Analytical study on different blade-shape design of HAWT for wasted kinetic energy recovery system (WKERS)

J B Goh¹,², Z Jamaludin², F A Jafar², M Mat Ali³, M N Ali Mokhtar³, and C H Tan³

¹Centre of Graduates Studies, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia
²Faculty of Manufacturing Engineering, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia
³Sales Department, Technojis Enterprise Sdn. Bhd., Setiawalk, Persiaran Wawasan, 47160, Puchong, Selangor, Malaysia

E-mail: *Jaybee-Goh@hotmail.com and M051510046@student.utm.edu.my

Abstract. Wasted kinetic energy recovery system (WKERS) is a wind renewable gadget installed above a cooling tower outlet to harvest the discharged wind for electrical regeneration purpose. The previous WKERS is operated by a horizontal axis wind turbine (HAWT) with delta blade design but the performance is still not at the optimum level. Perhaps, a better blade-shape design should be determined to obtain the optimal performance, as it is believed that the blade-shape design plays a critical role in HAWT. Hence, to determine a better blade-shape design for a new generation of WKERS, elliptical blade, swept blade and NREL Phase IV blade are selected for this benchmarking process. NREL Phase IV blade is a modern HAWT’s blade design by National Renewable Energy Laboratory (NREL) research lab. During the process of benchmarking, Computational Fluid Dynamics (CFD) analysis was ran by using SolidWorks design software, where all the designs are simulated with linear flow simulation. The wind speed in the simulation is set at 10.0 m/s, which is compatible with the average wind speed produced by a standard size cooling tower. The result is obtained by flow trajectories of air motion, surface plot and cut plot of the applied blade-shape. Besides, the aspect ratio of each blade is calculated and included as one of the reference in the comparison. Hence, the final selection of the best blade-shape design will bring to the new generation of WKERS.

1. Introduction

The world is full of energy. Most of the energy are extracted from the fossil fuels (e.g., coal, natural gas, petroleum etc.), which are also the primary source for energy in the world [1]. Overharvesting of fossil fuels brings negative impacts on human health and environment by the emissions of greenhouse gas [2]. For developing sustainability in long term, the utilization of renewable energy such as solar, wind, tides and waves are encouraged. To minimize the negative impacts on energy supply chain in Malaysia, renewable energy is considered as the fifth energy under the Fifth Fuel Policy which was launched in 2000 [3].

Renewable energy industry is still new and unfamiliar in Malaysia; the professionality of the local experts is still a distant to what the country needs. The common renewable energy available in Malaysia are solar power, hydropower, and wind power [4,5]. However, Malaysia is not a great geographical location for expansion of wind power since the wind speed is unstable. National Wind
Watch defines that the cut-in speed of a standard modern HAWT is about 3 m/s to 4 m/s (7-9 mph), but the average annual wind speed in Malaysia is analyzed to be less than 2.0 m/s [6–8]. On the other hand, a standard industrial cooling tower can produce a constant wind speed up to 11.0 m/s. The blade design is the most important part to be investigated to harvest the best lift effect from the cooling tower outlet. Therefore, three different blade-shape designs are analyzed in this study.

2. New HAWT’s Blade-shape Design

The three blade-shape designs are elliptical blade, swept blade, and NREL Phase VI blade. The ideas of both elliptical and swept blade-shape are from the aircraft wing, whereas the NREL Phase IV blade is from a standard modern HAWT. To complete this research work, three blade-shapes are designed and analyzed then further compared to select the best design for future research work.

2.1. The Consideration of Three Blades HAWT

The number of blade is one of the important issues that need to be considered before developing a wind turbine [9,10]. A turbine with only one blade will be the cheapest costing for development, but the presence of unbalancing is one of the problem. Anyway, the one-bladed turbine is able to rotate at high tip-speed ratio. The even number of blade will affect the stability of the turbine and has a lower inertia moment. Thus theoretically, the lesser the number of blade, the higher the aerodynamical efficiency configuration of a wind turbine [9,11], but is not advisable in reality due to its stability issue.

Rationally, wind turbine with two blades is better to overcome the stability problem, but the wind turbine itself will face a wobbling phenomenon. In other words, it is similar to gyroscopic precession. Since the wind turbine is facing the wind all the time, the blades direction need to change perpendicularly to the wind direction. So, according to yawing theory, when the blades are in line with the tower and the axis of rotation (vertical position), the resistance to the yawing force is very low. On the other hand, when the blades are not in line with the tower (horizontal position), the blades spin at longer distance from the axis of rotation so it experiences much resistance to yawing motion. Therefore, the yawing motion is experiencing starts and stops twice for every revolution, and this causes the turbine to stress due to blade chattering [11]. Figure 1 shows the graph of power coefficient $C_p$ variation against tip-speed ratio for the computational result of two, three and four blades of Savonius wind turbine.

