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EFFECTIVENESS OF BLADE TIP ON LOW SPEED HORIZONTAL AXIS WIND TURBINE PERFORMANCE

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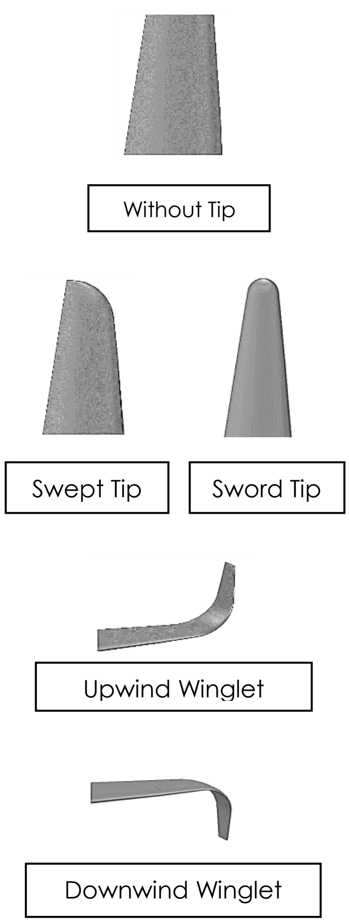
Graphical abstract



Abstract

There has been an increasing demand for renewable energy in order to create a sustainable society as the non-renewable energies such as fossil fuel resources are limited. Modern wind turbines claim that they have a high efficiency in term of wind energy extraction. However, there are still having losses due to tip vortex causing to a reduction in performance. Motivated by this reason, this research aims at exploring the possibility to increase the performance of low speed small-scaled horizontal axis wind turbine with various tip devices using Computational Fluid Dynamics (CFD). Four wind turbine blades with different tip devices which consist of sword tip, swept tip, upwind winglet and downwind winglet are compared with wind turbine blade without tip device in term of CP. The application of tip device can significantly reduce induced tip vortex and improve wind turbine performance. For TSR below than 4, adding a sword tip increases C_P about 7.3%, swept tip increases C_P about 9.1%, upwind winglet increases C_P about 1.8% and downwind winglet increases C_P about 3.2%. It is observed that the best tip device for low wind speed application is swept tip as it give the highest performance increment compared to without tip device.

Keywords: Wind turbine, tip device, swept tip, sword tip, upwind winglet, downwind winglet

Abstrak

Terdapat peningkatan permintaan terhadap tenaga boleh-diperbaharui untuk mewujudkan masyarakat yang mampan memandangkan tenaga yang tidak boleh diperbaharui seperti sumber bahan api fosil adalah terhad. Turbin angin moden mendakwa bahawa mereka mempunyai kecekapan yang tinggi dari segi pengeluaran tenaga angin. Walau bagaimanapun, masih terdapat kehilangan akibat oleh hujung pusaran menyebabkan kepada pengurangan dalam prestasi. Didorong oleh alasan ini, kajian ini bertujuan untuk meneroka kemungkinan untuk meningkatkan prestasi kelajuan rendah turbin paksi angin mendatar berskala kecil dengan pelbagai peranti tip menggunakan dinamik bendalir pengiraan (CFD). Empat bilah turbin angin dengan peranti tip yang berbeza-beza terdiri daripada tip pedang, tip menyapu, sayap lawi huluan dan sayap lawi hiliran telah dibandingkan dengan bilah turbin angin tanpa peranti tip dari segi pekali kuasa (C_P). Penggunaan peranti tip boleh mengurangkan pusaran tip teraruh dan meningkatkan prestasi turbin angin. Untuk nisbah kelajuan-tip (TSR) kurang daripada 4, penambahan tip pedang meningkatkan C_P kira-kira 7.3%, tip menyapu meningkatkan C_P kira-kira 9.1%, sayap lawi huluan meningkatkan C_P kira-kira 1.8% dan sayap lawi hiliran meningkatkan C_P kira-kira 3.2%. Diperhatikan bahawa peranti tip yang terbaik untuk aplikasi kelajuan angin rendah ialah tip menyapu kerana ia memberi peningkatan prestasi tertinggi berbanding tanpa peranti tip.

Kata kunci: Turbin angin, peranti tip, tip menyapu, tip pedang, sayap lawi huluan, sayap lawi hiliran

1.0 INTRODUCTION

Recently, the increasing of negative issues related to the environment pollutions, global warming and high oil prices had increased the interest of researchers in alternative energy development as well as promoting renewable energy awareness [1, 6]. In the ASEAN region, Philippines, Thailand and Vietnam already move forward to utilize the wind energy in their country. Back then, there has been an increasing demand for renewable energy in order to create a sustainable society because the non-renewable energies such as fossil fuel resources are limited [3]. Although the modern wind turbines claim that they have a high efficiency in term of wind energy extraction, there are still having losses due to tip vortex [4].

Tip devices can be further classified into two designs which are winglet design and tip extension design. In 1970s, Richard Whitcomb first invented winglet concept for aircraft wings to decrease drag and increase lift. The establishment of winglet for aircraft wings yielded 7% increase at cruise speed [5]. The performance of the wind turbine blade for any particular tip devices can be measured relative to the performance of the same blade design with no tip devices. In one study by Heyson, et. al. which allowing identical increases in root bending moments, winglets produced better improvement results that tip extensions [6]. However, in another study by Jones, et. al. which integrated bending moments were constrained, winglets and tip extensions produced the same results [7].

