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Power Optimization of Horizontal Axis Wind Turbine Rotor Capacity of 1 MW on Various Parameters of The Airfoil, Angle of Attack, And A Pitch Angle

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Abstract. The rotor is one of the main components of a wind turbine. In the design of the rotor, the expected result is the most optimal power. Many factors affect the power output of a wind turbine rotor, namely the type of airfoil, the selection of the angle of attack, and the selection of the pitch angle using simulation. The purpose of the study was to optimize the parameters of the wind turbine rotor with a capacity of 1 MW. The parameter variations used are airfoils (NACA 4412-2412 T.E mod, NACA 2412-4412 T.E mod, NACA 4412-2412 L.E mod, NACA 2412-4412 L.E mod), angle of attack (0˚, 2˚, 4˚, 6˚), and pitch angle (0˚, 1˚, 2˚, 3˚). The simulation method uses Blade Element Momentum (BEM) and the Taguchi method for optimization based on the L_{16} orthogonal array matrix. The ANOVA analysis was used in this study to determine the contribution of each parameter to the power generated by the wind turbine rotor. Simulation and optimization results show that the most optimal parameter to be applied was a NACA airfoil 4412-2412 L.E mod, at 0˚ angle of attack and 0˚ pitch angle, with the resulting power reaching 1015780 watts. The ANOVA analysis shows the airfoil parameter has the greatest contribution to the rotor power of the HAWT compared to the pitch angle and angle of attack.

Keyword: airfoil, angle of attack, blade element momentum, HAWT, optimization, pitch angle, wind speed

1. Introduction

The Southeast Asian region has wind energy that is quite potential to be used in wind turbines, one of the areas with potential is Indonesia at wind speeds reaching 4-7 m/s [1]. Therefore, based on the Beaufort scale, the wind speed is classified as low-medium wind speed [2]. Moreover, the medium wind speed classification has the potential to be utilized but has not been able to produce effective and high power. Wind speed of 2-7 m/s is relatively suitable for small capacity power plants, namely 10-100 kW [3], that is necessary to develop wind energy conversion tools according to the wind speed.

One potential utilization of wind energy is to use a wind energy conversion tool, namely the horizontal axis wind turbine rotor, which is the first component of the turbine to receive wind kinetic energy to produce mechanical energy to rotate the rotor for further conversion into electrical energy [4]. Nevertheless, HAWT relatively low wind speed in Indonesia can be used because of its high efficiency of HAWT [5]. Ordinarily, the design of the rotor influences the power generated, components and parameters that are considered in designing the rotor is design a proper blade. Parameters in designing a blade are includes selecting the airfoil type, setting the angle of attack and the angle of inclination of blade.

Testing the wind turbine rotor performance should be as fast and accurate as possible. One of the software that can simulate parameter values affecting wind turbines is called Qblade software. This software allows users to design airfoils and can be directly integrated into the simulation and rotor design. Besides that, there is also a method to predict wind turbine efficiency that has been designed more cost-effectively, namely Blade Element Momentum (BEM) [6]. BEM theory uses to analyze the rotor power of the wind turbine, optimize the rotor geometry, and evaluate the force and torque acting on the blades [7].

Research related namely the simulation, optimization, and analysis of a horizontal axis wind turbine on a rotor diameter of 25 m using 8 types of NACA airfoils such as 0020, 0018, 0015, 0012, 5520, 5518, 5515, and 5512 found that most optimal rotor design using 55xx blades to produce a power of about 500 KW at a wind speed of 9 m/s [8]. The study of the optimal angle of attack between the NACA 0012 blade and the NACA 2412 blade uses BEM to find that the maximum lift coefficient is when the angle of attack increases. Moreover, the NACA 2412 airfoil shows higher efficiency at a tip speed ratio of 7 and produces a maximum power output compared to the NACA 0012 airfoil [9].

The study focused on determining the optimal angle of attack between the NACA 0012 and NACA 2412 blades to obtain the maximum lift and drag ratio, using the Blade Element Momentum (BEM). Accordingly, the result is that the NACA 2412 airfoil shows higher efficiency at a tip speed ratio of 7 and produces a maximum power output compared to the NACA 0012 airfoil [10]. The effect of setting the pitch angle with 5 variations of displacement, namely +6°, +3°, 0°, -3°, -6° to get the power coefficient for TSR variations from 3 to 7 using BEM calculations, moreover the pitch angle setting of 0° and +3° has the best effect on turbine efficiency [11]. Study optimization of small-scale wind turbine design on the 10 variations of NASA airfoils, parameters angle of attack 0° to 20° obtains that lift coefficient value and lift to drag ratio best found the SD7080 airfoil [12].

Simulation and optimization of HAWT rotor power using NACA 2412 and NACA 4412 of the airfoil using blade Element Momentum (BEM), obtain to use the NACA 4412-2412 airfoil trailing edge modified at an angle of attack of 3° and a wind speed of 8 m/s is the most optimal parameter [13].

Airfoil modification on the leading edge for wind turbine rotors by adding bumps so that a higher lift coefficient was found when compared to wind turbines without additional bumps [14]. The same thing was also done in research [15][16][17] related to airfoil analysis with the addition of bumps on the wings of the aircraft in order to obtain better operating performance at a certain angle of attack.

According to the above literature, although research on the performance analysis of HAWT was conduct, the works are focused on certain factors, such as airfoil type, pitch angle, and angle of attack. The previous literature shows that even though study on the performance analysis of HAWT has been done, the works have a specific focus on the kind of airfoil, pitch angle, and angle of attack. It is essential to understand that while using a HAWT in low wind conditions, numerous factors may have unique and concurrent effects on the airfoil variation, pitch angle, and angle of attack. In order to obtain improved parameters of the performance of the HAWT power rotor, it underlines the requirement of concurrent investigation on optimizing airfoil type, angle of attack, and wind speed. Therefore, the goal of this study was to simulation and optimize the HAWT power from variations in airfoil shape, angle of attack, and pitch angle.

Method

This research is a simulation using the BEM method on Qblade Software to design and determine the rotor power, BEM is a method that is able to predict the performance of a turbine rotor [18]. The BEM method is based on the estimation of the force acting on each blade segment, the blade will be divided into several segments assuming each element is independent and the fluid flow of each segment has no interaction. Force and moment for each segment will calculated. Accordingly, the total forces and moments is the integration of all the forces and moments of each element [19][20]. The thrust generated by the blade segment based on the blade element theory can be determined using the equation:

$$dT = B\frac{1}{2}\rho V_{total}^{2}(C_l \cos\varphi + C_d \sin\varphi)\, cdr \tag{1}$$

After the thrust obtained, the torque which work on each blade segment can be calculated according to the blade element by using the equation:

$$dQ = B\frac{1}{2}\rho V_{total}^{2}(C_l \sin\varphi - C_d \cos\varphi)\, crdr \tag{2}$$

Where dT is the thrust, dQ is the torque on the blade sections, B is number of blades, ρ is the air density, V_{total} is the resultant velocity, C_l is the lift coefficient, C_d is the drag coefficient, φ the inflow angle, c is the airfoil chord, and r is the distance of the element from hub.

The force which acts on an airfoil, the chord line to the wind direction is the angle of attack (α) and the chord line to the line of rotation is the pitch angle (β) accordingly shown in figure 1a and 1b [13].

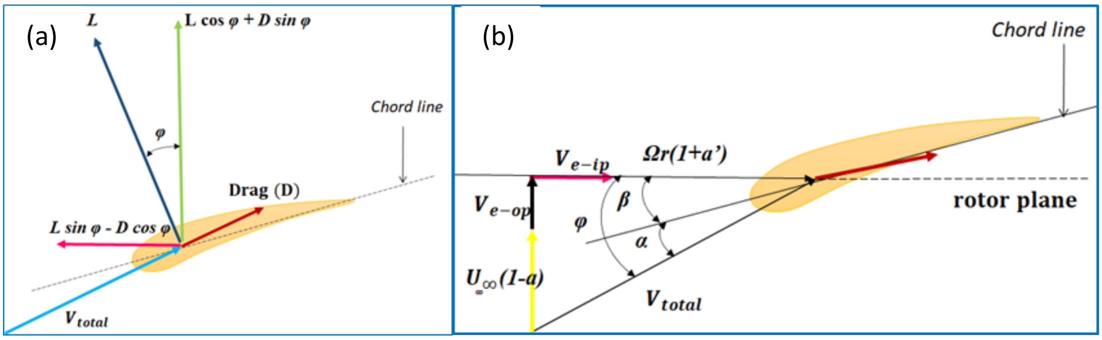

Figure 1 Local element (a) forces (b) velocities and flow angles [13]

Table 1. Parameter setup of the 1 MW HAWT Model

Specification	Value
Air density (kg/m^3)	1,225
Number of blades	3
Blade length (m)	55
Radius of hub (m)	1,25
tower height (m)	110
Swept Area (m^2)	10.023,67

The Taguchi method is used for the optimization process where the use of the Taguchi method aims to make the quality of a product better so that it can get more optimal results, where in designing more efficient experiments and analyzing data from simulations, an orthogonal array matrix is used which is a matrix of the number of rows and the columns are arranged based on the number of factors and levels in the experiment [21]. The main goal of Taguchi analysis is to produce a product that is resistant to interference so that an optimal solution or parameter can be find and has high resistance for the optimal product [22] [23].

