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DESIGN OF NACA 4415 TAPERLESS TWISTLESS WIND TURBINE BLADE USING TWIST OPTIMIZATION FOR INDONESIA WIND CHARACTERISTICS

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ABSTRACT

Lack of fossil fuel as energy resource of the world triggers a rapid development in renewable energy. Wind energy as one of renewable energy resource has a great potential to solve world's energy needs especially in Indonesia. Nevertheless, the application of wind energy technology is remain undone due to inappropriate design. One way to solve this problem is by creating a wind turbine blade design which suits wind characteristics in Indonesia. The blade which is designed by 50% and 75% linearization optimization can capture 53% of wind energy at Tip Speed Ratio (TSR) of 5. By using Russian pine wood as material, the design is being simulated under critical wind speed condition and proved to be feasible in this relating condition with Factor of Safety of 5.43. The research method uses various theoretical calculation and software simulation; QBlade and SolidWorks. The purpose of this scientific article is a NACA 4415 Taperless Twsitless Pitch +7 wind turbine blade is applicable in wind turbine system in order to produce an affordable, compact, and efficient wind turbine blades appropriate for wind characteristic in Indonesia.

Keywords: blade, efficiency, NACA 4415, taperless twistless, twist optimization, wind turbine.

INTRODUCTION

Lack of fossil fuel as energy resource of world triggers a rapid development in renewable energy. Wind energy as one of renewable energy resource has a great potency to solve energy needs especially in Indonesia. Indonesia is an archipelago country consisting 5.8 million km2 area of sea and 95.181 km length of coast line. These give Indonesia a great opportunity in wind energy utilization [1] specifically for energy source in coastal areas. In order to see its potency, various surveys in wind characteristic are made by various institutions. Mapping results by Lembaga Penerbangan Antariksa Nasional (LAPAN) which is Indonesia's aeronautics department shows that 120 spots in this country have average wind speed above 5 m/s. This wind energy potency can be utilized by implementing wind turbine generating electrical power as alternative source of energy in coastal rural areas.

Previously, our team has successfully implemented wind turbine and anemometer [2] in Muara Bungin, Bekasi, west Java which is one of coastal village in northern coast of Java island. The measurement was conducted from November 2014 to May 2015 in order to obtain the wind speed and energy fluctuations. According to the measured data, the wind begin to generate energy from minimum wind speed of 3-4 m/s which existence and duration probability is relatively high. In order to extract this energy generated in relatively low wind speed condition, we have to design a wind turbine appropriates for corresponding condition. Therefore, in order to achieve this objective, various optimizations should be conducted on turbine components especially the blade. These optimizations can be achieved by using various calculations and simulations to obtain a blade with good performance and high aerodynamic efficiency. Another factor that affects blade efficiency is manufacturing precision. A blade with sophisticated geometry is more difficult to be manufactured because a high manufacturing precision is needed to create a manufactured blade suits with its design. A poor manufacturing precision can potentially cause an inappropriate match between both which subsequently results in efficiency reduction. In order to prevent it, blade geometry simplicity must be considered properly in designing the blade. Consequently, based on both considerations, the research objective is to design a proper wind turbine blade which has high efficiency, good performance and simple geometry and suits with Indonesia wind characteristics.

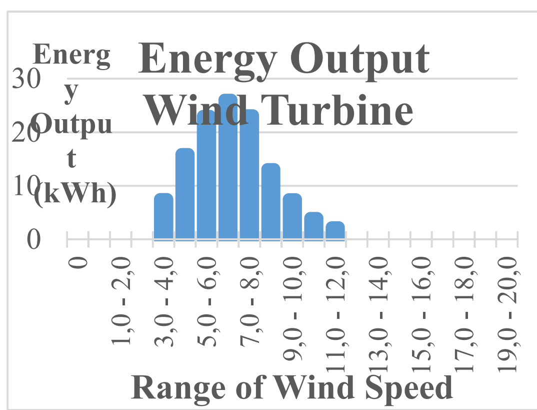

Figure-1. Energy output anemometer data.

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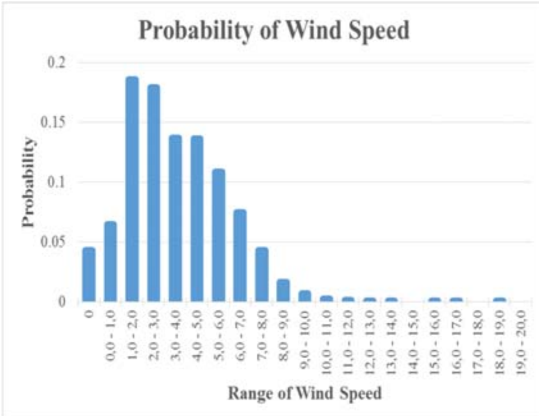

Figure-2. Probability of wind speed anemometer data.