An experimental investigation on small horizontal axis wind turbine rotor using winglet conducted by Saravanan, et. al. shows that there were significant performance difference with various type of winglet configurations [8]. The study just focused on winglet height and winglet curvature radius because there was a further report that those two factors are dominant than the other parameters [9]. Five wind turbine rotors with four different winglet configurations and one without winglet have been designed and tested in the wind tunnel. The values of C_P were high for low range of tip speed ratio for wind turbine rotor model with winglet compared to without winglet. When TSR value is above 3, the performance of winglets were found to be insignificant anymore. Furthermore, when the TSR above 3, the deviation of power coefficient was very small and when the TSR reaching 3.47, all winglet configurations including without winglet giving almost the same result. Comparing the power coefficient of all winglet configurations, the W2 configuration was found to be more efficient where it has advantage of extracting wind power (P_{wind}) at low wind speed. At TSR of 1.91, wind turbine rotor model with W2 winglet configuration produced 12.8% increase in CP compared to wind turbine rotor model without winglet (W0).

Hiroshi, et. al. reported in their numerical analysis that there were noteworthy performance difference with winglet that has various cant angle configurations [10]. Six wind turbine blades with five different cant angle configurations and one without winglet have been modelled and numerically tested by Vortex Lattice Method (VLM) with free wake model. Note that the blade tip extension rotor, which the cant angle was 90°, has almost the same value of power coefficient as the rotor without winglet. The increase in the axial force coefficient of the rotor with winglets suggests that the power captured from the wind was increased. The results from the study can be summarized as a higher enhancement of the power coefficient can be achieved for winglet that having smaller cant angle and rotors with winglets are more effective compared to the rotors with blade tip extension or without winglet.

An experiment conducted by Ali, et. al. which have done a wind tunnel test with three different blade configuration designs which are upwind winglet, downwind winglet and blade without a winglet [11]. The orientation of canted winglet also effect the lift-to-drag ratio (L/D) where the winglet has significant effect on the aerodynamic performance of the wind turbine blade. Lift-to-drag ratio (L/D) increases with the upwind winglet by approximation 26% while lift-to-drag ratio (L/D) decreases with the downwind winglet by approximation 27% compared to the blade without a winglet.

Tip extension is an extension of blade span that consist of various design of blade tips. In the other words, tip extension also known as conventional blade tip [7]. Different with winglets, tip extension has no cant angle and has longer blade span. Currently, most of the wind turbine blade tip are using tip extension such as sword tip, swept tip, rounded tip and others instead of winglet in order to reduce production cost [6, 13]. Tangler reported that previous test experience has shown that the streamwise edge or known as swept tip produces good performance in term of C_P and blade tip vortex reductions [12]. The other blade tip shapes of other geometries are broadly used by current wind turbine blade. Meanwhile, the sword tip is frequently chosen because of its low noise generation but at the expense of a reduction in performance where its capability to reduce the blade tip vortex is very low compared to swept tip.

Meanwhile, a CFD study on wind turbine blade tip extension by Ferrer, et. al. [14] shows that there were significant performance difference between no tip and tip extensions. Two wind turbine blade with tip extensions which are pitch axis tip and swept-back tip and one wind turbine blade without tip have been computed. The model have been simulated in periodical computational domain (120° domain) and the presented result were fully-turbulent converged steady state with $k - \omega$ SST model. Second order discretization schemes were used for all variables and SIMPLE algorithm selected to solve the pressure-velocity coupling. Surprisingly, very few studies have compared wind turbine performance between wind turbine with tip devices and without tip device in one study. Most of the studies just focusing either winglet configurations only or tip extension configurations only. So, this study proposed five cases of wind turbine tip configurations which are without tip device, sword tip, swept tip, upwind winglet and downwind winglet to be numerically simulated by CFD. The goals of this study are to perform a simulation study on the effectiveness of various tip devices on wind turbine and to compare the wind turbine performance between wind turbine with tip devices and without tip device. Lastly, the expected finding for this study is to increase the wind turbine performance by at least 2%.

2.0 METHODOLOGY

Five wind turbine blades with various tip devices were used as the model for CFD simulation. Then, they were divided into two groups (tip extension and winglet). Tip extension consist of sword tip and swept tip, while winglet consist of upwind winglet and downwind winglet. The CFD simulation results were approved by the seminar panel of Department of Thermo-fluids, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia.

