Comparative CFD power extraction analysis of novel nature inspired vertical axis wind turbines

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Abstract. The aim of this paper is to investigate the power extraction performance of three biologically inspired vertical axis wind turbine. In this study, the proposed turbines are simulated in 2D in Ansys using URANS approach based on two equation turbulent transport model-SST. The turbines are simulated under the similar solver and numerical configuration. FVM is adapted to analyse the turbines assisted by sliding mesh method (SSM) under non-conformal mesh configuration. The proposed turbine is analysed in terms of moment and power coefficient. Design 1 and Design 2 indicated promising result for a feasible and practical wind turbine. However, Design 3 indicated poor performance in power coefficient at high RPM value.

1. Introduction

Energy harvesting signifies the development of industrial and power growth of economy and socio-economy in a region. Energy harvesting can be classified into two major groups which is renewable and non-renewable energy. Both forms of energy harvesting have different degrees of impact on the sustainability of environment and pollution index. The use of fossil fuels without proper regulation resulted in rise of greenhouse gases (GHG) [1]. In depleting fossil fuels resources and the rise of environment pollution as a result of fossil fuel harvesting [2]. Shamsuddin [3] stated that from 1990 to 2006 Malaysia GHG emission is 7.9% compounded average growth rate (CAGR) placing itself globally among the countries with high GHG emissions. Thus, several countries have taken initiative in the development of renewable energy facilities. As a matter of fact, in 2008 19% the global energy utilization originated from renewable energy resources [4].

Renewable energy can be further classified into several types, the most prominent renewable energy is hydro, solar and wind. The fastest growing renewable energy sector is wind energy harvesting. There are two type of wind power facilities which is onshore and offshore. Wind turbines are classified into two type vertical axis and horizontal axis wind turbines. In terms of lifecycle GHG emission of electricity generation facility, wind power is considered as clean energy with the one of the lowest GHG emission index. Research shows that offshore wind harvesting has the lowest GHG index in comparison to other renewable energy resources [5, 6]. Furthermore, research shows that GHG emissions of offshore wind power facilities are 48% less than onshore facilities [7].

Meanwhile in Malaysia research and development in wind power begin in early 1990’s. Inadequate research methodology, poor location selection, inadequate instrumentation and inconsistent data presented failed to convince the general public on the credibility of wind power harvesting in Malaysia [8]. Since most of the research conducted in Malaysia are centered to costal and onshore wind. Hence
there is insufficient data on offshore wind power facilities in Malaysia. Pursuant to The Ministry of Energy, Green Technology and Water (KeTTHA) industry in Malaysia adapted the Five Fuel Diversification Strategy energy mix which is which comprise of nature gas, coal, oil, hydropower and renewable energy. The aim of the policy is to control the use of fossil fuels and to promote the use of renewable energy. Under Renewable Energy Act 2011 or Act 725, Sustainable Energy Development Authority (SEDA) is founded to administrate the funds assigned in Feed-in tariff (Fit) for the development of renewable energy resources in Malaysia. On the other hand, 90% of power generation in Malaysia are dependent on fossil fuels which is governed by subsidies. Since the subsidies are politically motivated, it incurs an obstacle for the development of renewable energy [8]. Although currently FiT are not available for wind power harvesting, with the geographical properties of Malaysia makes it suitable for wind energy harvesting. As a matter of fact, Tenaga National Berhad (TNB) was the pioneer in wind power harvesting. TNB installed a 200 kW capacity wind turbine in Perhentian island, in which TNB claims that the power generated by the wind turbine can supply electricity for 200 households [9]. Ministry of Science, Technology and Innovation (MOSTI) supervised the project conducted by Sirim, iWind Energy (M) Sdn Bhd and Sri Waja Resources Sdn Bhd on hybrid photovoltaic solar and wind turbine. Universiti Malaysia Terengganu (UMT) installed 3.3 kW wind turbine in Setiu, Terengganu [10]. More information on the feasibility of wind power farms in Malaysia can be found in [11–13].