Ordinarily, the analysis results from the Taguchi method will display the means, signal to noise ratio and standard deviations [24]. Moreover, seeing the number of variables to be taken, this research model is very suitable because it is able to provide a combination of 2 groups or more different variables to determine the result effect, besides that, the Taguchi method also has the advantage of being able to determine the minimum number of experiments with the most effective results possible. The S/N ratio on Taguchi is used to find the factors that affect the results of power variance, it also used to study the noise factor for the results variation of parameters because it is considered stronger, simpler and can be applied efficiently for quality improvement and control. Characteristics of the S/N ratio used, the bigger the better. The value of S/N Ratio can be calculated using the equation:

$$S/N_L = -10\, log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y^2}\right) \tag{3}$$

Where y is the value of data, and n is the number of samples.

This study uses 3 independent variables, each variable has 4 levels of variation, so an orthogonal array is needed to determine the minimum number of experiments to be carried out. DOF calculation conducted to find out the fewest experiments that must be done, that is:

$$\begin{aligned} Total\ dof &= \text{(number of factor) x (number of level)} \\ &= 3 \text{ x } (4\text{-}1) = 9 \end{aligned} \tag{4}$$

So it found as many as 9 attempts at least. The orthogonal array matrix that will use has a level 4 standard. Nevertheless, based on the three standard OA matrices whose available values are L_{16}, the orthogonal array matrix used is $L_{16}(4^3)$. This study also uses two-way ANOVA analysis to determine the effect of each input parameter on the resulting rotor power [25]. The output of ANOVA analysis includes the degrees of freedom for each factor, the total degrees of freedom, the degrees of freedom of error, the final percentage, the mean squared and the F-ratio. Ordinarily, the conditions that must fulfil in the ANOVA test are the independence of observation, the data studied must be normally distributed and the variance of the group is homogeneous, when all these conditions have been fulfil, the ANOVA test can be doing. The test whether the data is normal or not, many methods can be use, the Kolmogorov Smirnov test has been used in this study.

$$F\ (Xi) = f(X \geq Xi) \tag{5}$$

$$F\ (Zi) = f(\leq Zi) \tag{6}$$

$$Zi = \frac{Xi - \bar{X}}{s} \tag{7}$$

$$Di = |F(Zi)F(Xi)| \tag{8}$$

Where $\bar{\bar{X}}$ is the mean of sample, $F\ (Xi)$ is the cumulative probability of the value of (Xi), $f(Xi)$ is the probability of the value (Xi), Zi is the standardized sample normal value from transformation result (Xi), $F(Zi)$ is the cumulative probability from the value of (Zi), and Di is the result of komogorov smirnov normality.

In a study, the used data need to be known whether it comes from a sample or population that is uniform/homogeneous. If there are at least 2 groups with the same data variance in a data, the data is considered uniform. Accordingly, Barlett equation is used to determine the homogeneity of the data in this study.

$$S^2 = 1 + \frac{n\sum_{n=}^{n} x^2 - (\sum_{n=i}^{n} x^2)^2}{n(n-1)} \tag{9}$$

$$S^2 j = \frac{\sum\ db.S^2}{\sum\ db} \tag{10}$$

$$B = (\sum \quad db)\,(\log S^2\, j) \tag{11}$$

Where S^2 is the square variance, i is the data at-i, x is the value of data, n is the number of data, db is the degree of freedom, and B is the barlett result.

Confirmation test is carried out to determine whether the parameter settings recommended by Taguchi optimization can produce good data or vice versa. Confirmation test results can be estimated by predictive value and confidence interval using the equation:

$$\mathrm{N} = \eta + \textstyle\sum_{i=1}^{p} (\eta opt - \eta) \tag{12}$$

$$\eta = 1/\eta t + \textstyle\sum_{i=1}^{\eta t} \eta i \tag{13}$$

Where η is the mean of replication data, p is the optimal factors and levels affecting quality characteristics, ηi is the replication data at-i, $\eta t$is the number of test, and ηopt is the mean for optimal factors and levels.

$$Cl = \sqrt{F_{a,1,Dfe} . Ve \,. \left(\tfrac{1}{neff} + \tfrac{1}{r}\right)} \tag{13}$$

$$neff = \tfrac{n}{1+Vt} \tag{14}$$

Where Ve is the average square of the error in the ANOVA table, $F_{a,1,Dfe}$ is the F ratio at significance level a% (F0.5), Dfe is the degree of freedom $error$ on ANOVA table, $neff$is the total effective value, n is the number of test, and r is the number of confirmation test.

The main purpose of this study is to find the influence of variations parameters against rotor power using the Qblade software and the optimization settings of these three parameters on the rotor power. Variations of parameters used are as Table 2.

Table 2. Variation of Rotor Power Optimization Parameters

Parameters	**Factor**	**Levels**			
		1	2	3	4
Pitch Angel	**A**	0^o	1^o	2^o	3^o
Angel of Attack	**B**	0^o	2^o	4^o	6^o
NACA Airfoil Type	**C**	4412-2412 T.E Mod	2412-4412 T.E Mod	4412-2412 L.E Mod	2412-4412 L.E Mod

Taguchi optimization with orthogonal array L_{16} is used in determining simulation parameter settings. The design of the OA matrix adjusted to the number of factors and levels used in the simulations as shown in Table 3. The L_{16} orthogonal array matrix is used in input setting parameters at Qblade software to obtain HAWT rotor output power data.

Table 3. Matriks Ortogonal Array L_{16} (4^3)

No		**FACTOR**	
	A	**B**	**C**
1.	4412-2412 T.E Mod	0	0
2.	4412-2412 T.E Mod	2	1
3.	4412-2412 T.E Mod	4	2
4.	4412-2412 T.E Mod	6	3
5.	2412-4412 T.E Mod	0	1
6.	2412-4412 T.E Mod	2	0
7.	2412-4412 T.E Mod	4	3
8.	2412-4412 T.E Mod	6	2

9.	4412-2412 L.E Mod	0	2
10.	4412-2412 L.E Mod	2	3
11.	4412-2412 L.E Mod	4	0
12.	4412-2412 L.E Mod	6	1
13.	2412-4412 L.E Mod	0	3
14.	2412-4412 L.E Mod	2	2
15.	2412-4412 L.E Mod	4	1
16.	2412-4412 L.E Mod	6	0

There are 2 types of main airfoils in this study, namely NACA 4412 (Figure 2) as the 1st variation and NACA 2412 (Figure 3) for the 2nd variation. Furthermore, the 3rd variation uses a combination of NACA 4412 with NACA 2412, then and the last variation is a modification of the lower surface prior to the trailing edge of the two airfoils NACA4412mod-2412mod. The form difference of the NACA 4412 and NACA 2412 airfoils before-after modification is found on the lower surface before the trailing edge such as the area marked in circular red (modified form) in Figures 4 and Figure 5. The standard NACA airfoil with NACA modification has a y-coordinate difference of 0.06 for the NACA 4412 airfoil (Figure 6) and 0.0148 for the 2412 airfoil (Figure 7) on the lower surface at points 0.9 to 1.

This study uses 4 types of airfoils, namely 2 modified NACA airfoils on the leading edge and 2 modified NACA airfoils on the trailing edge, all the airfoils are shown and described in the following Figure 2 to 5.

