape and it represents the overall computational domain. While the rotating domain embodies the rotor and the rotation of the model achieved. Moreover, meshing is among the most critical processes in completing an accurate simulation. The meshes are composed of elements that contain nodes that describe the geometry's form. Therefore, as shown in Figure 3, the adaptive parameters from the mesh dimensioning feature are used to obtain more uniform mesh cells around the domain, allowing for an evenly distributed composition of the mesh cells around the airfoil body, as the validity and reliability of the flow solution are heavily dependent on the effectiveness of the mesh cells generated in this process. Furthermore, in order to obtain accurate results, the grid-independent test performed. The mesh independence is obtained by successfully completing several levels of re-meshing refinements. In this study, four levels of element sizing were used to gradually optimize the mesh, particularly around the airfoil, which is the most important component of this study, as shown in Table 1. As a result, it becomes optional to choose which size of the element to use for the remainder of the study in order to achieve an accurate finding with the least processing and computing solving time. Thus, for this study, an element size of 0.025 mm was chosen for the remainder of the mesh because it has a reasonable number of elements close to the software limit of 512,000 elements and a relative error of 6.88 percent, which is suitable and takes less time to solve, as shown in Table 1.
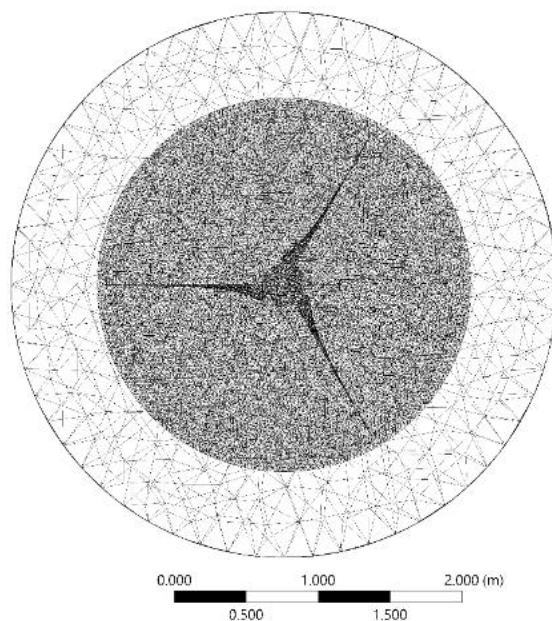
Fig. 3. Bionic blade mesh

Table 1
Details of grid independence study

| Velocity (m/s)	10	Torque (N.m)	25		
No.	Size of Elements (mm)	No. of Elements	Skewness	Torque Output (N.m)	Relative Error (%)
1	0.204	61313	0.3468	22.36	10.56
2	0.102	125,614	0.2736	22.48	10.08
3	0.051	192,077	0.2911	23.02	7.92
4	0.0255	387,923	0.3343	23.28	6.88

The flow parameters of the specified simulation environment can be represented numerically by boundary conditions, which produce a specific solution by guiding the motion's flow, and this approach is defined as the boundary condition. As a result, it is critical to accurately describe the boundary conditions of each geometrical component during the pre-processing phase, as the formulation of flow issues is predicated upon that, and any unpartitioned boundary conditions might trigger errors during simulations or lead to inconsistent findings. This research includes various boundary conditions, including inlet, outlet, wall and interface boundary conditions. The current study was set up by using an inlet velocity of 10 ms^{-1}, 12 ms^{-1}, 15 ms^{-1}, and 20 ms^{-1}. The aim of setting the velocity to the various values is to investigate the aerodynamic performance of the bionic blade of a horizontal axis wind turbine at various wind speeds. While the outlet pressure is set to zero at gauge pressure or equivalent to the atmospheric pressure of 1.013 bar.

