An aerodynamic performance analysis of a perforated wind turbine blade

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Abstract. Wind power is one of the important renewable energy sources. Currently, many researches are focusing on improving the aerodynamic performance of wind turbine blades through simulations and wind tunnel testing. In the present study, the aerodynamic performance of the perforated Eqwin blade (shell type blade) is investigated by using numerical simulation. Three types of slots namely circular, horizontal rectangular and vertical rectangular were evaluated. It was found that the optimum angle of attack for a perforated shell type blade was 12º with maximum $C_{l}/C_{d}$ value of 6.420. In general, for all the perforated blade cases, $C_{l}/C_{d}$ tended to decrease as the slot size increased except for the circular slot with 5 mm diameter. This was due to the disturbance of the airflow in lower side region which passed through the bigger slot size. Among the modified slots; the circular slot with diameter of 5 mm would be the best slot configuration that can be considered for blade fabrication. The $C_{l}/C_{d}$ obtained was 6.46 which is about 5% more than the value of the reference blade. Moreover, the introduced slot would also reduce the overall weight of the blade by 1.3%.

1. Introduction

Many countries worldwide including Malaysia recognize that the current energy trends are not sustainable and thus a better balance between energy securities, economic development and environmental protection must be found [1]. Power has been extracted from the wind over hundreds of years with historic designs, typically large, heavy and inefficient in terms of overall energy conversion process. A greater understanding of aerodynamics and advances in material led to the improvement of wind energy harvesting process. Nowadays, wind power devices are used to produce electricity parallel with high demand in power source and commonly termed as wind turbine.

Currently, wind energy is considered as one of the economical alternatives that meet the needs of modern societies, by protecting the atmosphere from the adverse consequences of global warming. The Malaysia’s economy has witnessed an active growth in the last decades. Consequently, the demand for energy has also increased [2].

The potential of wind energy generation however depends on the availability of the wind resource that varies with the time of day, season, height above ground and most importantly the type of terrain [2]. Proper sitting in windy locations away from large obstructions enhances a wind turbine's performance [3]. The energy available in the wind varies as the cube of the wind speed so an understanding of the characteristics of the wind resource is critical to all aspects of wind energy exploitation process [4].

Apart from environmental problems, technological problems such as selecting proper aerofoils that have a high lift to drag ratio generally increase the wind turbine efficiency. As the aerodynamic lift is the force responsible for the power yield generated by the turbine and therefore it is essential to maximize this force using appropriate design. A resistant drag force which opposes the motion of the blade is also generated by friction which must be minimized [5].
However, the wind potential in Peninsular Malaysia can generally be classified as Class 1 wind categories [1]. Note that, according to national renewable energy laboratory (NERL) average wind speed that falls between 0 - 4.4 m/s at 10 m height above the ground is considered Class 1. Thus a low wind speed wind turbine based on the average wind speed of Malaysia has been successfully designed, built and tested. This particular wind turbine is called “Eqwin Turbine”. Eqwin is the short form of Equatorial Wind and this particular type of wind turbine is not only good for Malaysia but also for all countries in the equatorial regions [6].

With an introduction of a low wind speed turbine based on the average speed of Malaysia called Eqwin blade, the wind power generation in Malaysia was realized. Since wind speed is low and critical, performance of the wind turbine blade to capture the wind energy becomes important. A modification or improvement on the blade design is expected to improve the blade performance in terms of wind streamline on the blade surface and a movement of the blade against gravity (weight).

The modification is done by adding slot of various shapes and sizes and then the performance of lift versus drag is evaluated. It is believed that introducing slots will not only enhance the aerodynamic characteristics of the blade but also reduce the ever rising material cost and be able to compete with many other existing energy sources [7]. The evaluation was carried out using the computational fluid dynamic (CFD) software; Ansys and the results of modified blade are compared to the reference blade which is current shell type blade. Finally, the optimum blade design or modification is proposed.

As such, this study intends to evaluate the aerodynamic performance of the shell type blade by determining optimum angle of attack (AOA) and lifts to drag coefficients ratio, and proposes a modified optimum design. This shell type blade is almost identical with the infamous Eqwin turbine blade with a slight change in terms of dimension and shape.

2. Eqwin wind turbine

Eqwin is a wind turbine that specially designed to work in wind regions of average velocity of 3 – 5 m/s. Eqwin starts to operate in wind speed of as low as 2.5 m/s and has been designed to have its maximum rating at 5 m/s wind. The structures have been designed to withstand the Malaysia once in 50 years wind speed of 23 m/s. The design had been taken into consideration of the availability of local manufacturing (manpower and technology), availability of material and installation to ensure effective low production cost. Estimated Eqwin will have a minimum lifetime of 15 years with very nearly maintenance free. The tested prototype was 3 m diameter capable of producing 0.5 -1.5 kW maximum power in wind speed ranges from 3 – 5 m/s at a height of 10 m above ground [6].