2.1 Modelling Process

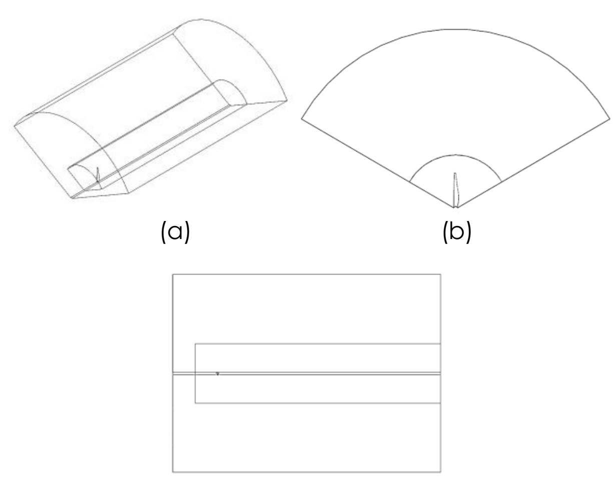
For numerical simulation, 3 blades with radius of 200 mm was employed as a model wind turbine. NACA 4412 was chosen as the blade airfoil profile which is popular geometry for wind turbines. The blade airfoil profile was used slightly beyond from the hub to the tip which was from 6% to 100% of radial position. For the hub fitting, 21 mm diameter of circular shape was used from 0% to 6% of radial position. The twist angle of the wind turbine blade was neglected as to simplify the modelling process in SOLIDWORKS 2015. Other than that, the chord lengths of each section ranged from 8 mm at blade tip, 29 mm at one-third of the blade length and 21 m at blade root. The design revolution speed was 601.61 RPM and the operating speed is expressed by TSR which was set in range from 1 to 6 with the design TSR of 4.2. For this study, TSR will be varied by changing the wind turbine revolution speed while keeping the inlet velocity fixed to 3 m/s as to match along with mean monthly wind speed during Northeast (NE) and Southwest (SW) monsoon season at Mersing Station, Johor, Malaysia [1].

Table 1 Wind turbine blade specifications

Description	Specification
Blade Length	170 mm
Wind Turbine Rotor Radius	200 mm
Chord Length (Tip - 1/3 Span - Root)	8 mm – 29 mm – 21 mm
Angle of Attack (α)	13°
Twist Angle	0°
Design Revolution Speed (Without Tip)	601.61 RPM [TSR = 4.2]
Blade Airfoil Profile	NACA 4412

The tip extension modelling process was done by a lofting features and these tip extensions will be attached at the wind turbine blade tip region by mating features. Same as the tip extension, the winglet can also be divided into two types which are upwind winglet and downwind winglet. The winglet modelling process was also done by a lofting features and these winglets will be attached at the wind turbine blade tip region by mating features. Once again, overall wind turbine blade length with tip extension and winglet configurations were scaled down to 200 mm as to make wind turbine rotor diameter constant for all cases. After scaled down, tip extensions have 20 mm of length while winglets have 20 mm of height with 83° of cant angle.

The cylindrical domain was the most suitable computational domain for wind turbine CFD simulation. Furthermore, the cylindrical domain can be further reduced to 120° periodical domain which contains one wind turbine blade instead of three wind turbine blades in 360° domain. The advantages of 120° periodical domain with one wind turbine blade are the number of cells in the computational domain can be significantly reduced and the 3D model could be simplify for numerical simulation. This method promote to effectiveness of computational time as the same results could be obtained by assigning periodic boundary condition at both left and right side of the 120° periodical domain. The coordinate system implemented was such that the positive x-axis in the right side direction, the positive y-axis in the upward vertical direction and the negative z-axis in the streamwise direction. Meanwhile, the origin of the coordinate system was located at the center of the hub, so the z-axis was the rotational axis with the blade revolving in the counterclockwise direction.

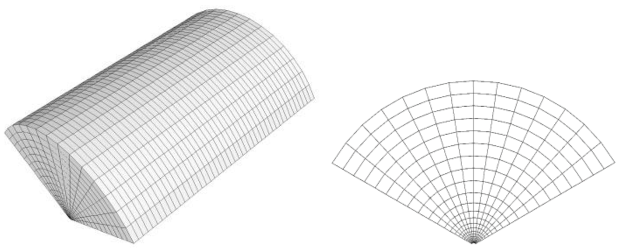


(a) (b) (c)

Figure 1 (a) Isometric View, (b) Front View, (c) Top View

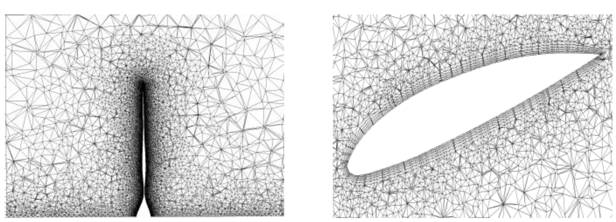
2.2 Meshing Process

As for non-expert CFD users' development and convenient procedure, hybrid mesh was used. For rotating computational domain where the blade inside it were meshed with tetrahedral cells meanwhile for static computational domain were meshed with hexahedral cells for high quality mesh resolution. By using this approach, it is possible to get rid of the difficulties of mesh generation around complex geometry such as blade surface. Furthermore, the change of wind turbine blades with various tip configurations can be simply exchanging the corresponding modified wind turbine blades in rotating computational domain. In short, hybrid meshing allows non-expert users to avoid the difficulties of mesh generation which is a major obstacle in CFD. For rotating computational domain, the mesh was further refined at wind turbine blade boundary layer where inflation mesh was implemented as to create a proper unstructured mesh around the blade. This is important as to ensure all 1st cells around the wind turbine blade could capture viscosity effect.



