Experimental and simulation of aerodynamic performance of the small-scale wind turbine blades for usage in Malaysia

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Abstract. The enormous growth in manufacturing technology has contributed to the global climate change as well as the extinction of the conventional energies. The effort of replacing these energies with renewable energy found that the energy return of investment is high for wind energy. While the required minimum wind speed for operating efficient wind turbine is 3.5-7 m/s, certain locations in Malaysia meets the requirement for implementing the wind turbine. In this paper, a comparison is made between two wind turbines with equal blade length: the first turbine blade (TB1) does not use any airfoils while the second turbine blade (TB2) applies airfoils of SG6042, NACA4412, NACA5510 after undergoing shape optimization process. Both blades were fabricated using a 3D printing machine. Aerodynamic performances of the TB1 were studied through experimental work i.e. the turbine blade was given wind, flowing at several speeds in a wind tunnel. For the TB2, Q-blade software was used for conducting the shape optimization process and determining its aerodynamic performances. It was decided to use several airfoils throughout the blade length of the TB2. Experimental work was also conducted on the TB2 similar to the TB1. Analysis from Q-blade software showed that TB2 produces power efficiency of around 40%. It was found from the experiment that the TB2 gives twice amount of power compared to TB1.

1. Introduction

The growth of technologies in manufacturing are enlarging in nowadays industries. As such, the conventional energy sources such as oil, gas and coal are at the age of extinction while at the same time causing the global climate change due to the emission of CO₂ as well as SO₂ [1-5]. Consequently, great effort has been made to replace these conventional energy sources with renewable energy. Statistical graph in Figure 1 [6] indicates global consumption of renewable energy in terawatt-hours (TWh) per years is growing rapidly throughout the last decades. A study showed that, with the development of technologies in renewable energy, the energy returns of investment, which is defined as the ratio of cumulative electricity generated to the cumulative primary energy required is high for wind energy as compared to other renewable energy sources, leading the wind energy towards a more economically viable solution for power generation [7]. Wind energy is essentially produced by a specialized and designated conventional wind turbine that will generate particular amount of electrical power as it transforms kinetic energy of wind to mechanical energy by linking to the generator of the wind turbine.
A study indicated that China and the USA have been leading the world in wind energy consumption [6]. But does Malaysia have the potential in producing electrical energy by using a small scale basis of wind turbine? Unlike other countries with big wind energy consumption, the wind power in Malaysia is limited where the wind has the mean speed of not more than 2 m/s as the wind does not flow consistently and varies according to months and regions [8]. The minimum speed required for a wind turbine to be efficient in generating electrical power is when the flow of the wind is consistent around 3.5-7 m/s and occasionally between 3-25 m/s. However, Malaysia has two major seasons in a one-year period which are the southeast monsoon that occurs from May/June until September while having the wind speed below 7 m/s and northeast monsoon that occurs from November until March where the wind speed has the capability of reaching 15 m/s. Mekhilef et al. [9] highlighted that there were several potential sites in Malaysia to generate off-grid wind energy power. The wind turbine must be within a small scale category to ensure the blade is self-rotatable, highly efficient for best power generation and having durably strong structure to refrain from buckling and other failures. Furthermore, it is certainly helpful if the wind energy works in combination with other renewable energy such as solar energy to produce electricity. Henceforth, it is crucial that the design of wind turbine blade to be aerodynamically efficient in converting wind energy and structurally effective to resist wind force.

A review on the small scaled wind turbine was conducted by Roslan et al. [10]. Bai et al [11] conducted an aerodynamic study on wind turbines based on the BEM method while considering the stall delay model, Viterna-Corrigan stall model, tip-loss factor, and centrifugal pumping effect. While the cord length was maintained throughout the length, the pitch angles were made to vary linearly with the blade span. The torque and thrust obtained here showed good correlation with the CFD results. In a
study by Shuwa et al [12], a micro HAWT was tested experimentally and using the BEM theory. Using the wood blade, it was found the experimental value is reduced by 28% as compared to the theoretical results.