Malaysia is situated in the equatorial wind zone of the globe. Thus Eqwin Turbines could also be an advantage to some countries in the same wind zone. Eqwin Turbine could be utilized to produce electricity in about 60% of the area of the country indicating that this type of wind turbine is suitable not only for stand-alone applications but also for wind farming. The implementation of Eqwin Turbines is very beneficial in areas where the supply from national main grid is not available [6].

3. Methodology

The application of simulation software has always been advantageous over an experimental method in terms of time and cost while providing comparable prediction of the actual condition in the field of study. Thus the existing shell type blade (Figure 1) is used as the reference blade and then it is modified with various types of rectangular and circular slots on the blade surface and its performance is observed. As [10] also previously carried out similar work on NACA4412 aerofoil using horizontal and vertical slots and indicated that aerodynamic performance could be enhanced by introducing slots on the blade surface.

Looking back at the objectives of this work, this study is divided into two stages; the first stage focuses on the determination of optimum AOA while the second stage evaluates the aerodynamic performance of the modified blade by obtaining the lift to drag coefficient ratio.
3.1. Model design and grid meshing

The modelling process adopted the Pro Engineer Wildfire 4.0 software to develop the CAD model. The existing Eqwin blade of shell type is used as the reference model. The modification of rectangular horizontal slots (Figure 2), rectangular vertical slots (Figure 3) and circular slots (Figure 4) were then introduced on the blade surface. As shown in Table 1, in total there are 25 different blade configurations involved in this simulation including the smooth blade (Figure 5) which does not have any slots and bending sections. These modifications are intended to observe the effect of the modification that includes the type of rectangular or circular slots, the distance between those slots and their total number on the blade surface as tabulated in Table 1.

On the other hand, the meshing of the model was dominated by tetrahedral elements with maximum element size of 0.5 m. Further refinement was applied at the region of interest which is the blade wall. Thus, the element size at the blade was set to 3 mm, and 10 layers of inflation were applied in order to account for boundary layer effects. Note that the maximum skewness was maintained below 0.9 in order to achieve accurate solution.

3.2. Simulation solver and boundary conditions

The simulation process adopted the commercial CFD package CFX as the flow solver. Steady state simulation with pressure based solver is chosen, which is considered appropriate for incompressible flow problems [8]. The most suitable turbulent model was found to be k-epsilon viscous model. The
numerical scheme adopted pressure velocity coupling for appropriate flow and turbulence consideration. The convergence absolute criteria are set to 1e-5 in order to allow the flow to fully converge by providing sufficient number of iterations.

The main boundary conditions that were defined during the setup are velocity inlet, pressure outlet and wall. In the inlet boundary condition, a uniform velocity was defined as 3 m/s along the x-axis, and it is referring to the average wind speed in Malaysia. The outlet boundary condition is set to atmospheric pressure condition (101,325 Pa). While the blade surface is set to wall, with no slip wall condition. Free slip wall boundary conditions are also set at the lateral boundaries of the simulation domain.

### Table 1. Samples details.

| Sample Name           | Slot Size (mm) | Distance between slots |
|-----------------------|----------------|------------------------|
| Circular Horizontal rectangular | 5 10 15 20 25 50 75 100 200 |
| Vertical rectangular | 5 10 15 20 25 50 75 100 150 |
| Smooth blade          | Without slots & bending sections |

### 4. Results and discussion

In this section the aerodynamic performance analysis are presented. The optimum AOA had been investigated first, and then it was used to evaluate the aerodynamic performance for the modified blade. The aerodynamic performance of the modified blades was then compared with the reference blade in order to determine their best aerodynamic performance.

#### 4.1. Optimum angle of attack determination

Lift and drag coefficients are the crucial parameters for aerodynamic performance evaluation. The critical and optimum AOA can be estimated by plotting the lift and drag coefficients in a line graph. For AOA evaluation, there was no initial data representing the optimum AOA for the reference blade. Therefore, the reference blade has been adopted to find the optimum AOA. The simulation process used an AOA in the range of -90º to 90º for the reference blade. The simulation was carried out to find the values of lift and drag coefficients. The AOA with maximum value of lift to drag ratio was considered as optimum AOA.