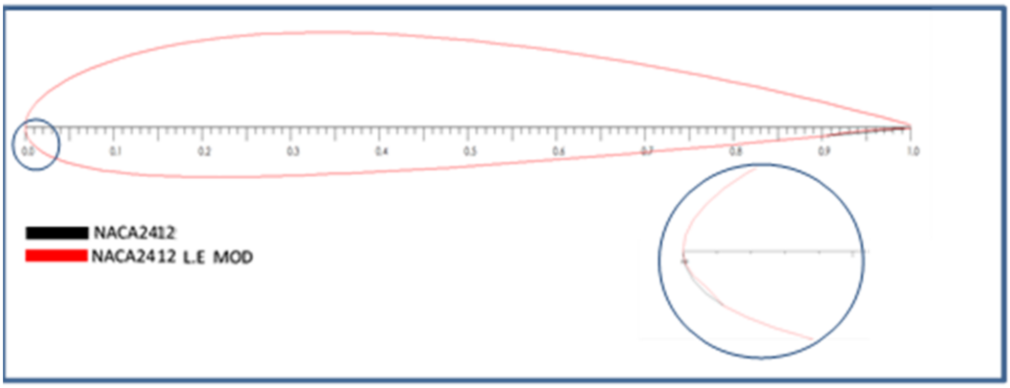

Figure 2 Geometry of NACA 2412 L.E Mod Airfoil

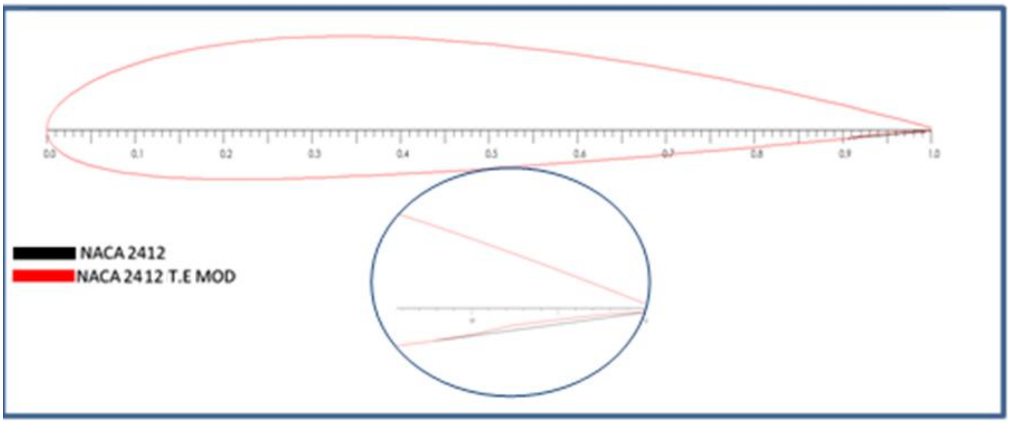

Figure 3 Geometry of Airfoil NACA 2412 T.E Mod

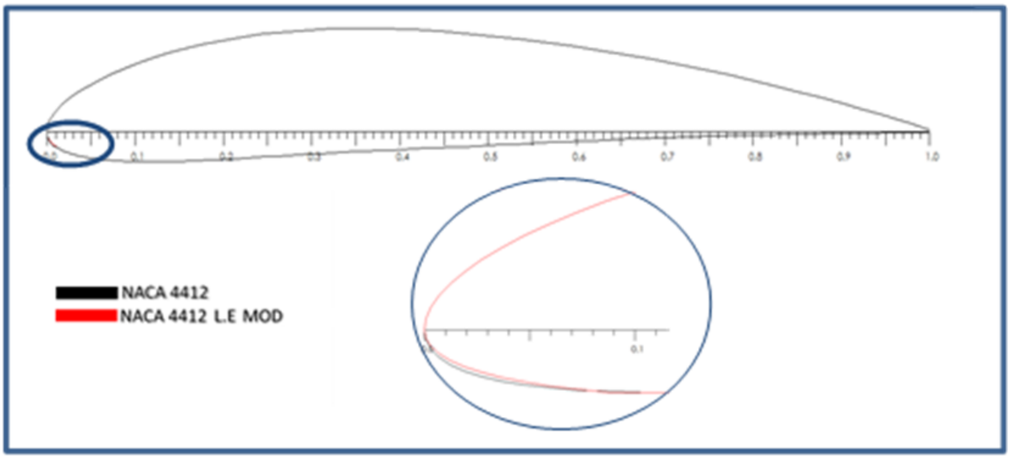

Figure 4 Geometry of Airfoil NACA 4412 L.E Mod

NACA 2412 L.E Mod Airfoil (Figure 2) modified 6 points coordinate on the leading edge of NACA 2412 airfoil and change it with 6 points coordinate on the leading edge of airfoil NACA 1410 so it can get higher lift coefficient than 2412 NACA standard airfoil.
NACA 2412 T.E Mod Airfoil [9] shown in Figure 3 was modified 6 points coordinate on the trailing edge of NACA 2412 airfoil so it can get higher lift coefficient than 2412 NACA standard airfoil.

NACA 4412 L.E Mod Airfoil (Figure 4) modified 11 points coordinate on the leading edge of NACA 4412 airfoil and change it with 11 points coordinate on the leading edge of airfoil NACA 2410 so it can get higher lift coefficient than 4412 NACA standard airfoil.

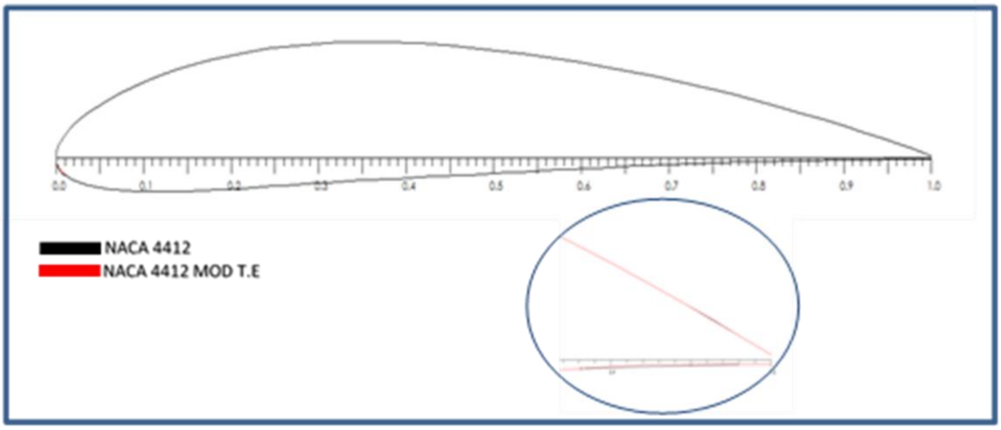

Figure 5 Geometry of Airfoil NACA 4412 T.E Mod

NACA 4412 T.E Mod Airfoil [9] shown in Figure 5 was modified 6 points coordinate on the trailing edge of NACA 2412 airfoil so it can get higher lift coefficient than 4412 NACA standard airfoil.

After selecting the airfoils, the blade design is conducted by inputting the airfoil in each segment. Each rotor has 3 blades and has 54 m radius, design of chord for each segment is using the design according to [9]. Furthermore, input the angle of attack using the optimization menu on Qblade software for the optimal blade rotorThe blade design in Figures 6 to 9 uses circular airfoils in the first and second segments [9], then 4412 T.E Mod airfoils on segments 3 to 9, and NACA 2412 T.E Mod airfoils on segments 10 to 11.

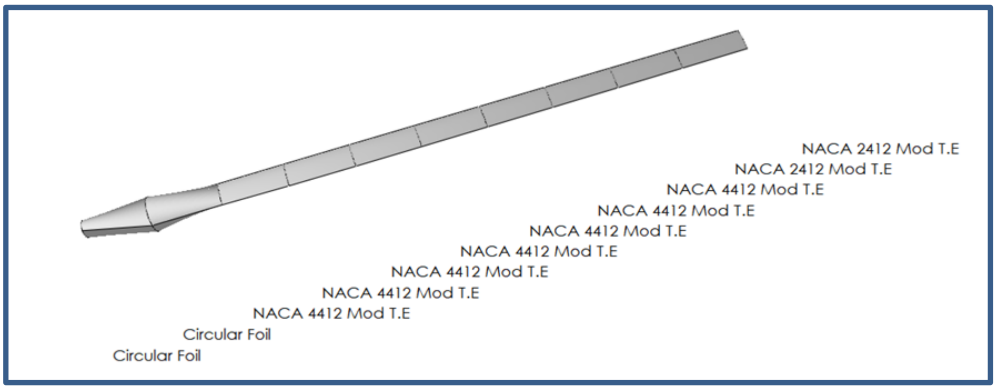

Figure 6. Blade Design using NACA 4412-2412 T.E Mod Airfoil

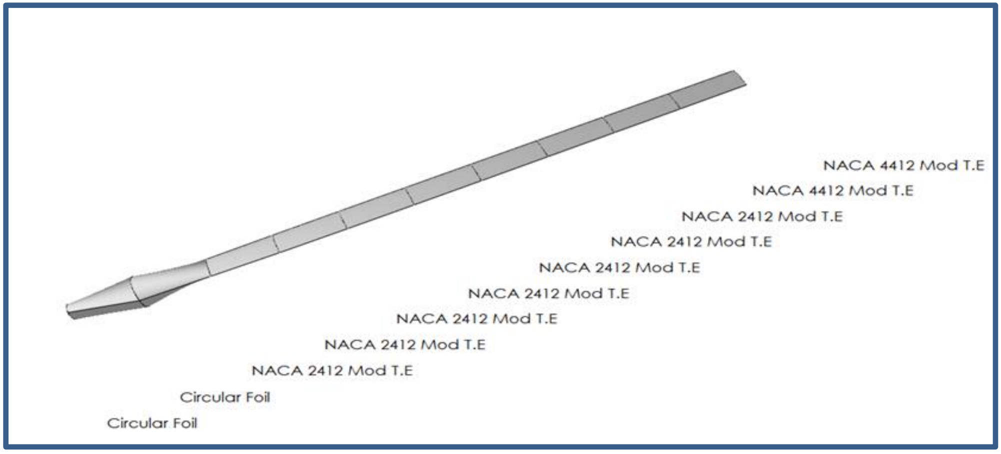

Figure 7. Blade Design using NACA 2412-4412 T.E Mod airfoil

The design in Figure 6 uses circular airfoils in the first and second segments then NACA 2412 T.E Mod airfoils on segments 3 to 9 and NACA 4412 T.E Mod airfoils on segments 10 to 11.