4. Results and Discussion
4.1 Model Validation

Before moving ahead with the simulation tools, one imperative procedure must be accomplished: the simulation results must be compared to the results of previous studies. This tells us that the simulation method is secure and reliable enough to be used for the remaining simulation models. As a result, a validation process was performed, in which certain settings from the previous study were

applied to the detailed simulation settings in order to acquire the nearest findings to the prior studies possible. Generally, the performance of a wind turbine is analyzed through its torque value compared to the tip speed ratio or the power coefficient, particularly in comparison to the tip speed ratio. In this study, the velocity values were attained from ANSYS simulation using previous study settings as mentioned earlier, and the results were compared to Hua *et al.,* (2019) [16] results. As shown in Figure 4, the power coefficient value was plotted against the corresponding tip speed ratio (TSR) between the current study results and previous study results using the same NACA0021 airfoil. The graph shows that the trend between the current and previous study results is similar from beginning to end, which is promising and acceptable. The average relative error was calculated to be around 10% which is in the acceptable range.
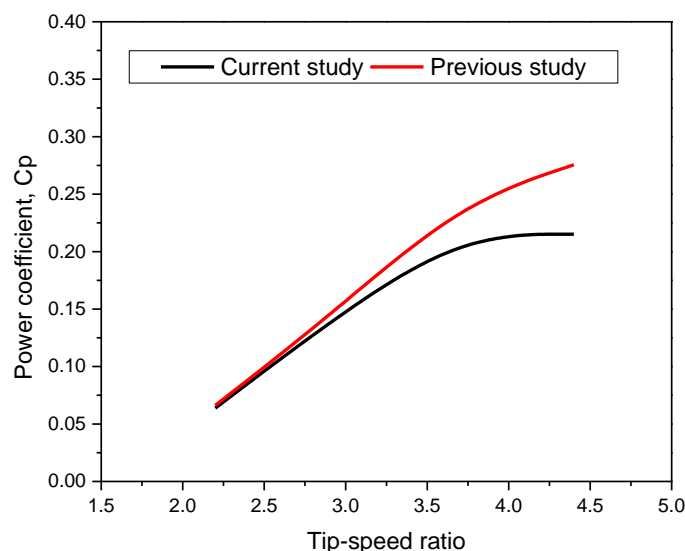
Fig. 4. Validation in terms of Cp against TSR of present with the previous studies

4.2 Analysis of Torque and Torque Coefficient

In general, aerodynamic performance, such as torque and power coefficient, determines the behavior of a wind turbine. As a result, the quantitative torque coefficient obtained in the computational fluid dynamics simulation of the bionic blade for horizontal axis wind turbine in ANSYS Fluent with a constant rotational speed of 350 revolutions per minute is presented in figures, as shown in Figure 5. In order to obtain the torque coefficient, calculated from the torque obtained through the simulations run in the computational fluid dynamics software, ANSYS Fluent. The figure of torque output against tip speed ratio is presented in Figure 5. As observed from Figure 5, the torque output peaked at the tip speed ratio of 2.2, and it was lowest when the tip speed ratio was at 4.4. Therefore, it can be deduced that the torque output is inversely proportional to the tip speed ratio, as when the tip speed ratio decreases, the torque output increases.

From the results in Figure 5, it can be observed that as the tip speed ratio increases, the torque coefficient of the bionic blades decreases. It can be deduced that the relationship between the torque coefficient and the tip speed ratio is inversely proportional. This is due to the increased wind speed which made it easier for the rotor to overcome the torque and rotate faster. In addition, the highest value of the torque coefficient lies at the point where the tip speed ratio is equal to 3.7, where the torque coefficient is 0.0587. Thus, the torque coefficient peaked at the value of the tip speed ratio of 3.7 and reached its lowest point at the value of the tip speed ratio of 2.2. A study by Rachman *et al.,*