Due to the geographical coordinates of Malaysia at 1°22’N latitude and 103°55’E longitude of Southeast Asia. Malaysia experiences strong wind from the Indian Ocean in the Northeast and Southwest. Furthermore, Malaysia wind are mainly influenced by Northeast and Southwest monsoons. Where Northeast monsoon begins from November to March and Southwest monsoon occurs between June to September. Studies shows that, wind speed can reach up to 15 m/s in the east coast region during the monsoon seasons [14]. Furthermore, the occurrence of typhoon in Philippines, influences the wind speed to reach up to 10 m/s in the offshore regions of Sarawak and Sabah [15]. The average offshore wind speed potential is higher than onshore thus able to produce 50% higher electricity than onshore wind farm [16, 17]. In terms of onshore wind farm, the regions of Peninsular Malaysia have a low wind speed potential with an average monthly wind speed of 1.5 to 2 m/s. However, several authors stated that the assessment of wind speed data presented by researchers are inadequate due to lack of substantial data in wind speed assessment methodology and parameters. Methodology and parameters such as the apparatus and instrumentation used for wind data assessments, the height of study, proper air density of the selected location, capacity factor of turbine generator, numerical methodology in wind speed probability distribution analysis and etc.

Onshore wind turbines require vast land site for wind farm construction which is limited. However offshore facilities are not limited to construction space due to the vast spatial area in ocean. Wind behavior varies in onshore and offshore where, offshore wind is stronger, higher energy and less turbulent effect than onshore wind. Furthermore, offshore load centers are more effective in interstate power transmission than onshore sites. On the contrary, there are disadvantages to offshore wind facilities in comparison to onshore. Offshore wind power construction cost is approximately three times higher than onshore wind turbines. This this because site of offshore wind turbines has to constructed with stronger structures that extends to the ocean floor. The turbines were design to withstand strong wind and storm which often happens in the regions of oceans. Furthermore, extensive cost incurred on the power transmission lines which extends from offshore to the onshore power grids.

This aim of this study is to present a comparative study of three novel wind turbine for offshore regions of Malaysia based on power extraction analysis. Based upon the inconsistent wind speed in offshore region due to the seasonal weather influence. Hence a novel blade design is being proposed to accommodate the offshore wind speed potential of Malaysia. Based on the literature review, the overall optimal offshore wind speed potential in Malaysia is 8 m/s. Thus, the theoretical CFD numerical investigation of the proposed turbines were conducted relative to freestream velocity of 8 m/s in 2D. Since the proposed wind turbine at preliminary stage and to save numerical analysis time,
the study was conducted in terms of moment coefficient and power coefficient based on theoretical assumption.

2. Literature survey

2.1. Bio-inspired wind turbines
Herrera et al. [18] presented a horizontal axis wind turbine blade design inspired from Triplaris Americana tree seed. The author analyzed the curvature and aerofoil characteristic of the tree seed for the design of the proposed turbine. Result shows that, a minimum of 2.5 m/s is required to produce energy. Cognet et al. [19] presented a novel elastic bio-inspired wind turbine. The design is inspired by insect flight and plant reconfiguration. The author stated that the elastic bio-inspired blade had improve the efficiency by 35% in comparison to rigid blade design. Fish et al. [20] investigated tubercles of humpback whale’s flippers for the integration of wing model. The author stated that by the integration of tubercles on the wing model, the lift value had increased and consequently decreased the drag properties. It is found that the tubercles contributed to the improvement of the motion of flipper by passive flow. As manifested in literature survey, it shows that with proper design methodology and optimization could improvise the performance of the wind turbine.