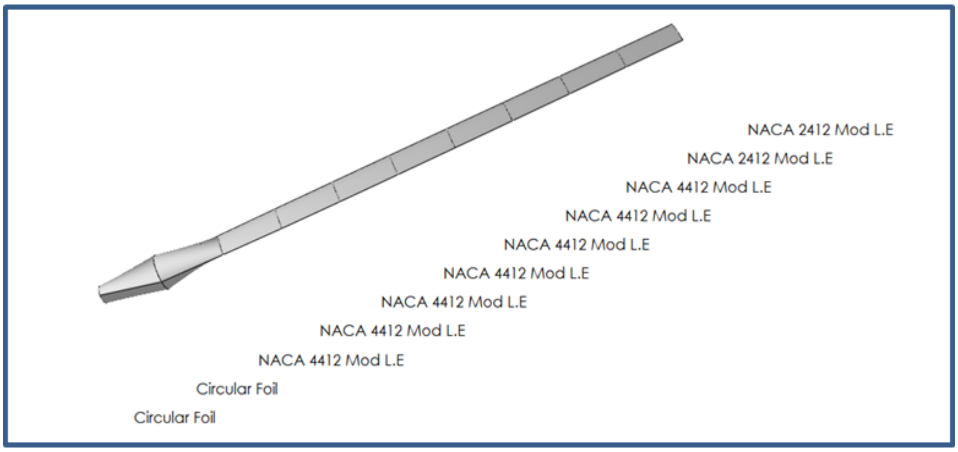

Figure 8. Blade design using NACA 4412-2412 L.E Mod airfoil

The design in Figure 8 uses circular airfoils in the first and second segments [9] then NACA 4412 L.E Mod airfoils on segments 3 to 9 and NACA 2412 L.E Mod airfoils on segments 10 to 11.

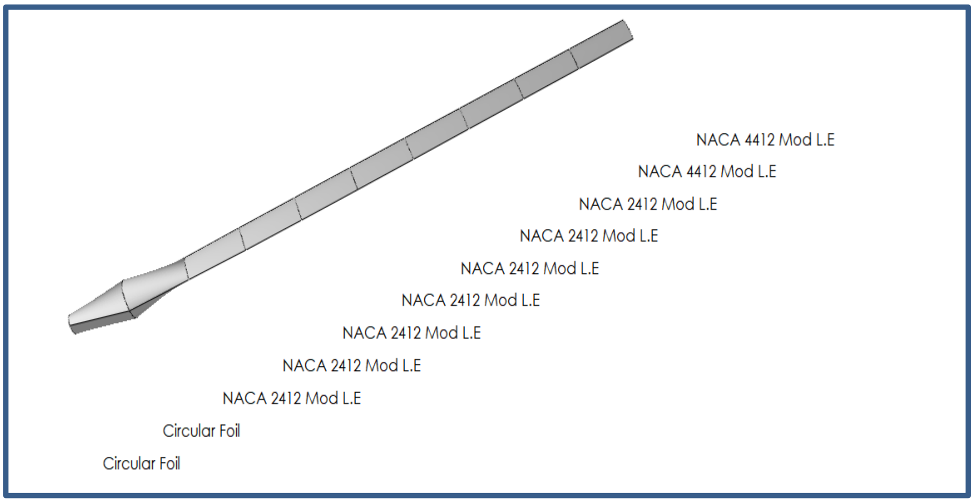

Figure 9. Blade design using NACA 2412-4412 L.E Mod airfoil

The design in Figure 9 uses circular airfoils in the first and second segments [9] then NACA 2412 L.E Mod airfoils on segments 3 to 9 and NACA 4412 L.E Mod airfoils on segments 10 to 11

2. Results and Discussion

The simulation was carried out by inputting parameters in the Qblade software according to Taguchi's level, referring to the factor arrangement in Table 4. Furthermore, the results of the rotor power show that there are parameter settings capable of producing power above 1 MW.

Table 4. Rotor Power Simulation Result Data

No	**Factor**			**Power Rotor (Watt)**
	Airfoil Type	**Angel of Attack (º)**	**Pitch Angel (º)**	
1	4412-2412 T.E Mod	0	0	1013803
2	4412-2412 T.E Mod	2	1	995530
3	4412-2412 T.E Mod	4	2	957850
4	4412-2412 T.E Mod	6	3	838845
5	2412-4412 T.E Mod	0	1	888720
6	2412-4412 T.E Mod	2	0	905600
7	2412-4412 T.E Mod	4	3	907220
8	2412-4412 T.E Mod	6	2	884855
9	4412-2412 L.E Mod	0	2	1006630
10	4412-2412 L.E Mod	2	3	975030
11	4412-2412 L.E Mod	4	0	976680
12	4412-2412 L.E Mod	6	1	930290
13	2412-4412 L.E Mod	0	3	907830
14	2412-4412 L.E Mod	2	2	916300
15	2412-4412 L.E Mod	4	1	903520
16	2412-4412 L.E Mod	6	0	877710

The ANOVA test has conducted to determine the effect, contribution value, and level of significance of the parameters, namely, the type of airfoil, the angle of attack, and the pitch angle on the HAWT rotor power. The ANOVA test on the simulation results of rotor power shows the airfoil type has a significant effect where the P-Value is less than 0.05. As shown in the following table, parameters of the angle of attack and pitch angle do not have a significant effect, whereas P-Value is above 0.05 (Table 5).

Table 5. Analysis of Variance Data Result

Source	*DF*	*Seq SS*	*Contribution*	*Adj SS*	*Adj MS*	*F-Value*	*P-Value*
Airfoil Type	3	16704809417	42,34%	16704809417	5568269806	4,95	0,046
Angle of Attack	3	12685333787	32,16%	12685333787	4228444596	3,76	0,079
Pitch Angel	3	3316094414	8,41%	3316094414	1105364805	0,98	0,461
Error	6	6743167731	17,09%	6743167731	1123861288		
Total	15	39449405348	100,00%				

Based on Table 5, shows the different P-Value values, where the airfoil factor has a P-Value value of 0.046, the angle of attack with P-Value is 0.079 and the pitch angle with P-Value is 0.461, accordingly it can decided that only the airfoil factor has a significant effect on the power generated by the horizontal axis wind turbine rotor because the P-Value value of the airfoil factor 0.05, while the angle of attack and pitch angle factors have a P-Value value 0.05 so it is declared to have no significant effect on the power generated wind turbine rotors. The airfoil factor has the highest contribution value i.e 42.34%, followed by the angle of attack factor with a contribution percentage value of 32.16% and the last is the pitch angle factor with a percentage value of 17.09%.

The analysis result of the average response value and signal to noise ratio are used in determining factors and setting the optimal level. Table 5 shows the results of the SN ratio for each factor level setting. Figure 9 shows a graph of the factors and levels that affect the HAWT rotor power output.

Table 6. Signal to noise response of Rotor Power

Level	**Airfoil Type**	**Angel of Attack**	**Pitch Angle**
1	119,54	119,6	119,48
2	119,05	119,5	119,36
3	119,75	119,4	119,47
4	119,10	118,9	119,14
Delta	0,7	0,7	0,34
Rank	1	2	3

Based on Table 5, the airfoil type has the largest contribution to rotor power, followed by angle of attack and pitch angle setting. According to table 5 and figure 9, The optimal combination of parameter settings for optimal rotor design is airfoil level 3, namely airfoil NACA combination 4412 -2414 L.E Mod, setting the angle of attack at level 1 which is 0 °, and setting the pitch angle at level 1 which is 0°.