Figure 6 shows the lift coefficient, drag coefficient and lift to drag ratio as a function of AOA which ranges from -90 to 90º for the reference blade. It showed that maximum value of lift coefficient, $C_L$ was 0.702 at 30º AOA. Although the blade required high value of $C_L$ however, the drag coefficient at the same AOA was high which result in lower lift to drag coefficient. Moreover, it is also observed that the maximum lift to drag ratio was at 10º AOA with the value of 6.119. However, since the optimum AOA may lays between 0 to 20º the current 10º AOA obtained may or may not be the exact actual AOA.

It is worth to note that, the determination of optimum AOA is crucial in such that very large angle may prevent the achievement of useful lift force which might lead to stalling [9]. Therefore, further detailed simulation need to be carried out by using an AOA that ranges from 0 to 20º. The new value of lift to drag ratio $C_L/C_D$ obtained could be used to determine the best performance of the blade.
4.2. Detailed angle of attack (AOA) simulation

The detailed simulation of AOA was carried out from 0° to 20° with an increment of 1° between each case. It was found as in figure 7 that the maximum value of lift to drag ratio was 6.420 at 12° AOA. This value agreed with the result in Figure 6 as the maximum value of lift to drag ratio was between 0 and 20° AOA. Thus, this 12° AOA was taken as the optimum AOA and used for later simulation which studied the performance of the modified blade.

It was also noticed that lift coefficient increases from 0 to 20° AOA. However, the drag coefficient showed that the lift to drag coefficient increased to max of 6.420 before it started to decrease as illustrated in Figure 7.

4.3. Modified blade with circular slots

The reference blade has been modified with 8 different circular slots. Their variation is in terms of diameter sizes which are 5 mm, 10 mm, 15 mm, 20 mm, 25 mm, 50 mm, 75 mm and 100 mm. The distance between each circular slot centre was fixed at 200 mm and the total quantity of circular slots on each blade was also fixed at 168. The only variable was the diameter of circular slot.

From figure 8, it is shown that the value of lift coefficient was inversely proportional to the slots' diameter. The drag coefficient was found to increase as the diameter increases. The lift to drag ratio decreases when the diameter increased. This indicates that the blade could convert only small amount of the air passing through it because of the larger circular slots. Thus smaller diameter should be used if circular slots are being adopted.

As compared to the reference blade, all blades had low lift to drag ratio except 5 mm circular slot. The 5 mm circular slot produced lift to drag ratio of 6.46 compared to the reference blade of 6.426. The velocity profile indicated that the 5 mm diameter circular slot was not big enough for the wind streamline to pass through the blade and change side from lower to upper side of the blade. Obvious difference was observed compared to 100 mm diameter slot; such that the wind streamline could easily pass through the circular slot. This resulted in the changes in wind velocity profile on top surface of the blade and the pressure region also changes as a result. This phenomenon denotes that increasing the circular slot size may not be a useful strategy to enhance the performance of the blade.
4.4. Modified Blade with Horizontal Rectangular Slots

For the horizontal rectangular slot cases, the distance between each slot was fixed at 150 mm. The length was fixed at 150 mm and the width varied from 5 mm to 100 mm. The total quantity of slots on each blade was also fixed at 56. Figure 9 shows that the lift coefficient reduced as the horizontal rectangular slot size increased. Moreover, the value of lift to drag ratio decreased when the slot size increased.

The 5 mm horizontal rectangular slot size had the closest ratio to the reference blade, which indicates that it can convert the incoming flow much better comparing to the larger slot size. The lift and drag force also decreased as the slot size increased. This is again due to the fact that only small portion of the incoming fluid being harnessed by the blade. Moreover, the bigger slots are also contributing to the viscous friction which created more drag on the blade.

4.5. Modified Blade with Vertical Rectangular Slot

For the vertical rectangular slot cases, the distance between each slot was kept constant at 150 mm and only the slot width was varied from 5 mm to 100 mm. From the tabulated result in figure 10, the lift coefficient showed reduction as the slot size was increasing.

The value of lift to drag ratio ($C_l/C_D$) also decreased as the slot size increased. The value of the lift coefficient or lift to drag ratio was less in vertical rectangular slot compared to horizontal rectangular slot. This may be due to vertical slot which had longer space for wind streamline to penetrate the blade from lower side to upper side of the blade. The lift and drag force also decreased as the slot size increased.

The 5 mm slot size had the highest value of lift coefficient of 0.306 and lift to drag ratio of 5.871. However, these two values were much lower compared to the reference blade. The performance of the vertical slot modification blade was also considered less compared to reference blade.
4.6. Modified Blade with a Smooth surface

The reference blade was referring to local manufacture capability to produce as close as desired shape of the blade. That was why there were various bending points on the blade to get as close as the designed blade.