In this study, an improvement is intended in term of aerodynamic performance for the firstly fabricated wind turbine (TB1). This TB1 does not use any forms of airfoils. A new turbine blade (TB2) having the same length has been designed using the Q-blade software where this TB2 considered several airfoils in the design stage. Through the aerodynamic performance analysis, the airfoils that give the best blade efficiency are selected. The performance of the first and second turbine blades are compared experimentally, by passing through them wind that flows at several speed in a wind tunnel.

2. Materials and methods
In this study, the aerodynamic performance comparison is made between the TB1 and TB2. Recalled that the blades for TB1 do not apply any airfoils while blades for TB2 use several airfoils after undergoing shape optimization process. Both blades are 1 m length and belong to the category of small-scaled turbine blade that should fit the Malaysian low wind speed condition. In this section, both blade dimensions are elaborated. The five types of airfoils considered in the design of the TB2 are given. Some of the theoretical methods behind the aerodynamic performance analysis of the turbine blades in the Q-blade software are explained.

2.1. The wind turbine component
Both wind turbines use the same the same tower, nacelle and base such as shown in Figure 2(a). Here the wind turbine shown are the TB2. All components are made of ABS plastic and were fabricated through a 3D printing machine, Raise3D, model Pro2 available at the Advanced Precision lab, MIJIT, UTM Kuala Lumpur, presented in Figure 2(b). The dimensions of these wind turbine components are shown in Figure 3. The specifications of the ammeter and generator are shown in Table 1.

![Figure 2. (a) Wind turbine construction (b) The Raise 3D, Model Pro2 3D printer](image)
2.2. The design of TB2
The blade of TB2 was designed using the Q-blade software where shape optimization process was conducted. Five airfoils were considered to be applied for the TB2. Those were NACA 4412, NACA 5510, NACA 63412, S809 and SG6042. The selection was made based on the good performances shown by these airfoils in previous researches [13-16]. Through the Q-blade software, the dimensions of the blade cross-sections with different airfoils can be compared. Figure 4 and Table 2 shows that the S809 airfoil has the highest thickness while the NACA 63412 has the highest chamber.

Figure 3. The dimensions of wind turbine components

Table 1. Specifications for the ammeter and generator

| Equipment       | Model                                      | Specifications                                      |
|-----------------|--------------------------------------------|---------------------------------------------------|
| Generator       | Wind DC Generator Hand Dynamo 5v/6v/12v/24v 1500mA 20W Motor | Motor out. Vol.: 5V-24V Max. Out. Current: 1500mA Max. load Power: 20 watts |
| Multi-meter     | ZOTEK/ ZOYI ZT-X Digital Multi-meter        |                                                   |
| Wind tunnel     | De Lorenzo SPA – DL WT25 Open circuit wind tunnel | Max. speed: 30m/s Closed, rectangular test section Cross section: 1350mm (w) x 1000mm (h) x 9000mm (l) Overall: 22.7m x 3.4m x 3m |
Figure 4. Geometric comparison of the considered airfoils

Table 2. Geometric comparison of the considered airfoils

| Name      | Thick (%) | at (%) | Chamber (%) | at (%) | Points |
|-----------|-----------|--------|-------------|--------|--------|
| NACA4 412 | 12.00     | 29.10  | 4.00        | 39.50  | 99     |
| NACA 5510 | 10.00     | 29.10  | 5.00        | 50.70  | 99     |
| NACA 63412| 9.39      | 27.90  | 7.15        | 0.00   | 69     |
| S809      | 20.99     | 38.30  | 0.99        | 82.30  | 66     |
| SG6042    | 10.00     | 33.51  | 3.75        | 47.91  | 81     |

Furthermore, through the XFOIL functionality of the Q-blade software, the coefficient of drag ($C_D$), the coefficient of lift ($C_L$) and the sliding ratio ($C_L/C_D$) for all airfoils can be determined. Following that the shape optimization process which is based on the boundary element momentum (BEM) theory can be conducted using the Q-blade to determine the best shape of the blade that gives the best and most consistent power coefficient of the blades.