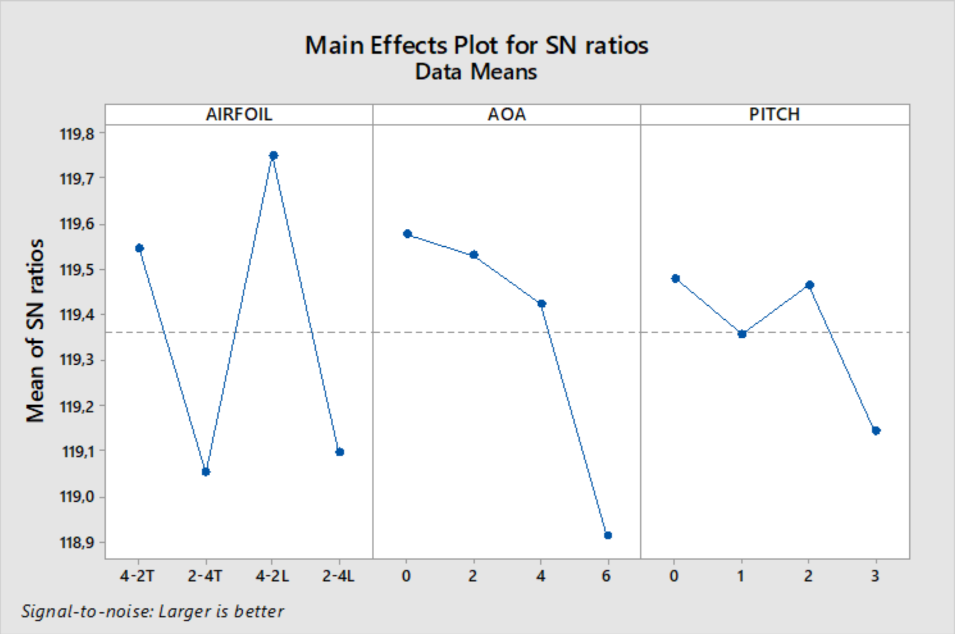

Figure 10. Signal to noise Ratio Graph of Wind Turbine Power Rotor

In order to know the optimal parameter settings capable of giving good results, a confirmation test was carried out on the power generated by the wind turbine rotor. Before conducting a confirmation test, it is necessary to calculate the predicted value and tolerance of the power generated. Furthermore, a simulation is carried out with the Taguchi recommendation parameters, if the confirmation test results show a value that is still within the interval range, the Taguchi experimental design stated successful. The results of the predicted rotor power in the optimal parameter setting conditions can be seen in Table 6 with the optimal value of 1009050.375 watts and interval at range ±69213,139, then a confirmation test was carried out using the Taguchi recommendation parameter setting with the aim of whether the predicted value was in accordance with the results of the confirmation test experiment.

Accordingly, the results of the confirmation test in Table 7 show the results of 1,015,780 watts where the results of the confirmation test are still within the range of the predicted value interval of ±69213,139. Moreover, the value of the results of the confirmation test itself is in accordance with the desired capacity, which is more than 1MW.

Table 7. Prediction Value and Interval of Rotor Power

Prediction	**Interval**
1009050,375	±69213,139

Table 8. Confirmation Test Result

NO	**Parameter**			**Power (watt)**
	Airfoil type	**Angle of attack** (°)	**Pitch angle** (°)	
1	4412-2412 L.E Mod	0	0	1.015.780

This study conducted a validation test to confirm the result validity level with previous studies using the CFD method. Research analyzes the rotor using the CFD method with the parameters shown in Table 4.9 where with these parameters, the CFD simulation in research [26] produces a power of 927,78 Watts.

Table 8. CFD simulation research Data Parameter

Blade Degree (°)	***Airfoil***	**v (m/s)**	**Blade Lenght (m)**	**Density (kg/m^3)**	**Power(watt)**
0	0018	31,94	2,6	1,225	927,78

These parameters are entered into the rotor simulation using the BEM method to compare the power value of the CFD simulation results with the power value obtained from the BEM simulation results, the BEM simulation results are shown in Figure 10. Accordingly, based on the BEM simulation results graph shows the power generated is 952 Watt.

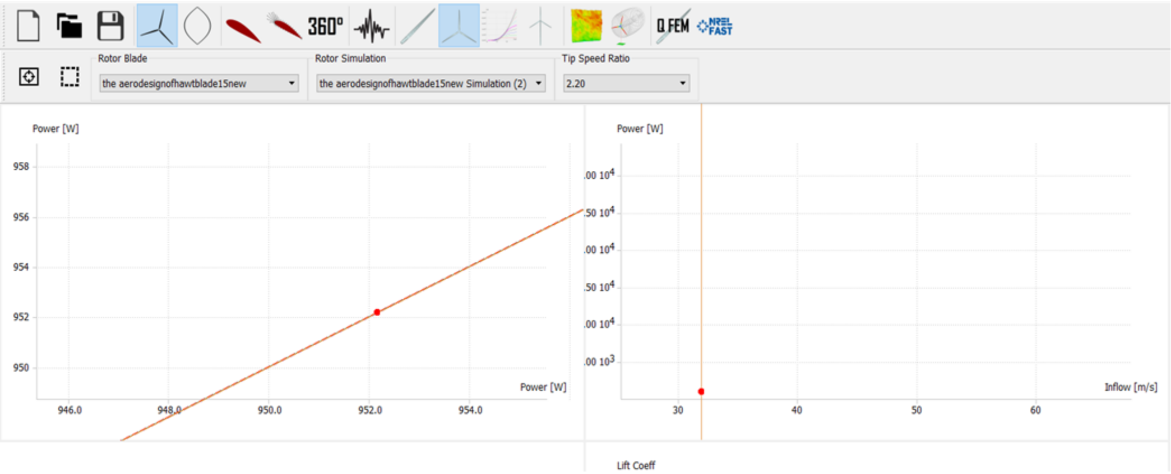
Rotor Blade: the aerodesignofhawtblade15new
Rotor Simulation: the aerodesignofhawtblade15new Simulation (2)
Tip Speed Ratio: 2.20

Figure 11. Power Rotor HAWT with BEM Simulation on Qblade Software

Table 9. Comparison of Power Results Using the BEM vs CFD Metode Method

Simulation Method	**Blade Degree (°)**	***Airfoil***	**v (m/s)**	**Blade Lenght (m)**	**TSR**	**Density (kg/m^3)**	**Power(watt)**
CFD	0	0018	31,94	2,6	-	1,225	927,78
BEM	0	0018	31.94	2,6	2,2	1,225	952

% *Error*:

$$\frac{(X2 - X1)}{X1} = \frac{(952 - 927{,}78)}{927{,}78} x\ 100 = 2{,}7\%$$

The results of the aerodynamic simulation between the CFD by research [2] and the BEM values are not too far apart, an error test has also been carried out and the percentage error result is 2,7%. Accordingly, the BEM aerodynamic simulation on the turbine rotor is quite in accordance with the desired conditions. Validation was also obtained by looking at research [27] on the comparison between the Ansys Fluent CFD method and the Qblade BEM using the following rotor parameters:

Table 10. Research Parameter Data Comparison of CFD and BEM

Radius (m)	**Wind Speed (m/s)**	**Number of Blade**	**Airfoil type**
1	12	3	NACA 4412

The results are shown in Figure 11 where the difference in the coefficient of maximum power produced by the turbine using the CFD method is 0.45 moreover the BEM is 0.48 not so far away with a percent error of 6.67% where the BEM method does not use the calculation of turbulent effects which causes the power coefficient of the result. Nevertheless, BEM simulation > power coefficient from CFD simulation [27] so that the BEM aerodynamic simulation on the turbine rotor is quite in accordance with the desired conditions

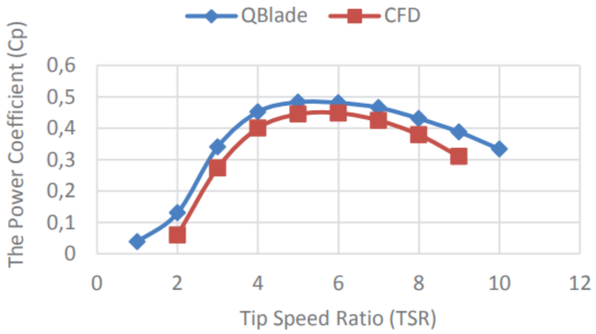

Figure 12. Comparison of power coefficient results using Qblade BEM vs CFD [10]

$$\frac{(\mathrm{X2}-\mathrm{X1})}{X1}=\frac{(0{,}48-0{,}45)}{0{,}48}x\ 100=6{,}67\%$$

3. Conclusions

HAWT power rotor simulation results by optimizing airfoil type parameters, setting the angle of attack and pitch angle on the HAWT power rotor have obtained using Qblade Software. The optimization method used was Taguchi orthogonal array L_{16} and the significance process parameters was analyzed through ANOVA. Based on the description that has explained, the conclusions obtained are:

1. Airfoil type has the most significant effect on the power generated by the HAWT rotor with the highest contribution value of 42.34%. Nevertheless, the angle of attack and pitch angle in Qblade software does not have a significant effect on the power generated by the wind turbine rotor, the angle of attack setting factor has a contribution percentage value of 32.16% and the pitch angle factor has the smallest percentage value, that is 17.09%.
2. The most optimal HAWT rotor power obtained on the variety of parameters airfoil type 4412-2412 L.E Mod, angle of attack 0° and pitch angle 0°, with these settings in the Qblade software capable of producing a rotor power of 1,016 MW.

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2. Bukti konfirmasi review (email dan OJS) dan hasil review pertama (27 Oktober 2021)

Kriswanto Unnes <kriswanto@mail.unnes.ac.id>

[J. Adv. Res. Fluid Mech. Therm. Sc.] Editor Decision

2 messages

Nor Azwadi <azwadi@semarakilmu.com.my> Wed, Oct 27, 2021 at 6:25 PM
To: Kriswanto <kriswanto@mail.unnes.ac.id>

Kriswanto:

We have reached a decision regarding your submission to Journal of Advanced Research in Fluid Mechanics and Thermal Sciences, "EIC-Rotor Power Optimization of Horizontal Axis Wind Turbine from Variations in Airfoil Shape, Angle of Attack, and Wind Speed".

Our decision is: Revisions Required

Please submit the revised article by 15 Nov 2021.