LITERATURE REVIEW

Rotor Type Selection

Basically, wind turbine is classified into two main types, i.e. Horizontal Axis Wind Turbine (HAWT) and Vertical Axis Wind Turbine (VAWT). The selection consideration is based on local wind characteristics. Based on our anemometer data, low wind speeds dominate because of their high value of probability. Therefore, in order to harness wind energy efficiently, we use HAWT as our wind turbine type because it has low Cut-In speed and long range of optimum operation [3].

Furthermore, HAWT has various types with different efficiency and performance, i.e. multi-blade, sail wings, Holland type and propeller. Considering our requirements of high efficiency and long range of optimum operation, the propeller type is the most suitable one [3]. This propeller type itself consists of various number of blades which each has inherent characteristics including performance and compatibility with our desired design. Previous research [4] has succeeded to compare various propeller rotor with different number of blades configuration operating under relatively low wind speed condition and the result shows that the three bladed rotor has the highest efficiency. Besides its high efficiency, this configuration also produces balanced rotational force thus preventing yaw to occur [5]. Therefore, we chose three bladed propeller rotor as our desired design.

Aerodynamic Profile

Airfoil selection for wind turbine blade should consider two criteria, i.e. high lift to drag ratio in low wind speed condition (anemometer data) and simple geometry to facilitate the manufacturing process. Previous researches has succeeded in comparing various types of airfoil implemented in wind turbine and the results show that NACA 4415 profile has high values of C_L/C_D [6] and efficiency [7] under low wind speed condition. Therefore, we choose NACA 4415 profile as our wind turbine airfoil because it meets our criteria.

Blade Type Selection

Basically, wind turbine blade can be divided into several types based on two parameters, i.e. chord length and twist angle. Based on its chord length, blade can be divided into taper type which chord becomes shorter as it reaches the tip, inverse taper type which chord is opposite to that of taper type and taperless type which chord is fixed along the blade structure. Moreover, based on its twist angle, blade can be classified into twisted type which twist angle varies along each section and twistless type which twist is fixed along the blade structure.

In order to facilitate the manufacturing process and reduce the production cost, taperless twistless type is the best option to meet this criteria because of its simple geometry. However, application of this blade type in wind turbine produces low value of efficiency and poor performance under fluctuate wind speed conditions. Therefore, in order to solve this problem, an appropriate angle should be selected so that the efficiency produced is high and the turbine works optimally under various wind speed conditions [8, 9].

Material Selection

In order to create a proper wind turbine blade, material selection should meet several criteria, i.e. easy material access, strength to weight ratio, simple and cheap manufacturing process and ability to withstand loads. Based on these criteria, generally, most wind turbines use composite and wood material which each has strength and weakness. Composite generally has better strength to weight ratio but required higher price and longer production time in small scale manufacturing process. Considering its availability and capability of Indonesia manufacturer, we choose wood as our blade material. Furthermore, wood type is selected based on material properties and its compatibility with our design. The selection is conducted among four types that are allowable to be traded in Indonesia [10]. As a result, we chose Russian pine *Pinus sibirica* type because its density and mechanical properties meet our criteria [11].

METHODS

Aerodynamic Efficiency Simulation

The first step was determining the geometry based on efficiency and shape simplicity considerations. The blade which radius was 1 m with 0.17 m hub was divided into ten sections starting from hub connection to the blade tip which each had a total length of 0.083 m. The purpose was to facilitate the numerical simulation along the structure so that the result obtained was accurate. Moreover, using NACA 4415 profile and three bladed propeller resulted in α of 6.5 at C_L/C_D of 129 and λ of 7.

The blade geometry could be determined by calculating some parameters using several formulas, i.e.

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- Partial radius

$$r = h + \left[i \times \left(\frac{R-h}{n} \right) \right] \quad (1)$$

- Partial TSR

$$\lambda_r = \frac{r}{R} \times \lambda \quad (2)$$

- Flow angle

$$\phi = \frac{2}{3} \tan^{-1} \left(\frac{1}{\lambda_r} \right) \quad (3)$$

- Twist

$$\beta = \phi - \alpha \quad (4)$$

These parameters were plotted into table to calculate each section geometry and inputted to Microsoft Excel to obtain Twist vs Partial radius graph. The graph was used to facilitate the optimizations as the next step in blade design.