3. Computational configuration

3.1. Parametric design adaptation
The parametric proposed models were prepared using equation (1) to equation (3) which is relative to vertical axis configuration. CATIA V5 feature such as surface morphing and wireframe modelling were used in the preparation of the models. The models are a result of hybrid fusion of elements from nature. A novel approach has been developed to design and develop a physical design feature of wind turbine by the combination of aerodynamic and non-aerodynamic elements. CFD numerical analysis were conducted to test the credibility of the algorithm in generating feasible and practical wind turbine design for offshore regions. Since the proposed methodology in preliminary stage, the simulations are conducted in 2D in order to save computational load. In this study, two types of aerodynamic configuration of wind turbine is being modelled which is drag and lift type. The presented designs are model under the similar design configuration.

As expressed in equation (3), the swept area of the turbine, \( S_A \), is the product of rotor diameter, \( D_r \), and blade height, \( H \). Since the simulation approach is in 2D, the blade height is set to 1 m due to the default setting in ANSYS [21, 22]. \( A.R \) represents the aspect ratio of the turbine. Since the aim of the study is to analyse the aerodynamic performance of blade, no specific attention was given to the design of rotor hub. For simplicity the proposed models are labelled as Design 1; Design 2; Design 3 as shown in figure 3; figure 4; figure 5 respectively. Design 1 is modelled in lift aerodynamic configuration where else Design 2 and Design 3 are drag driven wind turbines. Design 1 is design based on National renewable energy laboratory (NREL) S819 aerofoil. NREL administrate the classification of aerofoil type according to aerofoil type and families of aerofoils. On the other hand, Design 2 is designed relative to Savonius wind turbine configuration. In order to simplify the analysis, design parameter such as blade height, \( H \), overlap ratio, \( O.R \), and rotor diameter, \( D_r \), of a conventional Savonius wind turbine, were adapted for the modelling of Design 2. Figure 1 shows the proposed parametric blade configuration of Design 2 in comparison to traditional Savonius blade. Meanwhile, Design 3 is a curved non-uniform drag driven blade. The blade is composed of novel shaped cavity bucket vane as shown in figure 2(a). The blade is a result of cavity vane at three different sizes by surface multi-section labelled as A, B and C as illustrated in figure 2(b). Detailed information on Design 3 parameters and simulation configuration can be found on research presented by Ashwindran [23].
\[ A.R = \frac{H}{D_r} \]  
\[ S_{A-Actual} = D_r \times H \]  
\[ S_{A-simulation} = D_r \times H \]

**Figure 1.** Parametric proposed shape of Design 2 and Savonius configuration.

**Figure 2.** (a) Cavity vane profile of Design 3 and (b) Cavity vane A, B, C with different size.

**3.2. Design configuration**

Figure 3 shows the 3D model of Design 1 inspired by epilobium hirsutum and maple seed. The design is separated into two segments as shown in figure 3(a). The top section of the turbine is adapted from epilobium hirsutum and the base section is adapted from maple seed. The blade is composed of NREL S819 aerofoil twisted at 4° angle of attack (AoA). The turbine consists of four blade spaces at 90° to each other. The turbine has a vertical height, \( H \), of 1.33 m; rotor diameter, \( D_r \), of 1.6 m, swept area, \( S_d \), of 2.93 m², and aspect ratio, \( A.R \) of 0.83. Meanwhile, the solidity of the airfoil, \( \sigma \), is 0.25, the aerofoil thickness is 56 mm and chord length is 310 mm. As shown in figure 3(b), the planar section labelled as \( C \) at the height of 0.8 from datum were selected for the simulation procedure. For more information on Design 1 can be found in research article presented by Ashwindran [24].
As shown in figure 4, the drag driven wind turbine blade is inspired by SPO algorithm and cycloid curve. In terms of complex geometry analysis, the most abundant design pattern in nature is the spiral geometry. Spiral geometry pattern can be found in flowers, plants, storm pattern, and the very shape of the Milky Way galaxy. This phenomenon even inspired mathematician such as Euler and Fibonacci to study its principals in geometry. Hence in this study, a modified SPO algorithm and cycloid curve were used to generate the desired blade shape in Savonius wind turbine configuration as shown in figure 4(a). More information on spiral configuration and algorithm can be found in [25]. In this study, the design feature of Savonius wind turbine from Sandia Laboratories [26] were used as benchmark to analyse the performance of the proposed wind turbine. Figure 4(b) shows the design configuration of Savonius wind turbine. Both the turbines are designed under the similar design parameters and configuration. The height of the blade, $H$, is 1 m, rotor diameter, $D_r$, of 0.9 m and overlap ratio, O.R of 0.1 m.