Editorial Comments:

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Reviewer A:

Grammar and Spelling:

Occasional language errors. Please carefully read and check the sentences structures and correct all grammatical errors in your paper. Abstract should be only in one paragraph. Also, in conclusion, there should not be a comma before and, “3˚ angle of attack, and 8 m/s wind speed”. Furthermore, the second last sentence of conclusion is incomprehensible and rather convoluted.

Abstract:

Missed one element, which is introduction and points are not connected properly. The abstract needs english proofread.

Quality of Tables and Figures:

Tables and figures have excellent clarity and numbered. However, figures 1, and 9 are not stated in the text. I believe Figure 8 mentioned in the text supposedly be Figure 9.

Conclusion:

Conclusion related to objective. However, please check the sentence structure due to unclear sentences.

References:

Citing related and recent articles. Most of the references are updated and reliable.

Recommendation: Revisions Required

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

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Kriswanto Unnes <kriswanto@mail.unnes.ac.id> Sun, Nov 14, 2021 at 10:27 PM
To: Nor Azwadi <azwadi@semarakilmu.com.my>

Ok, I will do it. Thank you for the information on the results of the review and suggestions. I have revised my manuscript according to the editor's comment.
I have cited several articles according to the editor's suggestion, including:

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Thanks a lot

Best regards
Kriswanto
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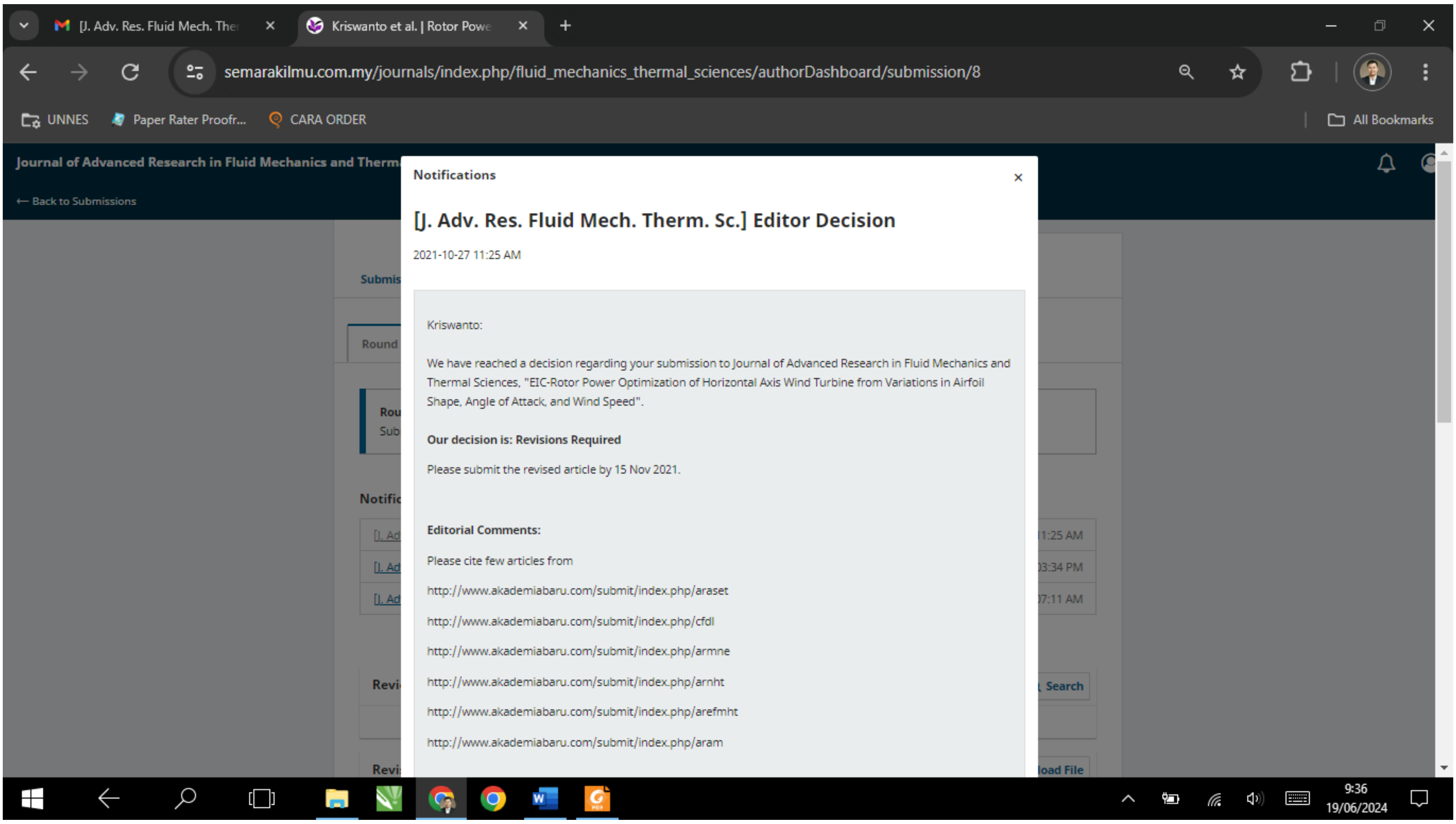

[J. Adv. Res. Fluid Mech. Therm. Sc.] Editor Decision

2021-10-27 11:25 AM

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Editorial Comments:

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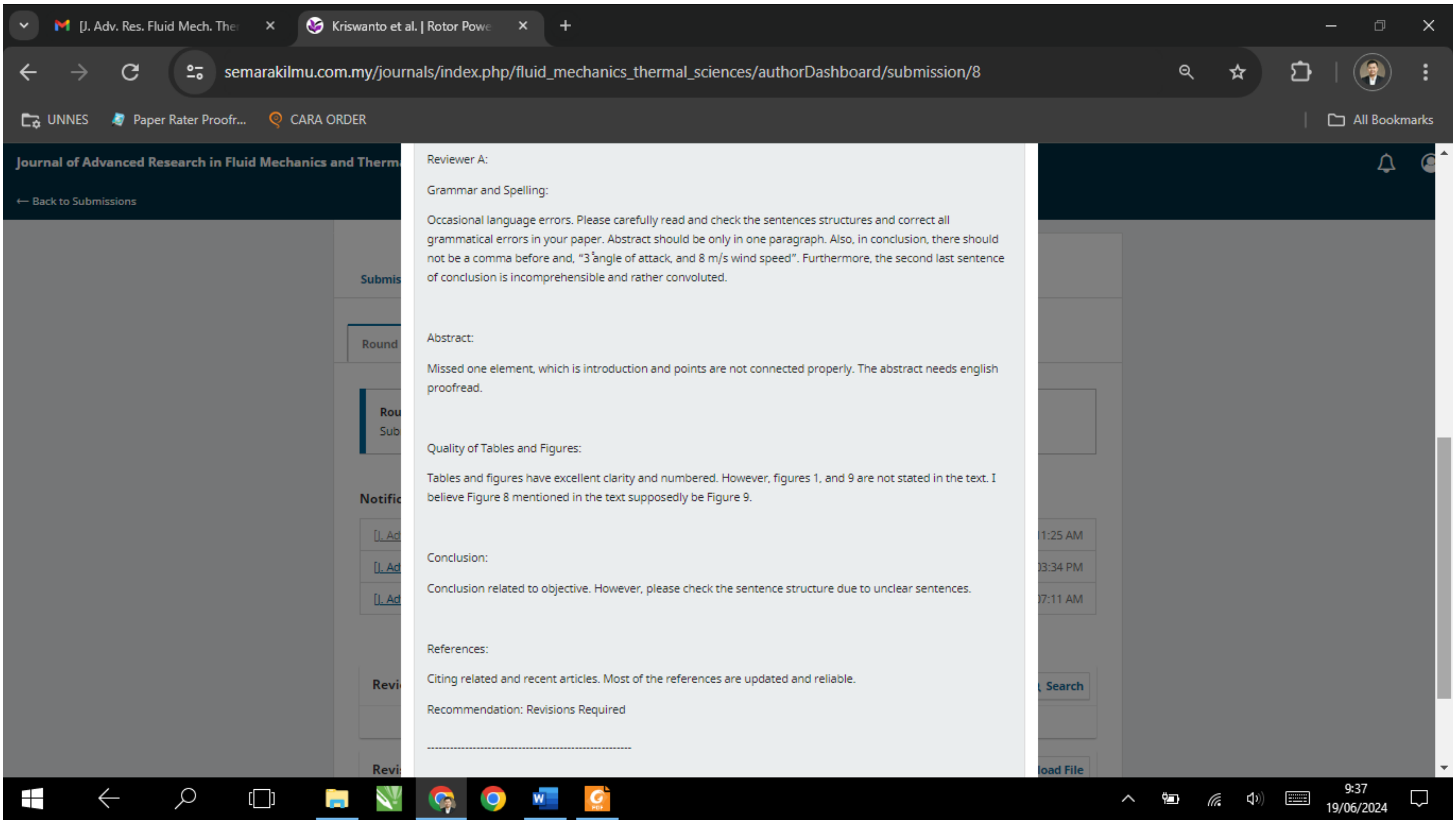

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Recommendation: Revisions Required

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3. Bukti konfirmasi submit revisi, respon kepada reviewer, dan artikel yang diresubmit (14 November 2021)

References:

Citing related and recent articles. Most of the references are updated and reliable.