The design of blade geometry was basically governed by optimization in wind energy extraction [12]. In order to obtain a high efficiency and easily manufactured blade, various optimizations were required [13, 14]. Based on our previous literature studies, we used two advance optimizations to be applied in our desired design, i.e. 50% and 75% Linearization Optimizations [15, 16]. Subsequently, both optimizations were compared in order to choose which one had better efficiency and TSR stability range. Because our design was taperless twistless, then the parameter which being optimized was the pitch.

Performance Simulation

Besides aerodynamic efficiency simulation, performance simulation was necessary to obtain the blade performances which were shown in multi Blade Element Momentum (BEM) parameters [17, 18]. These parameters including power, torque, wind speed, and rotational speed became the most significant factors in designing a proper wind turbine rotor to create efficient turbine mechanical system and sufficient amount of power output. The desired rotor was designed based on these multi BEM parameters and the probability of wind speed data. By using both, we could determine appropriate wind turbine work phases, such as cut-in, optimum, and cut-off which consequently made the rotor to generate power optimally and harness wind energy efficiently.

Cut-In was a phase where the turbine started to generate power by converting wind energy into electrical energy and produced minimum electrical power output. This phase could be determined by selecting an appropriate wind speed condition in which its probability value was high enough and the torque generated by rotor exceeded that of required to rotate itself and shaft. To obtain the required torque value, we used several steps, i.e.

- Material specifications could be obtained by setting an appropriate dimension and determining its mechanical properties based on literature references.
- The rotor and shaft inertia

By assuming the rotor and shaft were solid cylinder, the inertia could be calculated using the equation below.

$$I = \frac{1}{2} \left(m_S r_S^{\ 2} + m_R r_R^{\ 2} \right) \quad (5)$$

- Minimum torque required

$$T_{Min} = I \times \frac{\Delta\omega}{t} \quad (6)$$

After obtaining the torque value, we could determine the Cut-In speed by using one of the T vs TSR graph. In an appropriate range of TSR we could determine ω and v in corresponding T which should be higher than T_{Min}. As a result, the Cut-In condition parameters could be obtained.

Optimum was a phase where the turbine could harness wind energy at most in each wind speed condition. Considering the fluctuate motion of the wind flow, the turbine efficiency could not remain constant at its inherent TSR which produced the highest C_P. Therefore, an appropriate range of TSR should be determined to make it feasible for the turbine to operate optimally.

Cut-off was a phase in which the turbine stopped to generate power by switching off the generator from converting mechanical energy into electrical energy. The purpose was to prevent the turbine from over speed rotation which subsequently resulted in overheating. This phase was determined by setting the wind speed condition which probability value was relatively low according to the measured anemometer data.

Structure Loading Simulation

Wind flow had mass and velocity which simultaneously produced the kinetic energy. The wind could strike the blade by converting this energy into force which subsequently generated stress along the blade structure and affected its stabilization [19]. An overload could potentially cause the structure to crack and fail. In order to prevent it, we could use the Finite Element Method (FEM) with SolidWorks software simulation to

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calculate stress generated along the structure and predict which part of the structure was prone to failure.

By using software assistance, we could simulate the components under various wind speed condition based on anemometer data, i.e. 0-19 m/s. However, because the stress was proportional to wind speed, we just needed to choose only one condition which generated maximum stress called the critical wind speed condition. In this condition, the structure was subjected to maximum displacement and minimum Factor of Safety (FOS) due to the maximum load applied. Therefore, if the structure could withstand under this critical condition, then it was safe under other wind speed conditions [20].

RESULTS AND DISCUSSIONS

Blade Aerodynamic Efficiency

Using theoretical calculations have fully facilitated us to determine the basic parameters for blade geometry calculation. The β and r on each I is plotted into a graph to facilitate the optimizations calculation. Both optimizations theory said that the blade begin to harness wind energy from 50% and 75% of its radius measured from its base. The 75% optimization use I value of 8 and 9 which derives from 75% of maximum value of I (11), i.e. 8.25, while the 50% use 5 and 6 because 50% of 11 is 5.5. These I values are selectively plotted into a line and subsequently used to create *trendline* for each optimization. From both *trendlines,* we can obtain two equations for each optimization, i.e.