(a) (b)

Figure 2 Hexahedral Mesh for Static Computational Domain (a) Isometric View, (b) Front View



(a) (b)

Figure 3 Inflation Mesh around Wind Turbine Blade (a) Side View, (b) Top View

2.3 Computational Model Validation

Grid independent test (GIT) or known in the other name as mesh convergence study was done to ensure that the obtained results would be fully mesh resolution independent where the change in the result became insignificant anymore. In the other hand, grid independent test enable users to select the optimum mesh size for further simulation process. Five grid models have been tested with different total number of cells which vary from 0.58 million cells to 2.26 million cells. As the total number of cells increases, both Q value for Model 4 and Model 5 were identical to each other. The GIT for Model 4 took less computational time compared to Model 5 with 8 cores parallel mode. In order to achieve efficiency in CFD simulation, Model 4 which was 1.87 million cells has been selected as the optimum model in GIT process.

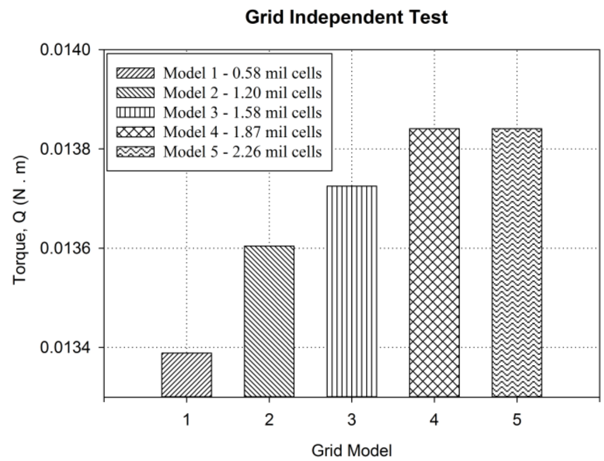


Figure 4 Grid independent test results

Table 2 Summary of grid independent test results

Grid Model	Total Number of Cells (Million)	Computational Time	Torque, Q (N . m)
Model 1	0.54	32 minutes	0.01339
Model 2	1.20	1 hour 6 minutes	0.01360
Model 3	1.58	2 hours 27 minutes	0.01373
Model 4	1.87	4 hours 31 minutes	0.01384
Model 5	2.26	7 hours 18 minutes	0.01384

Solver test (ST) was done to find suitable solver for CFD simulations and ST usually done after GIT process. For this study, only pressure discretization solvers were tested while solver in other discretization were set to 2nd order. In GIT section, Model 4 has been selected as the optimum model and this model will be tested in ST process. As the pressure discretization solvers varies, both Solver 2 and Solver 3 were almost give the same Q values. Meanwhile, only Solver 5 gives higher Q value than the other solver models. Most of the wind turbine CFD simulation, either Standard (Solver 1) or PRESTO! (Solver 5) are being used as the pressure discretization. Peyret has explained the difference between Standard and PRESTO! pressure discretization [15]. The Standard pressure discretization interpolates the pressure on the any faces using the cell center values while PRESTO! pressure discretization for pressure actually calculates pressure on the face.

In the other hand, PRESTO! pressure discretization gives more accurate results since interpolation errors and pressure gradient assumptions on boundaries are avoided. Surprisingly, computational time for both Solver 1 and Solver 5 took nearly the same with 8 cores parallel mode. In order to achieve accuracy, Solver 5 which was PRESTO! has been chosen as the best pressure discretization solver for further full-scale CFD simulations because it works better for problems with strong body forces or swirls.

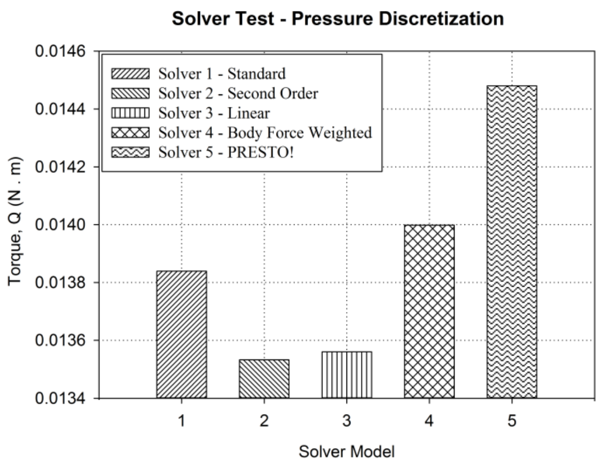


Figure 5 Solver test results

Table 3 Summary of solver test results

Grid Model	Pressure Discretization Solver	Computational Time	Torque, Q (N . m)
Solver 1	Standard	4 hours 31 minutes	0.01384
Solver 2	Second Order	4 hours 52 minutes	0.01353
Solver 3	Linear	5 hours 13 minutes	0.01356
Solver 4	Body Force Weighted	7 hours 36 minutes	0.01400
Solver 5	PRESTO!	4 hours 28 minutes	0.01448

In fluid dynamics, the law of the wall is the average velocity of a turbulent flow at a certain point is proportional to the logarithm of the distance from that point to the boundary of the fluid region. In the other words, wall function or Y+ aspect is basically the dimensionless wall distance and it is simple the wall distance times the shear velocity then divided by the kinematic viscosity. The main purpose of wall function is to validate the capability of 1st cells around the blade on capturing the viscosity effect where the Y+ value at the blade region is monitored by creating one plane passing through the blade radially at 60% of radial position. In order to achieve good 1st cells around the blade surface, the Y+ value should be less than 10 and mathematically, perfect Y+ value is 1.