Recommendation: Revisions Required

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

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Kriswanto Unnes <kriswanto@mail.unnes.ac.id> Sun, Nov 14, 2021 at 10:27 PM
To: Nor Azwadi <azwadi@semarakilmu.com.my>

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Thanks a lot

Best regards
Kriswanto
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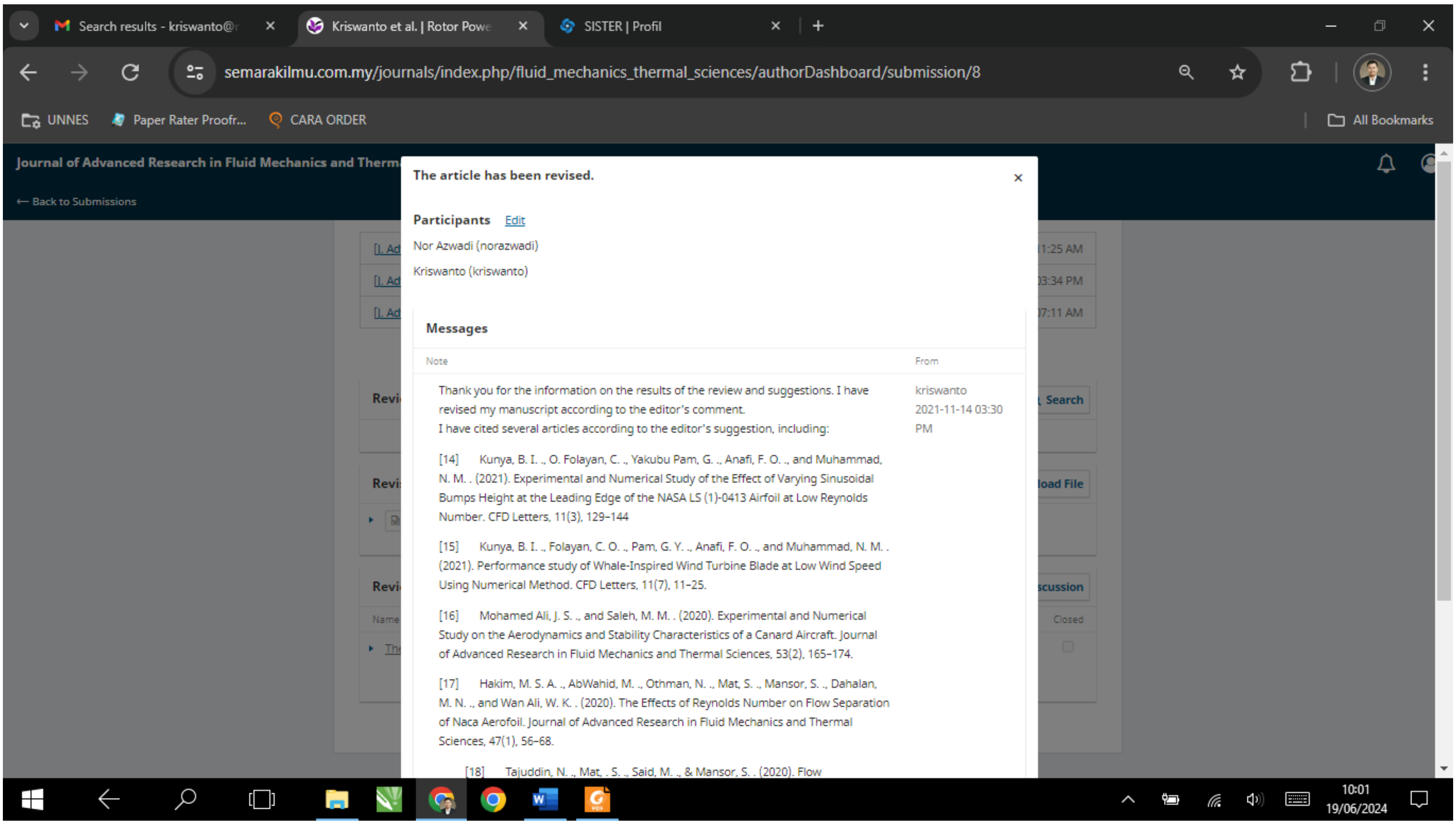

The article has been revised.

Participants Edit

Nor Azwadi (norazwadi)

Kriswanto (kriswanto)

Messages

Note	From
Thank you for the information on the results of the review and suggestions. I have revised my manuscript according to the editor's comment. I have cited several articles according to the editor's suggestion, including:	kriswanto 2021-11-14 03:30 PM

[14] Kunya, B. I. ., O. Folayan, C. ., Yakubu Pam, G. ., Anafi, F. O. ., and Muhammad, N. M. . (2021). Experimental and Numerical Study of the Effect of Varying Sinusoidal Bumps Height at the Leading Edge of the NASA LS (1)-0413 Airfoil at Low Reynolds Number. CFD Letters, 11(3), 129–144

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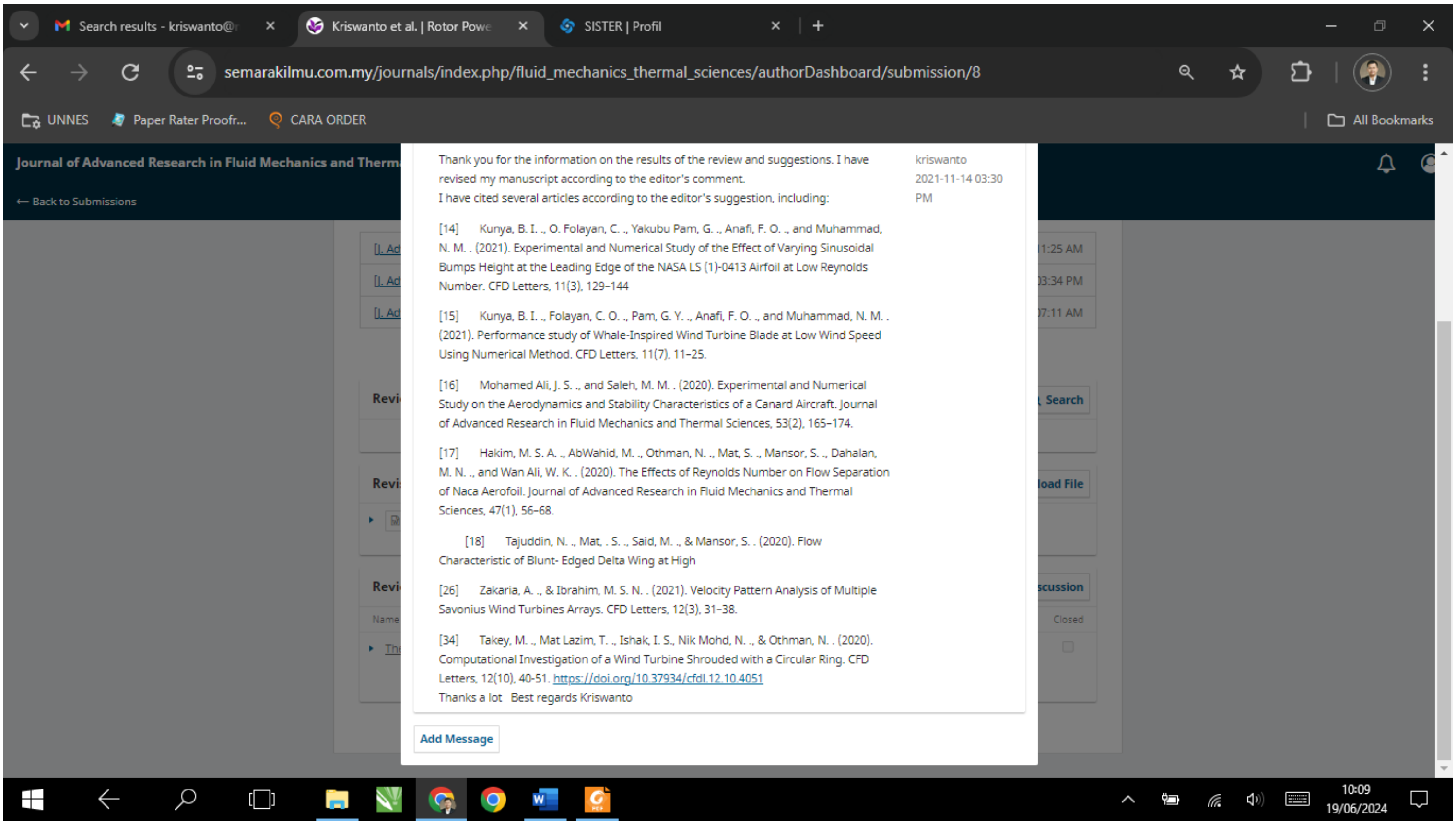