- Optimization linearization 75%

$$y = -8.4337x + 7.0137 \quad (7)$$

- Optimization linearization 50%

$$y = -17.349x + 12.799 \quad (8)$$

Both equations show the linear relation between twist (y) and radius (x) of each section of the blade. The y value obtained is calculated for each value of i and subsequently used as pitch for each design. Every design is compared and consequently one with the best aerodynamic efficiency is chosen as the model.

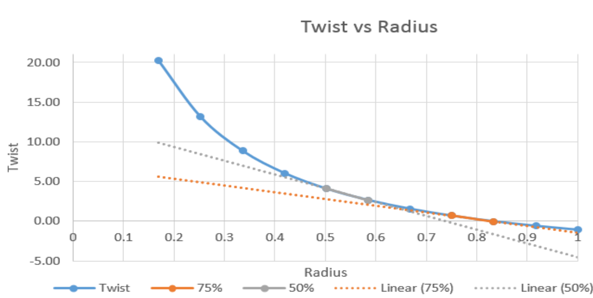

Figure-3. Twist vs radius graph for optimization.

As seen in the Figure-4 and Figure-5, the best efficiency is obtained in the pitch value ranging from 5.58 to 8.41. Therefore, another simulation is conducted in this selected range of pitch to obtain the best design. As seen in the Figure-6, pitch +7 configuration has the best C_P and good TSR range stability. As a result, it is chosen as our desired design because it is not only better in performance but also simpler in geometry.

Considering the value of pitch (7), the chord value which is initially 12 cm changes because the pitch directly twists the blade section and subsequently create an angle which affects the blade chord length. The changes can be calculated using the equation below.

$$C_2 = \frac{C_1}{\cos(p)} \quad (9)$$

The results show that the chord value changes to 12.09 cm. Thus, we should conduct another simulation to compare this new design with the old one.

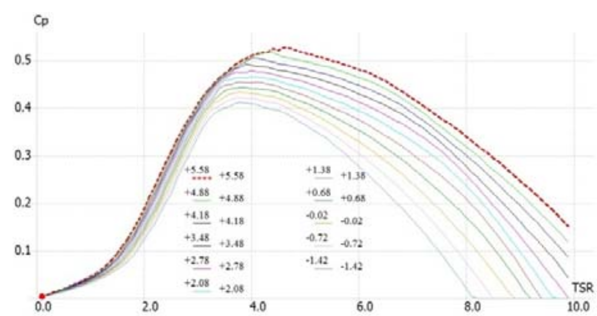

Figure-4. Pitch configuration of 75% optimization.

As shown in the Figure-7, the new design C_P is lower than the old one showing that the old design has better aerodynamic efficiency and performance. To maintain the chord length remains 12 cm, a modification on available material width should be applied. By using equation (9) and setting the C_2 value of 12, we can obtain the C_1 (material width) value of 11.91 cm. Consequently, the material should be cut by 0.09 cm to obtain such dimension. Nevertheless, conducting such cutting process required a high precision which if the poor one is applied, it can change the blade dimension and potentially reduce its aerodynamic efficiency. Therefore, based on both considerations, we choose the 12.09 cm design because its efficiency reduction is relatively small and compare with conducting such potentially risky cutting process.

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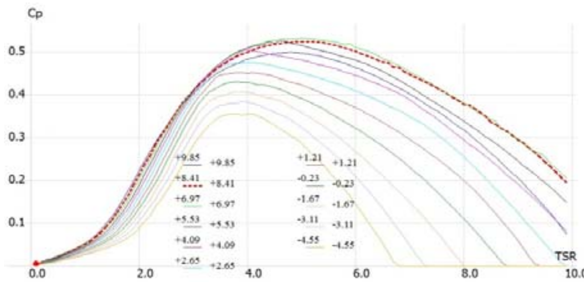

Figure-5. Pitch configuration of 50% optimization.

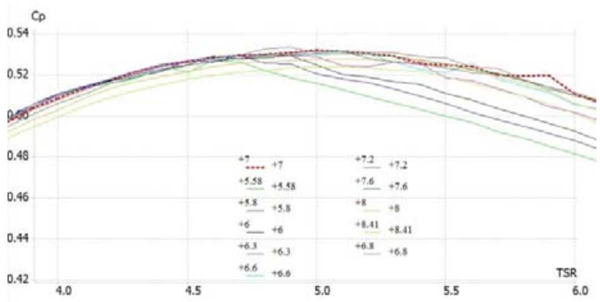

Figure-6. Pitch comparison between 5.58 and 8.41.