Based on Figure 8, Y+ values gives better distribution along chordwise position due to size and quality of boundary layer mesh around the wind turbine blade. Negative chordwise position was the leading edge side while positive chordwise position was the trailing edge side. The obtained wall function result shows that the Y+ values was in the range between 2.5 and 0.6. The obtained result means that 1st cells around the blade were capable to capture the viscosity effect around the wind turbine blade.

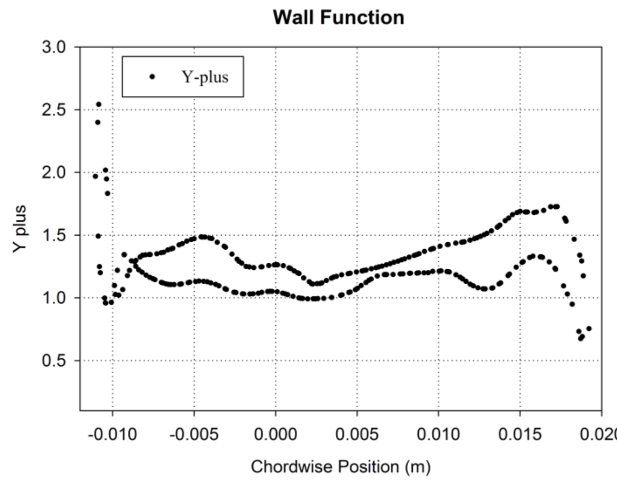


Figure 6 Wall Function Results at 60% of Radial Position

2.4 Computational Fluid Dynamics (CFD) Setup

The CFD simulation will be set to steady which means no parameters change with time and Pressure Based Navier Stokes (PBNS) which for subsonic incompressible flows. The turbulence model used in the numerical simulation was k-omega Shear Stress Transport (k-ω SST) where k and ω are turbulent kinetic energy and specific dissipation rate, respectively. This turbulence model is a two-equation of eddy viscosity model which has become very popular among CFD users especially on wind turbine cases. In addition, SST formulation combines two equations which are epsilon (ε) and omega (ω). In the other hand, k-ω SST can be used as a Low-Re Correction turbulence model without any extra damping functions. Many CFD users who use the k-ω SST frequently acknowledge it for its good behavior in adverse pressure gradient and separating flow cases. Thus, k-ω SST with Low-Re Correction was a perfect turbulence model to study the boundary layer transition and separation effects [16] that experienced by the wind turbine blade. Rotating volume positioned inside the static volume and having rotational velocity ranged from 143.24 RPM to 859.44 RPM where the rotational direction was counterclockwise. For this study, the inlet velocity was set to 3 m/s and its turbulent intensity was set to 5%. The left and right side of the computational domain boundary conditions, were set to periodic with 120°

offset angle because the flow across two opposite planes were assumed to be identical. Meanwhile, the sliding zone which was two overlap zones between the static and rotating computational domain were set to interface. Last but not least, all wall boundary conditions were set to no slip. For pressure-velocity coupling scheme, Semi-Implicit Method for Pressure Linked Equations-Consistent (SIMPLEC) was used with skewness correction set to zero. For spatial discretization where momentum, turbulent kinetic energy (k) and specific dissipation rate (ω) were set to second order upwind which gives more accurate and reliable results as well as having more stability in calculation compared to first order upwind. Last but not least, convergence value in solution monitor were set to 0.000001 (1e-06) in order to reach a good convergence level for every iterations.

Table 4 Summary of solution method setup

Solution Methods	Description	Setup
Pressure-Velocity Coupling	Scheme	SIMPLEC
	Skewness Correction	0
Spatial Discretization	Gradient	Least Square Cell Based
	Pressure	PRESTO!
	Momentum	Second Order Upwind
	Turbulent Kinetic Energy	Second Order Upwind
	Specific Dissipation Rate	Second Order Upwind
Solution Monitor	Convergence Value	1e-06

3.0 RESULTS AND DISCUSSION

In order to evaluate the wind turbine performance, the C_P is computed. C_P is obtained by dividing mechanical power (P_{mech}) with respect to available P_{wind} and P_{mech} is calculated from Q that produced by wind turbine blade. The Q results can be extracted from ANSYS Fluent after the simulation is done. There are two sections in wind turbine performance which are overall comparison of wind turbine performance and comparison of wind turbine performance between without tip and with tip devices. Additionally, the plotted C_P with respect to TSR graph has been set to least square fitted as to reduce relative error compared to polynomial that has more relative error.