*(*2013) [29] examined the effect of tip speed ratio against torque coefficient values and it was determined that at a high speed, the lift dynamics in the large radial distance for the turbine with multiple blades often seem to be very small to one that results in the low torque yielded of the turbine at the high rotational speed. In the meantime, the lift forces in greater radius for lower bladed turbines still are comparatively high at high rotational speed, allowing the turbines to retain torque at correlating rotational speed.
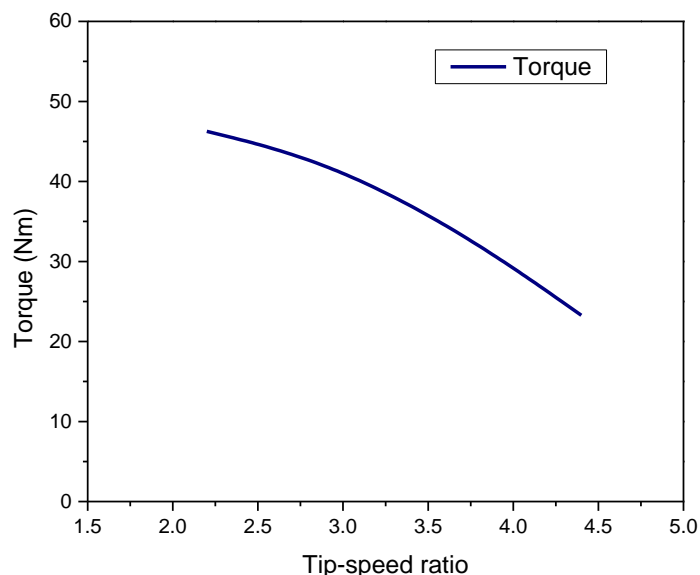

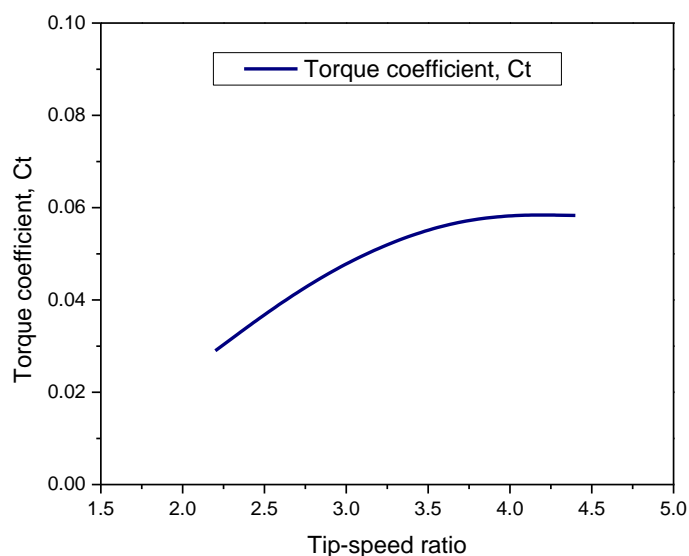**Fig. 5.** Torque output against tip speed ratio
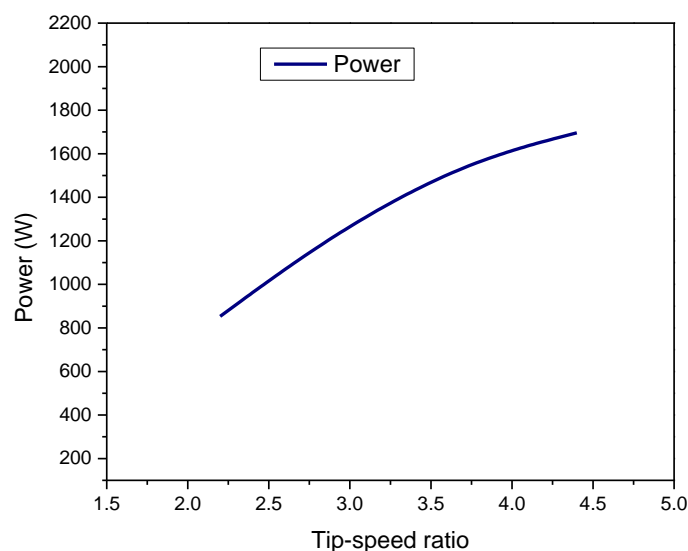