As for Design 3, the model is a hybrid fusion of three nature elements which is Albatross wing, tulip flower and pitcher plant. As aforementioned the developed algorithm merges aerodynamic and non-aerodynamic elements. The aerodynamic elements are the Albatross wing shape and tulip flower. Due to its large aspect ratio and unique wind shape the Albatross bird is regarded as one of the most aerodynamic bird [27]. Meanwhile, tulip petal curvature shape inspired the design of the proposed cavity vane. The pitcher plant vane configuration was adapted in order to generate curved polynomial blade as shown in figure 4(a) and 4(b) with regards to Design 3, the mid-section was selected for the simulation procedure.
3.3. Grid topology and domain configuration

FVM approach were adapted to analyse the proposed wind turbines. FVM is widely used by the wind turbine research community. FVM is a robust model in analyzing rotating machinery by means of analyse the model in a finite volume. FVM works by converting partial differential equation (PDE) into algebraic equation. It analysed finite volume by surface integral using divergence terms.
Due to the complexity presented by each of the geometry, separate domain at different dimension was modelled. For this study, sliding mesh method (SMM) were used to study the turbine. Relative to FVM methodology the domain is modelled as a virtual wind tunnel. The virtual wind tunnel is constructed relative to the rotor diameter of the respective wind turbine. Figure 6(a) shows the general structure of the virtual wind tunnel. The virtual wind tunnel consists of two domains which is main domain and sub-domain. The main domain consists of static mesh configuration. The sub-domain is considered as moving mesh. In order to prevent node connectivity between static and moving mesh domains, non-conformal mesh configuration was utilized. The main and sub-domain is separated by an interface as shown in figure 6(a). The virtual wind tunnel consists of inlet, outlet and two symmetry walls. The virtual tunnel is discretized with unstructured grid. The domain is defined with freestream velocity of 8 m/s from left to right of the virtual tunnel. Figure 6(b) shows the sub-domain of the proposed wind turbines. All the turbines are simulated under the similar simulation configuration. The difference is in the dimension of the virtual wind tunnel and mesh metric. The domain is discretized under fine and medium grid in order to analyse the grid sensitivity.

3.4 Boundary condition and solver configuration
FLUENT 16.2 were utilized to analyse the flow behaviour of the turbines. In order to simplify the study, the simulations are conducted in a specific direction. Relative to boundary condition and solver configuration, the proposed wind turbine is simulated under the influence of 8 m/s at the inlet from left to right of the virtual wind tunnel. The exit region is set as outlet pressure with 0 pascal. As for the blade regions of the respective wind turbine, were defined as no slip condition. In order to save computational load, the side walls are defined as symmetry type with free slip condition. This boundary condition would avoid solid blockage effect [28, 29]. Turbulent parameters such as turbulent intensity, $I$, and turbulent viscosity, $\mu/\mu$, are defined based on empirical observation of residual oscillation behavior. It is found that, Design 1 and Design 2 indicated stable residual oscillation with $I=5\%$ and $\mu/\mu=10\%$. Conversely, Design 3 exhibited unstable residual oscillation behavior under $I=5\%$ and $\mu/\mu=10\%$ turbulent values. Therefore, the turbulent parameters were numerated based on
equation (4) to equation (8). Hence the turbulent intensity, \( I \), is 2.8 % and turbulent viscosity, \( \mu_t/\mu \), is \( 1.71 \times 10^3 \) for Design 3.