3.1 Overall Wind Turbine Performance Comparison

The Q results that have been extracted from ANSYS Fluent just only for one wind turbine blade because of 120° periodical computational domain.

$$C_P = \frac{3\ x\ Q\ x\ \omega}{\frac{1}{2}\ x\ \rho_{air}\ x\ V_\infty{}^3\ x\ A_{rotor}} = \frac{P_{mech}}{P_{wind}} \quad (1)$$

By using Equation 1, P_{mech} for each wind turbine can be calculated from extracted Q results. The calculated P_{mech} results were divided with 2.078 W of calculated available P_{wind} in order to get C_P results which then be plotted against TSR.

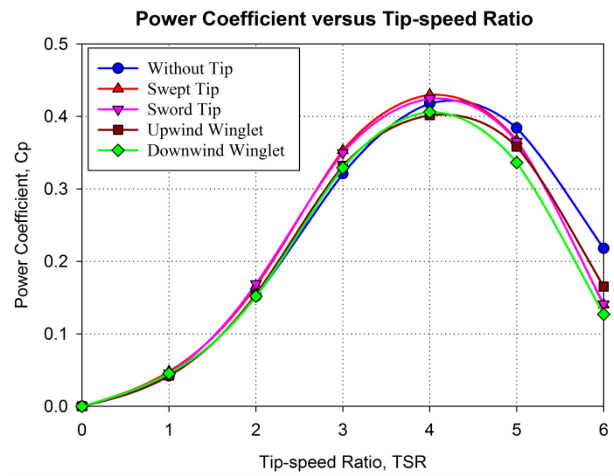
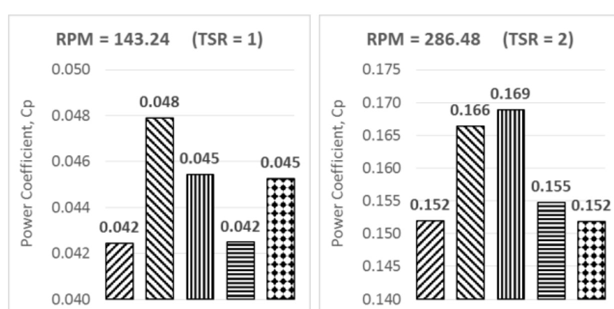


Figure 7 Overall Comparison of wind turbine performance

Based on the Figure 7, the increasing trend can be observed for TSR lower than 4 while the decreasing trend for TSR higher than 4. Detailed comparison for overall wind turbine CP for every wind turbine tip configurations, six bar charts have been plotted with respect to each TSR. Figure 8 shows the comparison of C_P with different TSR cases.



(a) (b)

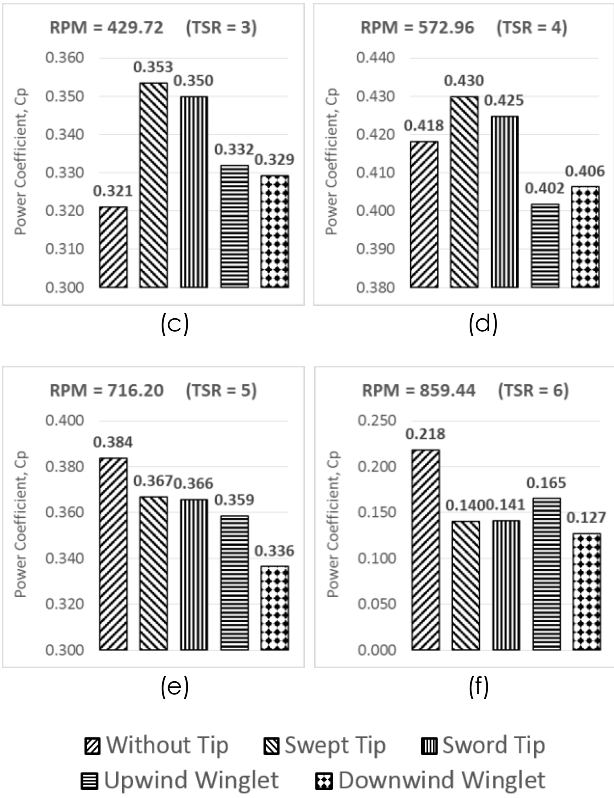


Figure 8 Comparison of Wind Turbine Performance for each Tip-speed Ratio Cases (a) TSR = 1, (b) TSR = 2, (c) TSR = 3, (d) TSR = 4, (e) TSR = 5, (f) TSR = 6

At TSR equal to 1, wind turbine with swept tip performed very well which is having 0.048 of C_P. In the other hand, both wind turbine without tip and upwind winglet were having lowest and same value of C_P which marked at 0.042. Additionally, wind turbine with sword tip and downwind winglet were having 0.045 of C_P.

Meanwhile, at TSR equal to 2, wind turbine with sword tip has the highest value of CP which marked at 0.169. This time, both wind turbine without tip and downwind winglet were having lowest and same value of C_P at 0.152. Wind turbine with swept tip and upwind winglet were having 0.166 and 0.155 of CP, respectively.

When TSR reached 3, wind turbine with swept tip has 0.353 of C_P which was the highest and overtake wind turbine with sword tip that has 0.350 of C_P. The lowest C_P was achieved by wind turbine without tip at 0.321 while wind turbine with upwind winglet and downwind winglet were having 0.332 and 0.329 of CP, respectively. The optimum TSR for wind turbine with tip configurations was at 4 while wind turbine without tip at its design TSR of 4.2.