2.3. The experimental works

The wind turbine TB1 and TB2 were given wind, flowing at several speeds in an open circuit wind tunnel to determine the power it may produce. The wind tunnel, see Figure 5, with specifications given in Table 1 is available at the UTM, Kuala Lumpur. The results of the power and power efficiency were the objective of the tests. Three measurements were taken for each case.

Figure 5. The open circuit wind tunnel
2.4. The BEM method
Aerodynamic performance analysis has been conducted on the TB2 with five airfoils. A wind turbine blade consists of airfoils that produce lift by virtue of the pressure difference seen in the actuator disc type of analysis. The blade design analysis includes the momentum theory and the blade element theory that when combined, it is well known as the blade-element momentum (BEM) theory. In order for the blade to reach its optimum performance, suitable and best airfoil for blade from the analysis of blade design theory must be chosen. The momentum theory refers to a control volume analysis of the forces at the blade based on the conservation of linear and angular momentum while a section of the blade which refers to an analysis of forces as a function of blade geometry is called the blade element theory where it is to determines the forces on the blade based on its characteristic of lift and drag force. By analyzing the aerodynamic response of the blades to the flow in which they are immersed, the effect of each elemental ring of the blade can be described.

3. Results and discussions
3.1. Aerodynamic performance of the second turbine blade
The Q-blade software has been used to conduct aerodynamic analysis on the TB2 blades each with five different airfoils. At the first stage, the sliding ratio, $C_l/C_d$ against angle of attack, $\alpha$ graphs were plotted such as in Figure 6. This is an important plot such that we are seeking for the airfoils that give the maximum $C_l/C_d$ over a period of time as this will increase the power coefficient of the TB2. It can be seen that except for S809 airfoils, the airfoils have given high values of power coefficient of around 30-40 such as shown in Table 3. For this reason, these airfoils will together be used for this TB2.

![Figure 6. The plots of $C_l/C_d$ vs angle of attack, $\alpha$, for several airfoils](image-url)
Table 3. The aerodynamic performance of the airfoils

| Type         | Sliding ratio, C_l/C_d | Angle of Attack, α | Coefficient of Power, C_p |
|--------------|------------------------|--------------------|---------------------------|
| NACA 4412    | 55.3                   | 9.0                | 0.394                     |
| NACA 5510    | 68.9                   | 7.5                | 0.394                     |
| NACA 63412   | 37.0                   | 3.5                | 0.260                     |
| S809         | 22.2                   | 10.0               | 0.220                     |
| SG6042       | 63.1                   | 6.0                | 0.410                     |

Having selected the airfoils, shape optimization process was conducted on the turbine blade using the Q-blade software. After several adjustments, the cord length, twist angle and the airfoils correspond to each blade element of the TB2 are as shown in Figure 7 and Table 4.

3.2. The experimental of aerodynamic performance

Experiments were conducted on the TB1 and TB2 using a wind tunnel. The results are given in Table 5 and Table 6 for TB1 and TB2, respectively. It shows an obvious increase in the power produced by TB2 that have undergone shape optimization process as compared to TB1 that has not used any airfoils. Table 7 shows that the improvement in term of power produced was high as more than 100% for the wind velocity of 10 m/s.

![Figure 7. The dimension of TB2 after shape optimization process](image)