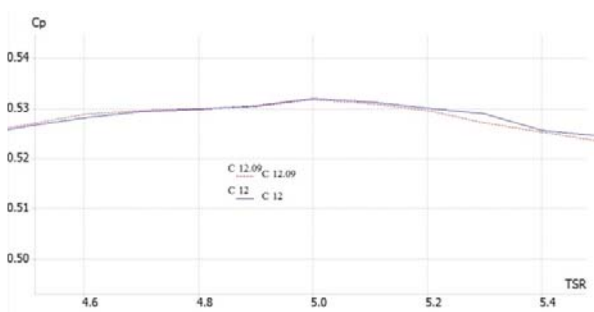

Figure-7. C_P comparison between pitch +7 designs.

Blade Element Momentum Parameters

`By using the BEM parameters, we can determine the phases of operation, i.e.

- The simulation results show that the rotor with joint addition has mass and radius of 2.915 kg and 1 m while shaft has 1.388 kg and 15 mm. By using equation (5), we can obtained the components inertia (I) which is 1.45 kgm^2. Other parameters required to calculate the T_{Min} are ω and t which can be determined by analyzing the rotor performance during various wind speed condition. The results show that to accelerate the rotor from rest to ω of 225 rpm, the time required (t) is 5 s. As all variables required are obtained, thus the T_{Min} value can be determined by using equation (6) and the result is 6.83 Nm. As seen in the Figure-8, at ω of 225 rpm the wind speed (v) condition which the torque generated (T) is higher than T_{Min} is 5.51 m/s. Therefore, this condition is set as the Cut-In speed producing T of 7.12 Nm, TSR of 4.28, C_P of 0.521 and power output (P) of 167.8 watt. Based on previous C_P vs TSR graph, the range of TSR which its corresponding efficiency is still relatively high is from 4 to 6. In this range of TSR, the efficiency value is ranging from 0.5094 at TSR of 4, reaching its highest value of 0.5317 at TSR of 5 and subsequently decreasing to 0.5093 at TSR of 6. After the TSR range, we have to determine the turbine range of operation by calculating the T_{Min} value for each ω. By using the time interval of 2.5 s to 5 s to equation (6), we obtained T_{Min} values and subsequently plotted them into a graph which yields two linear equations for both time intervals, i.e.

- Time interval of 2.5 s

$$y = 0.0607x - 6.829 \tag{10}$$

- Time interval of 5 s

$$y = 0.0304x + 0.0005 \tag{11}$$

Based on the TSR range and both linear graphs, the optimum phase occurs in the area inside both graphs and between TSR of 4 to 6.

- Cut-Off occurs when the power produced by the wind exceeds our generator maximum power input, i.e. 2000 watt [21]. Based on simulation graph, this phenomena takes place at wind speed condition above 12.51 m/s. Therefore, this condition is set as the Cut-off speed because it not only produces excess amount of power but also has a low value of probability.

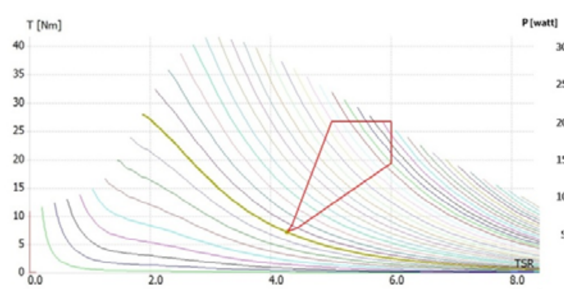

Figure-8. Rotor optimum operation phase region.

The results of this multi BEM parameters simulation has given us the appropriate wind turbine operation phase. This phase is an area inside the T vs TSR graph which is an intersection between the areas above the Cut-In torque value, inside both T_{Min} linear graphs, between TSR of 4 to 6 and below the Cut-Off speed condition. The area is marked inside the bold red line as seen in the Figure-8 where each colored line represents

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rotational speed. Another result obtained in this graph is the condition which the turbine generates maximum power output of 1959 watt which is achieved at ω of 700 rpm, v of 12.51 m/s, T of 26.7 Nm, TSR of 5.86 and C_P of 0.52.