![Figure 1. Power coefficient $C_p$ variation versus tip speed ratio [10].](image-url)

The wind turbine with four blades perform well at lower tip-speed ratio, but the three blades design has the best performance at high tip-speed ratio. In other words, the four-bladed design is the best choice for wind speed of 6 m/s; but when coming to the wind speed range of 6 m/s to 8 m/s, the three blades turbine will have the advantages [10]. Besides, the three-bladed wind turbine will only have a tiny vibration or chatter. This is because the resistance to the yawing motion will be balanced by two
blades when one blade is at the horizontal position (i.e. not in line with the axis of rotation and the tower) [11]. Therefore, a total number of three blades is proven to become a criterion wind turbine for the current industries based on the aerodynamic concept [9–12]. So, a wind turbine with three blades shows the perfect combination of high rotational speed and minimum stress.

2.2. Blade-shape Design
In this study, two aircrafts’ wing design (elliptical & swept) and one modern HAWT’s blade design (NREL Phase VI) are selected for the benchmarking analysis. Elliptical wing is the best for wind gliding purpose especially applied on Supermarine Spitfire fighter aircraft, which using aerofoil NACA 2209.4. Meanwhile, the swept wing on Boeing 747-8 commercial airplane using aerofoil BACxxx-il is the largest airbus until now. Even though Boeing 747-8 is huge and heavy, but its take off time and length is shorter compared to others. As mentioned, for the third blade-shape, NREL Phase VI is the exact design of a modern HAWT which is referring to aerofoil S809. For a better view, the 3D wireframe and solid modelling of three blade-shapes design are drafted in Figure 2, Figure 3 and Figure 4.

![Figure 2](image1.png)  
**Figure 2.** 3D Wireframe (a) and Solid (b) Modelling of Elliptical Blade-shape Design.

![Figure 3](image2.png)  
**Figure 3.** 3D Wireframe (a) and Solid (b) Modelling of Swept Blade-shape Design.
There are some standard formulae needed for calculation of benchmarking in the analytical process. For example, to calculate the aspect ratio, $AR$ as in Equation (2), the value of wingspan, $b$ and chord, $C$ are needed in Equation (1);

$$S = \frac{\pi \times b \times C}{4} \quad (1)$$

where $S$ is the wing area of the blade, $MAC$ illustrates the mean aerodynamic chord shown in Equation (4).

$$AR = \frac{b^2}{S} = \frac{b}{MAC} \quad (2)$$

For some reasons, the blade-shape is tapered to its tip, so the Equation (3) is needed for calculating taper ratio, $\lambda$, for the blade. Hence, in order to find the length of $MAC$ as in Equation (4) for swept blade and NREL Phase VI blade, the taper ratio is calculated;

$$\lambda = \frac{C_{tip}}{C_{root}} \quad (3)$$

$$MAC = C_{root} \times \frac{2}{3} \times \frac{(1+\lambda+\lambda^2)}{(1+\lambda)} \quad (4)$$

whereas the taper ratio is defined as the chord at the tip, $C_{tip}$, to the chord at the root, $C_{root}$. After all, the calculated aspect ratio is included as one of the criteria for the overall analysis process, as well as the twisted idea for the blade design since it is proven to optimize the blade performance [12–15].

3. Linear Flow Simulation

Computational Fluid Dynamics (CFD) analysis was ran by using SolidWorks software, all the designs are simulated with linear flow simulation. Linear flow simulation ran through every single blade-shape designs with gas/air velocity of 10 m/s as the fix variable. This 10 m/s wind speed is obtained through a calculation of the average wind speed measured from the outlet of the cooling tower. The cooling tower outlet is divided into several concentric parts to obtain the average wind speed from each band of measuring point as shown in Figure 5.

To analyze the elliptical blade by 3D SolidWorks linear flow simulation, all the desired information such as air velocity, air direction and air density were inserted into the project simulation. In this study, force is the main parameter for measuring the pressures applied on the surface of the blade. When each simulation had successfully run, a few features such as flow trajectories of air...
motion, surface plots and cut plot were selected for the purpose of showing a clear view of flow and pressure analysis on each part of the blade.

Figure 5. The Methodology of Measuring Discharged Air Velocity for each Band at the Cooling Tower Outlet.

3.1. Elliptical Blade Flow Discussion
In order to demonstrate the study of linear flow simulation on the elliptical blade, the flow trajectories, surface plot and cut plot and static pressure were used to visualize the wind flow from leading edge to trailing edge through the surface of the elliptical blade. Referring to Figure 6 and Figure 7, the leading edge of the elliptical blade experienced a higher pressure (≥ 101.345 kPa) and lower pressure (101.295-101.310 kPa) on the blade body. However, there is a slight higher pressure compared to the blade body along the trailing edge (101.325-101.330 kPa), which is showing that drag forces had exerted on the blade before the wind pass through the blade surface. Anyway, from the cut plot in Figure 8, the pressure is uniform along the blade surface, so the elliptical blade is very good for gliding purpose. Consequently, this is the reason that elliptical blade is usually being used on aircraft to perform aerobatic maneuver show.

Figure 6. Flow Trajectories of Elliptical Blade.
Figure 7. Surface Plot of Elliptical Blade.
According to the Bernoulli’s Principal, the visualization of the flow trajectories, surface plot and cut plot are clear to be understood. However, a graphical method will help to interpret more information on the mechanical motion of the elliptical blade. Pressure analysis of linear flow simulation along the leading edge to trailing edge on the elliptical blade is plotted as in Figure 9, with the position of the particular edges as reference.