Fig. 6. Torque coefficient against tip speed ratio

4.3 Analysis of Power and Power Coefficient

The power coefficient is determined from the power obtained from simulations computed through the ANSYS Fluent solver. Figure 7 depicts a graph of power output in the Watt versus tip speed ratio. According to a study by Magdi Ragheb & Ragheb, (2012) [30] the power coefficient is defined as the proportion of the power harvested by the turbines to the available energy in the wind stream, and thus, using the aerodynamic analysis theory and the numerical value of the torque

coefficient of the bionic blades obtained through three-dimensional simulations in the computational fluid dynamics ANSYS software, the power coefficients can be calculated and analyzed in a graph as shown in Figure 7. Figure 8 depicts the numerical value of the power coefficient as that function of tip speed ratio, in which the power coefficient result of the bionic blades is evaluated and represented graphically. From the graph, it can be realized that the value of the power coefficient peaks at the value of the tip speed ratio of 3.67, similar to that of the torque coefficient. The lowest value of the power coefficient also lies at the value of the tip speed ratio of 2.20. The highest value of the power coefficient is 0.2605 meanwhile the lowest value of the power coefficient is 0.0638. Therefore, it can be construed that in the current study, the relationship between the torque coefficient and the power coefficient is of a directly proportional relation where the former increases and the latter does too.

The ANSYS Fluent post-processing tool is useful for depicting the free flow pattern of fluid through the computational fluid dynamics system at varied velocity parameters. It is easier to view the influence of velocity and pressure on research findings by applying pressure, velocity and streamline contours to the model. To that end, pressure, as well as velocity contours, are used to analyze the influence of pressure and velocity. Contour lines are lines of magnitude for a test vector, and a profile plot projects these contours off from the edge along an eigenvector by an equation relating to the plotted variable's significance at each point on the surface. The following figures display the pressure contour, velocity contour and the streamline of the bionic blade obtained after the simulations of the bionic blade under the velocity of 10 ms^{-1}. Figure 9 visibly designates that those greater pressures eventuate at the leading edge of all blades. This evidenced that when the velocity increased, a pressure decrease occurred around all of the blades' leading edges. A study by Young, (1976) [31] deduced that by conferring to the Bernoulli principle, increasing velocity causes a reduction in pressure. Therefore, as a direct consequence, the greater the air velocity, the smaller the pressure where the pressure of the flow of air over an airfoil diminishes and the pressure loss across the upper layer is significantly larger than the rapid depressurization throughout the bottom surface. Meanwhile, as Figure 10 compared to Figure 9 it can be observed that where the pressure gradient is low, the velocity is high. This results in a lift force as stated by Young, (1976) [31].

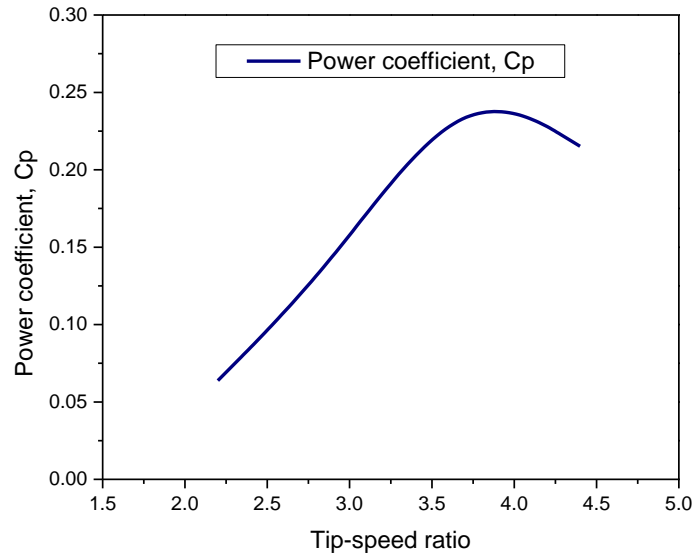**Fig. 7.** Power output against tip speed ratio