At this TSR, wind turbine with swept tip has the highest C_P of 0.430 and wind turbine with upwind winglet has the lowest C_P of 0.402. Surprisingly, wind turbine without tip suddenly overtakes both wind turbine with upwind winglet and downwind winglet by having 0.418 of C_P. In the other hand, wind turbine with sword tip and downwind winglet were having 0.425 and 0.406 of C_P, respectively.

Once TSR passing 4, all wind turbines with tip devices were starts to perform poorly. This can be shown exactly during TSR equal to 5 where wind turbine without tip performed very well with highest C_P of 0.384. In addition, it can be seen that both wind turbine with swept tip and sword tip have performed nearly the same where the C_P were 0.367 and 0.366, respectively. Remarkably, wind turbine with upwind winglet starts to overcome and performed better than wind turbine with downwind winglet which having 0.359 of C_P. The lowest C_P was achieved by wind turbine with downwind winglet at 0.336.

Last but not least, at TSR equal to 6, wind turbine without tip has the highest CP which marked at 0.218. Once again, both wind turbine with swept tip and sword tip have performed nearly the same where the C_P were 0.140 and 0.141, respectively. Wind turbine with upwind winglet performed better than wind turbine with swept tip, sword tip and downwind winglet by having C_P of 0.165. In the other hand, wind turbine with downwind winglet has the lower C_P of 0.127.

3.2 Wind Turbine Performance Comparison between Without Tip and Tip Extension

Figure 9 shows the comparison of performance between the wind turbine without tip and that with sword tip, and Figure 10 shows the comparison performance between the wind turbine without tip and that with swept tip.

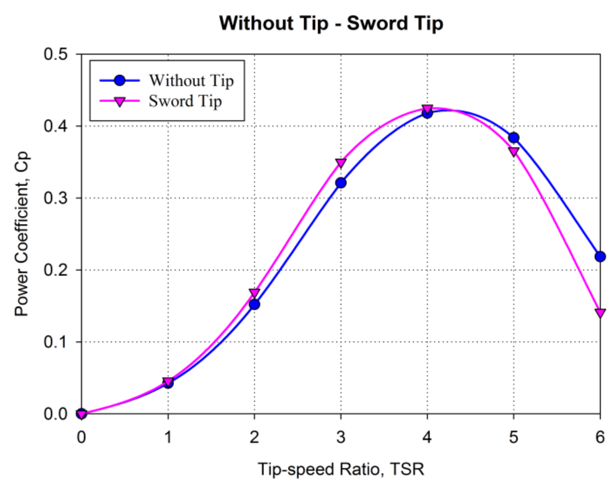


Figure 9 Comparison of wind turbine performance between without tip and sword tip

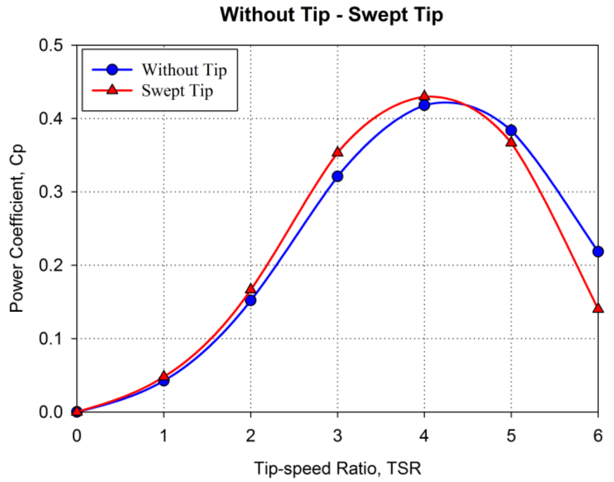


Figure 10 Comparison of wind turbine performance between without tip and swept tip

Both wind turbine with sword tip and without tip having same C_P of 0.423 at TSR around 4.3. For TSR lower than 4.3, wind turbine with sword tip performed better than wind turbine without tip by 7.3% of average percentage increment. In contrast, wind turbine without tip performed better than wind turbine with sword tip by 20% of average percentage increment at TSR higher than 4.3.

Meanwhile, both wind turbine with swept tip and without tip having same C_P of 0.420 at TSR around 4.5. For TSR lower than 4.5, wind turbine with swept tip performed better than wind turbine without tip by 9.1% of average percentage increment. In contrast, wind turbine without tip performed better than wind turbine with sword tip by 20.1% of average percentage increment when TSR higher than 4.5.

As reported by Tangler [12], swept tip produces less blade tip vortex compared to sword tip. Theoretically, the generated blade tip vortex will reduce the performance of the wind turbine as it convert the kinetic energy from wind to induced vortex at the blade tip instead of mechanical energy. In short, the more blade tip vortex generated, the lower the wind turbine performance. This results tally along with CFD simulation study by Ferrer, et. al. [14] that wind turbine blade with swept tip gives more performance increment compared to wind turbine blade with pitch tip and without tip. So, for tip extension configurations, swept tip is more practical to increase low speed wind turbine performance.