The line chart indicates the pressure between the leading edge and trailing edge. Based on the fluctuating of the line, Edge<1> has a higher pressure than Edge<2> as the air divides at the leading edge and flow neatly at the trailing edge. Besides, the line chart shows the pressure from the root chord to tip chord of elliptical blade is decreasing due to the different thickness. So, the thicker the aerofoil, the higher the pressure as the division of air occurs at the leading edge of the blade. After all, the line variation on Edge<2> is fairly consistent and shows the air flows smoothly along the trailing edge on elliptical blade.

3.2. Swept Blade Flow Discussion

The process of swept blade linear flow simulation is similar to elliptical blade. The result of flow trajectories, surface plot and cut plot for swept blade have been achieved as shown in Figure 10, Figure 11 and Figure 12. Referring to both Figure 10 and Figure 11, most leading edge and part of the trailing edge along the swept blade experience a high pressure (≥ 101.328 kPa) compared to other parts. However, a large region of blade body experiences a low pressure (≤ 101.32 kPa). According to
Figure 12, the performance of swept blade is ineffective while undergoing the air flow. This shows that swept blade is not advisable for the use of wind turbine due to the low wind speed source.

**Figure 10.** Flow Trajectories of Swept Blade.

**Figure 11.** Surface Plot of Swept Blade.

**Figure 12.** Cut Plot of Swept Blade.
In order to get a better view and understand the linear flow simulation of swept blade, Edge<5>, Edge<6>, Edge<7>, Edge<8> and Edge<9> play a critical role in the simulation process. Edge<5> presented in Figure 13 shows a high pressure occurring at the root chord of leading edge. However, the pressure is decreasing towards the tip chord along the leading edge. Edge<9> illustrates the pressure from the root chord slightly increasing to tip chord along the trailing edge. Lastly, the wingtip of the trailing edge showing pressure drop again which is presented by Edge<7>. This blade shows lower lifting force and greater dragging force compared to elliptical blade. Therefore, the swept blade can perform greatly on aircraft but may not be a suitable blade-shape design for wind turbine, since it needs a higher leading speed to provide lifting force.

![Figure 13. Pressure Analysis of Elliptical Blade (b) with the Edges Reference (a).](image)

3.3. NREL Blade Flow Discussion
The same processes as both elliptical and swept blade are done to NREL Phase VI blade when gaining the linear flow simulation result. Start from the leading edge of NREL blade, the air spreads the flow to both suction and pressure surface at the moment it experiences high pressure around 101.35 kPa then escapes with extremely low pressure which almost as low as 101.305 kPa through trailing edge as illustrated in Figure 14 and Figure 15. Based on the cut plot in Figure 16, the pressure at the leading edge is high but the pressure on the blade body and trailing edge is low and stable. Again, when referring to the trailing edge in Figure 14, the flow trajectories can be observed from root chord to tip chord which is effective smooth while passing through the blade surface.

![Figure 14. Flow Trajectories of NREL Blade.](image)
In order to translate the animation of flow simulation, the graph of pressure analysis of linear flow simulation along the leading edge to trailing edge on NREL Phase Vi blade is produced as in Figure 17, together with the references of specific edges position. The line graph illustrated the Edge<1> with unusually high pressure experience along the leading edge, in the meantime, excessively low pressure along the trailing edge which presented in Edge<2>. Besides, the Edge<2> also show the pressure slightly decreasing near the root chord of trailing edge. Hence, there are some turbulence flow near the root chord as shown in Figure 14.

4. Conclusion
This research work highlights the ability to maximize the horizontal axis wind turbine (HAWT) to improve the performance of wasted kinetic recovery system (WKERS) by benchmarking different blade-shape design. By analyzing the flow trajectories, pressure of surface plot & cut plot and pressure analysis graph along leading edge and trailing edge, NREL Phase VI blade is selected as the best blade design in this linear flow simulation as the lift is easily formed since it experiences the lowest pressure among three blades.

Moreover, NREL blade is the only blade which uses a wingtip and twisted blade in its design. Regarding to the supported documents by National Renewable Energy Laboratory, it is proven that the wingtip and twisted blade help the wind turbine itself to increase the performance. Therefore, it is believed that the winglet will reduce or block the vortices form at the wingtip in order to reduce the undesirable drag force. Therefore, this study conclude that the NREL Phase VI blade with a high aspect ratio, high lift and low drag will proceed to new revolution of WKERS.
In addition, with the selection of best blade design for WKERS, more energy can be harvested from the wind and more electricity can be generated. As a conclusion, WKERS with NREL Phase VI blade design is practical and can be implemented. Further enhancements and modifications will be carried out to improve the efficiency of the whale-inspired wind turbine:

- Conduct a rotational flow simulation for a better view of the wind flow before and after the WKERS.
- Organize another flow simulation by using another professional software to compare with the result obtained in this 3D SolidWorks design software.
- Apply the idea of whale-inspired design on the leading-edge of the blade to increase the performance of WKERS.
- Develop a real-scale prototype to validate the performance of WKERS.

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