In terms of solver configuration, the turbines are simulated under unsteady formulation. All the turbine is simulated using pressure-based solver based on transient formulation formulation. The proposed turbine is studied under the influence of three turbulent transport formulation such as \( k-\omega \); realizable with scalable wall function \( k-\varepsilon \); and SST for turbulent sensitivity study. It is found that, SST indicated more stable numerical oscillation in comparison to the counterparts. Hence SST model were chosen for the rest of the simulation procedure. Several authors suggested SST turbulent transport model are suitable for CFD analysis pertaining to rotating device because of blending functions of \( k-\omega \) and \( k-\varepsilon \) [30–32].

In order to save computational load, URANS approached were adapted to numerate NSE. Since URANS model is the summation of fluctuating and mean components of flow properties, therefore it would be a suitable mathematical model for analyzing the model at preliminary stage. COUPLE scheme was used for all the turbines for pressure velocity coupling. For Design 1 and 2 the Courant number is set to 10, where else for Design 3, the Courant number is set to 20. The explicit relaxation (ERF) factor and under relaxation factor (URF) is set accordingly based on empirical observation of the gather result and numerical behavior.

The expression for reference area of the turbine is defined based on the rotor diameter of the respective dimension of the turbine. The turbine is studied under wide range of RPM and tip speed ratios in order to study the moment coefficient and power coefficient performance. In this paper only numerical values from one tip speed ratios will be presented.

Turbulent intensity, \( I \)

\[
I = \frac{u'}{\bar{u}} = 0.16 (Re)^{-\frac{1}{8}} \quad (4)
\]

Turbulent kinetic energy, \( k \)

\[
k = \frac{3}{2} \left( u_{\infty} I \right)^2 \quad (5)
\]

Turbulent viscosity, \( \left( \frac{\mu_t}{\mu} \right) \)

\[
\frac{\mu_t}{\mu} = \left( C_p \right) \rho \frac{k^2}{\mu \varepsilon} \quad (6)
\]

3.5. Numerical parameters

Since the turbines is studied based on computational numerical analysis and theoretical assumption. Betz limit theoretical value were used as benchmark the power coefficient result of the proposed turbines. Pursuant to Betz theory, the maximum theoretical power coefficient \( C_p \) limit of any kind of wind turbine is \( C_p=0.593 \) regardless to its design and configuration. Which means the maximum amount of kinetic energy that can be extracted from the flowing wind by the wind turbine is 59.3%.

The proposed turbine is analysed in terms of moment coefficient, power coefficient and tip speed ratio. The numerical parameters are numerated based on equation (7) to equation (9). The equation is expressed relative to turbine properties such as rotor diameter, \( D_r \), rotor radius, \( R_s \), and swept area, \( S_A \).

Moment coefficient

\[
C_m = \frac{M}{\frac{1}{2} \rho S_A U_{\infty}^2 R_s} \quad (7)
\]

Tip speed ratio
\[
TSR(\lambda) = \frac{\omega \times \left(\frac{D_0}{2}\right)}{U_\infty}
\]

Power coefficient
\[
P = C_m \times TSR
\]

4. CFD numerical results

As aforementioned the turbine is discretized under fine and medium mesh configuration. Fine and medium mesh indicated trivial dissimilarities. Hence rest of the simulation is carried out under medium mesh configuration. Furthermore, \(Y^*\) study indicated adequate result relative to the turbulent transport model and grid configuration. \(Y^*\) presented an average facet result along the blade region under surface integral option, where the score is within region of \(Y^* > 30\) falls in log-law region layer. This is adequate for two equation turbulent transport model-SST and for the discretized grid at preliminary stage. The result indicated good convergence and stable numerical oscillation.