4. Conclusion

The aerodynamic performance of small-scaled horizontal wind turbines that are suitable for low wind speed countries like Malaysia have been investigated in this study. Specifically, a comparison is made between the aerodynamic performance of the TB1 that used no airfoils for its blades and TB2 that applied several airfoils for its blades after undergoes shape optimization process using the Q-Blade software. The shape optimization process has given the dimensions of the TB2 blade along its length. The experiments showed that the optimized turbine blade i.e. the TB2 has shown the improvement of the power produced by the blade is as high as 106%.
Table 4. The dimension of TB2 after shape optimization process

| No. | Radial Position (m) | Chord length (m) | Twist (°) | Foil       |
|-----|---------------------|------------------|-----------|------------|
| 1   | 0.000               | 0.030            | 25.07     | Circular Foil |
| 2   | 0.010               | 0.030            | 20.96     | Circular Foil |
| 3   | 0.015               | 0.030            | 19.31     | Circular Foil |
| 4   | 0.030               | 0.028            | 9.43      | SG6042     |
| 5   | 0.040               | 0.025            | 7.50      | SG6042     |
| 6   | 0.050               | 0.023            | 5.93      | SG6042     |
| 7   | 0.060               | 0.021            | 4.63      | SG6042     |
| 8   | 0.070               | 0.019            | 3.53      | SG6042     |
| 9   | 0.080               | 0.018            | 2.59      | SG6042     |
| 10  | 0.090               | 0.016            | -1.22     | NACA 4412  |
| 11  | 0.100               | 0.015            | -1.92     | NACA 4412  |
| 12  | 0.110               | 0.014            | -2.54     | NACA 4412  |
| 13  | 0.120               | 0.013            | -3.09     | NACA 4412  |
| 14  | 0.130               | 0.012            | -3.57     | NACA 4412  |
| 15  | 0.140               | 0.012            | -4.01     | NACA 4412  |
| 16  | 0.150               | 0.011            | -4.41     | NACA 4412  |
| 17  | 0.160               | 0.011            | -4.76     | NACA 4412  |
| 18  | 0.170               | 0.010            | -5.09     | NACA 4412  |
| 19  | 0.180               | 0.010            | -5.39     | NACA 4412  |
| 20  | 0.190               | 0.009            | -5.66     | NACA 4412  |
| 21  | 0.200               | 0.009            | -5.91     | NACA 4412  |
| 22  | 0.210               | 0.009            | -6.14     | NACA 4412  |
| 23  | 0.220               | 0.008            | -6.36     | NACA 4412  |
| 24  | 0.230               | 0.008            | -5.06     | NACA 5510  |
| 25  | 0.240               | 0.008            | -5.25     | NACA 5510  |
| 26  | 0.250               | 0.007            | -5.42     | NACA 5510  |

Table 5. The experimental results for TB1

| Wind Speed (m/s) | Voltage (V) | Average Voltage (V) | Current (mA) | Average Current (mA) | Average Power (Watt) |
|------------------|-------------|---------------------|--------------|----------------------|----------------------|
| 5                | 0.823       | 0.811               | 0.815        | 134.9                | 152.8                |
| 7                | 1.013       | 0.981               | 1.022        | 170.5                | 210.7                |
| 10               | 1.29        | 1.288               | 1.268        | 200.6                | 221.3                |
| 12               | 1.511       | 1.528               | 1.536        | 330.9                | 350.4                |

Table 6. The experimental results for TB2

| Wind Speed (m/s) | Voltage (V) | Average Voltage (V) | Current (mA) | Average Current (mA) | Average Power (Watt) |
|------------------|-------------|---------------------|--------------|----------------------|----------------------|
| 5                | 1.008       | 1.023               | 1.030        | 196.1                | 194.2                |
| 7                | 1.073       | 1.291               | 1.301        | 242.3                | 243.1                |
| 10               | 1.856       | 1.840               | 1.850        | 323.3                | 316.4                |
| 12               | 2.230       | 2.230               | 2.200        | 402.6                | 400.3                |
Table 7. Power comparison between TB1 and TB2

| Wind Speed (m/s) | Average power TB1 (Watt) | Average power TB2 (Watt) | % of increase |
|------------------|--------------------------|--------------------------|---------------|
| 5                | 0.125                    | 0.198                    | 58.4          |
| 7                | 0.213                    | 0.313                    | 46.9          |
| 10               | 0.284                    | 0.585                    | 106.0         |
| 12               | 0.534                    | 0.889                    | 66.5          |

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