The modified smooth surface blade (Figure 5) was considered as the suggested blade without any bending line throughout the blade surface. The lift coefficient and drag coefficient values were less than reference blade value as it is evident in Table 2. The lift to drag ratio was 7.011 which is higher than the reference blade value which was 6.426. This showed that the modified smooth surface blade improved the aerodynamic performance with referring to lift to drag ratio. Lifting force was slightly low but drag force was reduced due to the smooth surface of the blade as in Table 2. This smooth blade also indicates that even though perforated blades may be light weight but definitely not the most effective in terms of aerodynamic performance.

| Blade Type (modification) | Lift Coeff, $C_l$ | Drag Coeff, $C_d$ | Lift to Drag Ratio, $C_l/C_d$ |
|--------------------------|------------------|------------------|-------------------------------|
| Reference Blade          | 0.326            | 0.051            | 6.426                         |
| Smooth Blade             | 0.304            | 0.043            | 7.011                         |

4.7. Brief summary

Figure 11 shows all the simulation results for various types of modifications including the best blade configuration. The modifications can be classified into few types i.e. circular slot, horizontal rectangular slot and vertical rectangular slot with the total of 25 blades including one reference blade or current shell type blade. The results of $C_l/C_d$ for all modified blades were compared to the reference blade.

From the figure, it shows that only two modified blades could be considered as improved when they were compared to reference blade in terms of lift to drag ratio value. The two blades were the smooth blade and the modified circular slot blade with 5 mm diameter. Maximum value of lift to drag ratio was found to be 7.011 at the smooth surface blade.
5. Conclusion

There were four types of blade modifications that has been analysed to evaluate the improvement of aerodynamic performance using CFD approach. The main conclusions obtained are summarized as follows:

CFD simulation had proven that for shell type blade (reference blade) the most effective AOA was at 12° since lift to drag ratio ($C_l/C_d$) shows the maximum value at this AOA. It was also observed that among the modified blades, there were only two types of blade modifications could improve the lift to drag ratio, which are circular slot with 5 mm diameter and smooth reference blade modification. The ratio of $C_l/C_d$ for 5 mm diameter circular slot modification has become 6.46. While the smooth reference blade showed the maximum value of lift to drag ratio of 7.011.

However, the trend in the entire perforated blade cases, $C_l/C_d$ tended to decrease as the slot size increased except for the circular slot with 5 mm diameter, due to disturbance of the airflow in lower side region which passed through the bigger slot size. Thus, the circular slot with 5 mm diameter would be the best slot configuration among the modified slots. The $C_l/C_d$ obtained (6.46) was about 5% more than that of reference blade and reduced the overall weight of the blade by 1.3%.

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6. References

[1] Siti, M., M.Norizah, and M. Syafrudin 2011 The evaluation of wind energy potential in peninsular Malaysia International Journal of Chemical & Environmental Engineering. 2(4)

[2] Nik W W, Ahmad M F, Ibrahim M Z, Samo K Band Muzathik A M 2011 Wind energy potential at east coast of Peninsular Malaysia International Journal of Applied Engineering Research. 2(2) 360

[3] Didane D H, Ab Wahab A, Shamsudin S Sand Rosly N2016 Wind as a sustainable alternative energy source in Malaysia--a review ARPN Journal of Engineering and Applied Sciences. 11 1–8

[4] Burton T, Sharpe D, Jenkins Nand Bossanyi E 2011 Wind Energy Handbook John Wiley & Sons Ltd. 2nd ed.

[5] Schubel Peter J and Richard J. Crossley 2012 Wind Turbine Blade Design Energies 5(9)3425-3449

[6] Wahab A A, Mohd S, Dahalan M N, Mat S, Chong W T, Ismail M H, Abas M F and Muslimen R 2008 The break-through for wind energy implementation in Malaysia Proc., Int., Conf., 21–23 May 2008, Johor Bahru, Malaysia

[7] Din A T, Azraai S B and Thenamirtham K 2012 Design and development of a vertical wind turbine using slow wind speed for mini power generationConf.,2nd January 2012, Global City, Manila

[8] Castelli M R, De Betta Sand Benini E 2012 Proposal of a means for reducing the torque variation on a vertical axis water turbine by increasing the blade number International Journal of Engineering and Applied Sciences, 6 221-227.

[9] Gracey W 1958 Summary of methods of measuring angle of attack National advisory committee for aeronautics, Technical note 4351

[10] Noorazye S N and Mohd S 2014 Performance evaluation of slotted and continuous types wind turbine blade (MSc Thesis, Universiti Tun Hussein Onn Malaysia)