Figure 7 presents the moment coefficient result of Design 1; Design 2; Design 3 at 100 RPM for three revolutions. Result shows that Design 1 and Design 2 indicated stable numerical oscillation. On the contrary, Design 3 exhibited unstable numerical behaviour. Under the influence of constant 8 m/s Design 3 indicated poor performance at high RPM. This is due to the geometry of proposed blade, where the returning incurs high adverse pressure which consequently affected the advancing blade. The presented blade geometry of Design 3 consists of sharp edges which limits the blade for moment generation. Furthermore, the non-uniform geometry is responsible for the rise of form drag along the blade region which resulted in negative moment and power coefficients. The pressure on advancing cavity vane is significantly less than the returning blade. Unstable pressure distribution can be observed along the blade regions. Moreover, the large swept area worsens the credibility of the turbine in moment and torque delivery. Vorticity magnitude indicated strong and high turbulent internal vortices on the advancing blade, which makes it difficult for the advancing blade to initiate rotation. However, at low RPM the turbine indicated positive moment and power coefficient results due to the drop-in form drag and static pressure on retuning blade of the turbine. Design 3 at \(\lambda=0.2\) generated an average moment coefficient result of \(C_m = 0.143304\) and at \(\lambda=0.3\) indicated \(C_m=0.0847\). Meanwhile at \(\lambda=0.9\) the \(C_m = -0.104\).

On the country, Design 1 and 2 performed well at high RPM under the similar freestream velocity. Moment and power coefficient result of Design 2 is compared against a traditional Savonius wind turbine, which is simulated under the similar configuration. At \(\lambda=0.59\) (100 RPM) Design 2 generated a moment coefficient of \(C_m=0.401881\), where Savonius indicated a moment coefficient result of \(C_m=0.375023\). Concave and convex blade indicated stable pressure distribution. In terms of flow field properties, strong stagnation point was observed on the convex side of the proposed blade in comparison to Savonius wind turbine. Furthermore, the outer side of the concave blade of the proposed design indicated slightly higher pressure than the Savonius turbine. This explain the small percentage of improvement. The modification of blade and reduction in blade height of the proposed turbine resulted in higher moment coefficient by 4%.

Design 1 outperformed Design 2 and 3 by means of power extraction and moment coefficient. At \(\lambda=0.85\) (100 RPM) the proposed turbine indicated mediocre result. As the RPM value increase the performance of the turbine in energy capturing increases till the turbine reaches its peak performance. Figure 8 shows the power coefficient result of Design 1; 2; 3 at different tip speed ratios. As shown in figure 8, the peak performance of Design 1 is at \(\lambda=1.7\) (200 RPM), with average moment coefficient result of \(C_m=0.153991\). The performance start to decline as the RPM increases after the peak value. Similarly, the performance of Design 2 decline after the peak \(\lambda=0.59\). As for Design 1 at low RPM, the returning blade exhibited a strong wake property at the leading edge of the aerofoil which consequently affected the advancing blade. Since Design 1 operates in fixed AoA, the performance of the turbine can be further improved by altering the AoA in order to increase the lift generation.
5. Conclusion

This paper investigated the numerical performance of three biologically inspired wind turbine based on power extraction and moment coefficient. Design 1 and Design 2 indicated satisfying result for a feasible power extraction wind turbine. As for Design 3 further design modification is required in order to reduce the high adverse pressure on the returning blade region. Design 2 indicated higher efficiency in power extraction in comparison to conventional Savonius wind turbine. The proposed blade of Design 2 outperformance Savonius wind turbine in moment coefficient by 4% at $\lambda=0.59$. Meanwhile lift driven Design 1 turbine indicated stable power extraction at high RPM. However, in order to improve the performance of Design 1, the AoA of blade needed to be altered to ensure more lift is generated by the rate of change of momentum of flowing across the aerofoil as it faces the freestream wind. Since the simulation is conducted in specific direction, experimental result will be validated against the simulation result in the future for validation and verification.
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