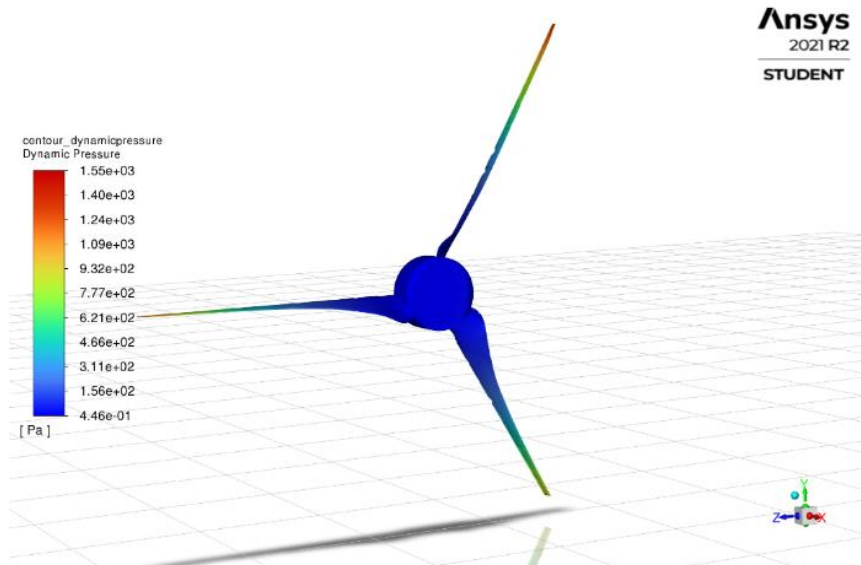**Fig. 8.** Power coefficient against tip speed ratio

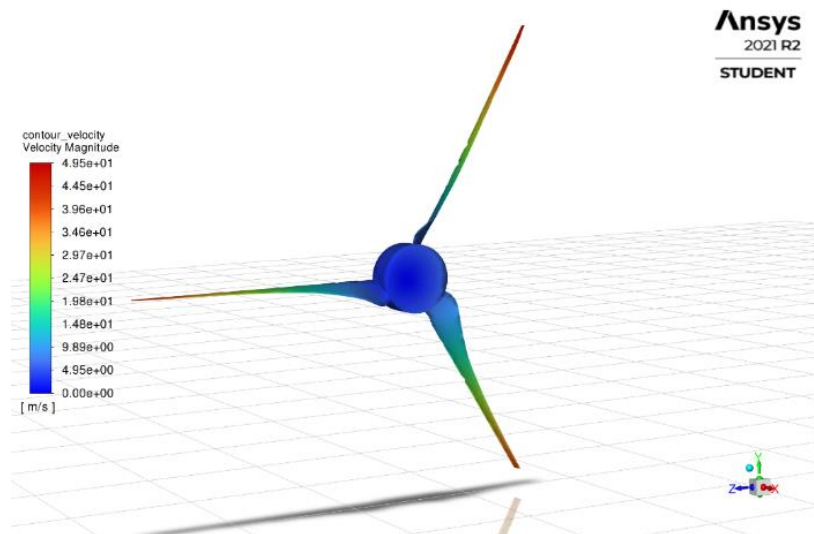**Fig. 9.** Pressure contour at 10 ms-1 inlet velocity

Fig. 10. Velocity contour 10 ms-1 inlet velocity

5. Conclusions

To investigate the performance of a bionic blade of a horizontal axis wind turbine, a simulation study in three dimensions using computational fluid dynamics was carried out. The software used to conduct the study was ANSYS Fluent 21, and a k-omega with a Shear Stress Transport model was chosen for all simulations. The model used for the study is a bionic blade configuration for a horizontal axis wind turbine based on the NACA 0012 airfoil with modification done to the angle of attacks, which was simulated using the computational fluid dynamics software at various inlet velocities and a constant angular velocity. Before progressing with the evaluation, a reliability analysis was completed in which a grid-independent study was performed to select the most appropriate mesh elements to use for improved accuracy. Moreover, the results were validated against the previous study's results with a relative error of about 10%. The results show that the bionic design was found to improve the overall performance of the standard NACA0012 blade design. Moreover, both power and torque coefficient outputs increase as the tip speed ratio (TSR) increases. However, the torque decreases as the TSR increases. In terms of power coefficient, the highest conversion efficiency was about 28% and it was achieved at 3.7 TSR. As a result, this study was considered successful because it met all of its objectives, which would include identifying the torque and power coefficient of the bionic blade of a horizontal axis wind turbine and correlating the results of the simulation of the bionic blade of a horizontal axis wind turbine to an earlier study.

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