3.3 Wind Turbine Performance Comparison between Without Tip and Winglet

Again, both wind turbine with upwind winglet and without tip having same C_P of 0.373 at TSR of 3.4. For TSR lower than 3.4, wind turbine with upwind winglet performed better than wind turbine without tip by 1.8% of average percentage increment. Oppositely, wind turbine without tip performed better than wind turbine with upwind winglet by 11.5% of average percentage increment at TSR higher than 3.4.

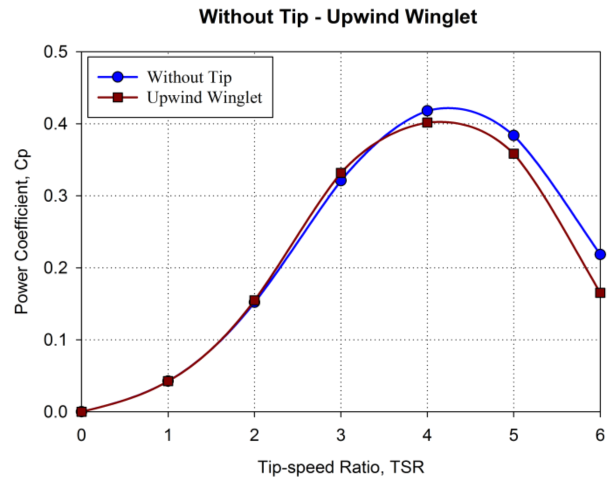


Figure 11 Comparison of Wind Turbine Performance between Without Tip and Upwind Winglet

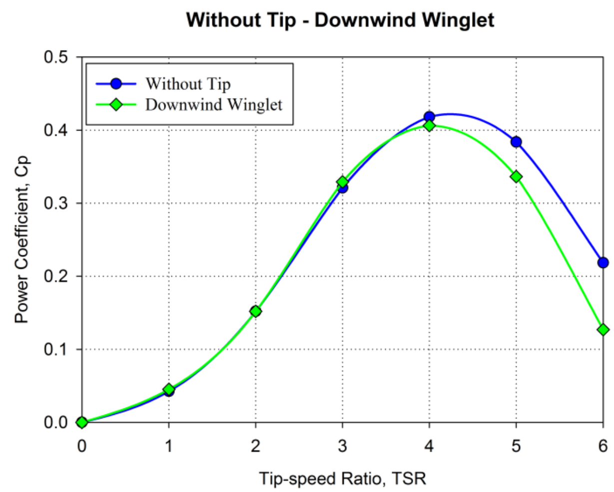


Figure 12 Comparison of Wind Turbine Performance between Without Tip and Downwind Winglet

In the meantime, wind turbine with downwind winglet and without tip having same C_P of 0.384 at TSR of 3.5. For TSR lower than 3.5, wind turbine with downwind winglet performed better than wind turbine without tip by 3.2% of average percentage increment while wind turbine without tip performed better than wind turbine with downwind winglet by 19% of average percentage increment at TSR higher than 3.5.

Winglet configuration offers a reduction in blade tip vortex at the expense of high centrifugal force and high bending load due to winglet weight at blade tip region. Most of the time, winglets are used on fixed wing as suggested by Richard Whitcomb [5] rather than on rotating blade like wind turbine blades or propellers. Saravanan, et. al. [8] reported that winglet can increase wind turbine performance at low wind speed region. When TSR reaching about 3.5, both wind turbine with winglet configurations and without tip are having same power coefficient or known as common point. This can be proven from the results obtained where the common point for upwind winglet and without tip was at TSR of 3.4 while downwind winglet and without tip was at TSR of 3.5. Both cases give nearly the same value of common point as well as the experiment that have been done by Saravanan, et. al.

But, downwind winglet performed better as it gives more performance increment than upwind winglet. This situation is contradicted with experiment conducted by Ali, et. al. [11] where they reported that upwind winglet produced 27% performance increment while downwind winglet produced 26% performance decrement in terms of lift-to-drag (L/D) ratio. The experiment by Ali, et. al. have tested the wind turbine blade with winglet configurations but the test was done in static condition while this CFD simulation study was done in rotating condition as the Moving Reference Frame (MRF) capability of ANSYS Fluent. The method of approaching to the problem may differs the results, significantly. In short, for winglet configurations, downwind winglet is more practical to increase low speed wind turbine performance.

4.0 CONCLUSION

The influence of the blade tip on the wind turbine performance has been numerically investigated. From the findings, it can be concluded that wind turbine with tip devices are effective at low wind speed region. For tip extension configurations, swept tip has known for its capability in reducing blade tip vortex compared to sword tip. So, swept tip has been chosen as the best tip extension configuration as it offers 9.1% of performance increment while sword tip offers 7.3% of performance increment compared to without tip device for low wind speed application. Meanwhile, for winglet configurations, downwind winglet has been chosen as the best winglet configuration as it produces 3.2% of performance increment while upwind winglet produces 1.8% of performance increment compared to without tip device for low wind speed application. In term of overall tip device configurations, swept tip is more practical for low wind speed application while without tip device is more practical for high wind speed application.

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