Blade Structure Loading

In order to ensure that the design is absolutely safe, the simulation is conducted under the critical wind speed condition of 30 m/s which potentially happen under hurricane. The simulation results show that the blade produce a maximum von misses stress of 9.203×10^6 N/m2 at its blade and hub connection region and a maximum displacement of 16.86 mm at its tip. It is inappropriate to simulate the structure and analyzing its performance without determining whether it is safe or not under this relating critical condition. One way to determine its safety is by analyzing the Factor of Safety (FOS) distribution along the blade structure. The blade is categorized safe if the Factor of Safety (FOS) value at every section is more than 1 (FOS>1) otherwise it is regarded fail and the design had to be re-optimized gradually. The simulation result shows that the minimum Factor of Safety (FOS) produced is 5.43 (FOS>1) located at the connection region between blade and hub. The result means that the blade is 5.43 times safer under this critical wind speed condition and feasible to be built as one of the wind turbine components.

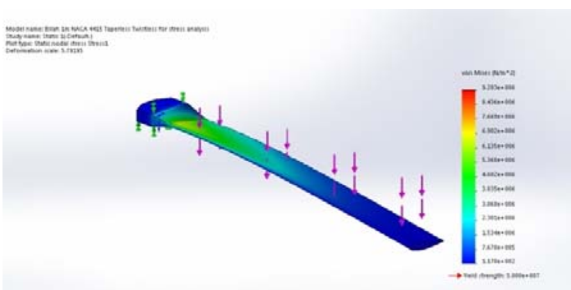

Figure-9. Stress distribution along the blade structure.

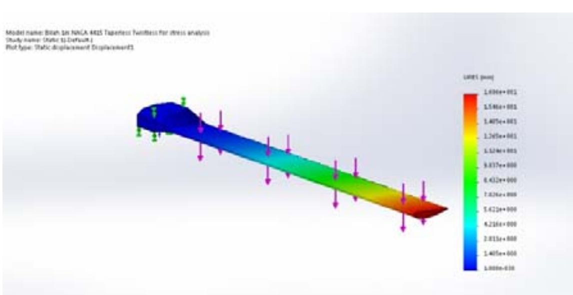

Figure-10. Displacement distribution along the structure.

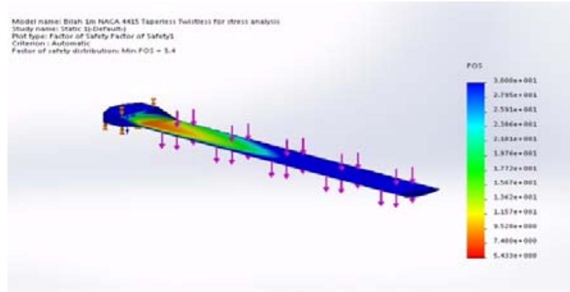

Figure-11. FOS distribution along the blade structure.

CONCLUSIONS

- Application of optimizations in blade geometry has produced a high efficiency blade which operates optimally at efficiency range of 50.94% to 53.17% and TSR range of 4 to 6. This value of efficiency is categorized high because it is only 6-8% lower compare to Betz limit [22].
- Selection of rotor operation phase has succeeded in making the turbine to generate mechanical power efficiently. This is proven by examining the Cut-In (5.51 m/s) and Cut-Off (12.51 m/s) speed condition where inside both conditions the energy outputs produced (kWh) are relatively high as seen in anemometer data. Considering the blade efficiency, these amount of outputs can be harnessed by 50.94 % to 53.17% to be converted into mechanical power.
- Wood material selection and geometry simplicity directly facilitate the manufacturing process. However, the implementation requires further researches and studies including material selection, manufacturing process and production cost and profit calculation. The purpose is to create a blade with affordable cost and efficient production time so the mass production is feasible.

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APPENDIX

Nomenclature		r_S	shaft radius [m]
		m_R	rotor mass [kg]
R	blade radius [m]	r_R	rotor radius [m]
h	blade hub [m]	v	wind speed [m/s]
r	partial radius [m]	ω	rotational speed [rad/s]
i	section number [-]	P	power [watt]
C_L	lift coefficient [-]	T	torque [Nm]
C_D	drag coefficient [-]	T_{Min}	minimum torque required [Nm]
C_P	power coefficient [-]	$\Delta\omega$	change of rotational speed [rad/s]
λ	Tip Speed Ratio (TSR) [-]	t	time interval [s]
λ_r	partial TSR [-]	p	pitch [rad]
ϕ	flow angle [rad]	C_1	Old chord length [m]
α	angle of attack [rad]	C_2	New chord length [m]
β	twist angle [rad]	FOS	Factor Of Safety
I	inertia [kgm^2]	BEM	Blade Element Momentum
m_S	shaft mass [kg]	FEM	Finite Element Method

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