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Thanks a lot Best regards Kriswanto

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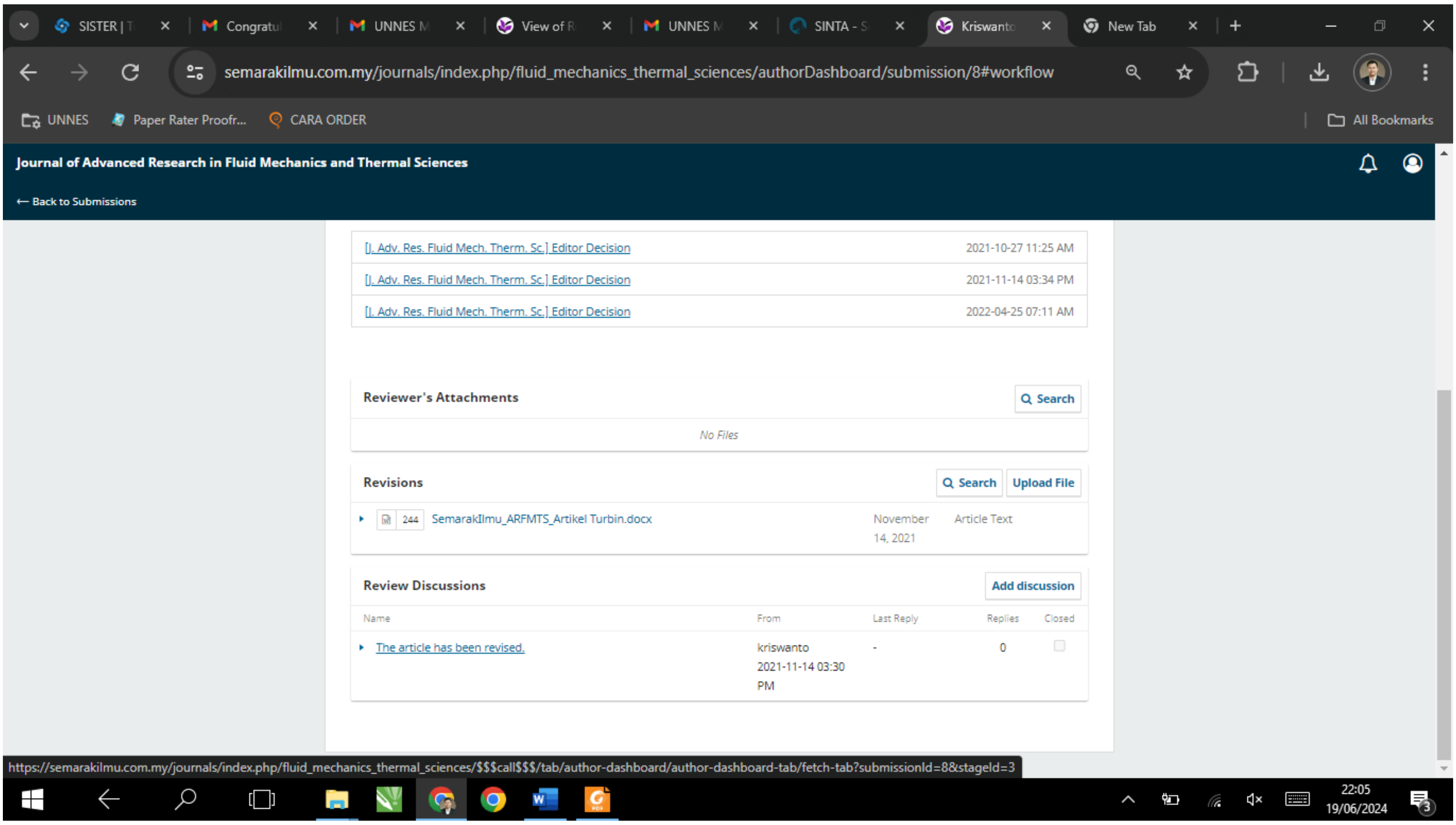

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Rotor Power Optimization of Horizontal Axis Wind Turbine from Variations in Airfoil Shape, Angle of Attack, and Wind Speed

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ABSTRACT

This paper presents rotor power optimization of the Horizontal Axis Wind Turbine of various parameters such as airfoil, angle of attack, and wind speed. Simulation of HAWT rotor power uses Blade Element Momentum (BEM). Furthermore, optimization using the Taguchi method with $L_{16}(4^3)$ orthogonal array. The parameters used in this study were: airfoil NACA (National Advisory Committee for Aeronautics) 4412, NACA 2412, NACA 4412-NACA 2412, NACA 4412mod-NACA 2412mod; angle of attack 3˚, 4˚, 5˚, 6˚; and wind speed of 5, 6, 7, 8 (m/s). The simulation uses the general parameter at 1 MW HAWT. Several types of NACA airfoil, angle of attack, and wind speed were simulated, then optimized to obtain optimal parameters for the HAWT output power. The results of this study found the most optimal rotor power, namely the condition of the NACA 4412mod-NACA 2412mod airfoil, 3˚ angle of attack, and 8m/s wind speed. Wind speed is the most significant influence factor based on ANOVA analysis ranked 1st based on S/N ratio analysis, 2nd rank is an airfoil, and 3rd rank is the angle of attack. The higher the wind speed, the greater the rotor power generated.

1. Introduction

Numerous locations in Indonesia have the potential for wind power generation growth, with wind speeds exceeding 5m/s [1]. However, at low wind speeds of the wind power systems at the inland sites, South East Asia does not produce substantial electricity [2]. According to IEC [3], a wind speed of 5 m/s was classed as low wind speed. A rotor blade is an essential part of the advancement of wind power generation. Another component that impacts wind turbine performance is bearings, particularly ones with exceptionally low friction that influences wind turbine performance. Since there's no mechanical contact between the shaft and the rotor blade, studying Permanent Magnetic Bearings (PMB) in wind turbine prototypes to substitute mechanical bearings can enhance rotational speed and torque [4].

The rotor blade affects wind turbine performance, wherein it is a component that initially receives wind power before converting it to mechanical. Because of the lift and drag forces acting on the blades, wind flowing over the airfoil can cause them to rotate. A minor adjustment in

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dimensions can have an impact on the blade's efficiency. The High-efficiency of the wind turbines converts the kinetic energy of the wind into electric power optimised so that the blade as the initial component associated with the wind requires selecting chord, alpha (α), twist (β) values that fit, and wind speed.

Many studied have been carried out to improve the rotor shape of Horizontal Axis Wind Turbines to maximize power output. Furthermore, optimize the design of low-speed wind turbine blades by using an NRELS series airfoil with a high aerodynamic performance from the application of the Wilson design method to obtain an average power of 628318W at a wind speed of 7m/s [5]. The study implementing the BEM Method also explains the relationship between wind speed and turbine output power, that the higher the wind speed, the higher power, and then the 1.5 MW of power reached at the wind speed of 14 m/s [6]. Comparison of power, lift and drag coefficients of a wind turbine blade from aerodynamics characteristics of NACA 0012 and NACA 2412 use three simulation models and experimental results getting NACA 2412 airfoils to have higher efficiency at the Tip 7-speed ratio and have a higher maximum power output than NACA 0012. Furthermore, NACA 2412 creates more efficient turbine blades than NACA 0012 [7].

The experimental and numerical comparison of the power coefficient (*Cp*) and the lift-to-drag ratio of NACA 0012 airfoils with NACA 4412 airfoils revealed that the CP of the NACA 4412 is greater than the *Cp* of the NACA 0012 [8]. The airfoils (NACA 4412, SG6043, SD7062, and S833) were simulations of QBlade software, and the overall power coefficient (*Cp*) of NACA 4412 at different ends of the velocity ratio was to be superior to the other three airfoils [9]. The angle of attack is the most crucial element in determining the aerodynamics of a wind turbine revolving blade [10]. Furthermore, it has a significantly influenced performance of a wind turbine blade since it is directly proportional to the forces exerted [11]. The study of unique aerodynamic mathematical models to determine the optimal blade chord and twist angle distributions over the blade span, in which this investigation combines blade design and the airfoil analysis procedure [12].

Numerous studies on the influence of leading-edge airfoils with or without bumps aimed at the airfoil allow it to operate and perform better at higher angles of attack before stalling [13-18]. The study [13-14][16-18]was for the airfoil on the airplane wing. Furthermore, the study of the airfoil for wind turbines with modifications to the leading edge with a bump gets the lift coefficient of the blade by adding a bump that is higher than the conventional blade [15].

According to the above literature, although research on the performance analysis of HAWT was conduct, the works are focused on certain factors, such as airfoil type, wind speed, or angle of attack. It the necessary knowledge that in HAWT performance, various factors may have distinct and simultaneous effects on the airfoil variation and angle of attack when used at low wind speeds. It emphasizes the necessity of concurrent study on optimizing airfoil type, angle of attack, and wind speed to gain better parameters of the performance of the HAWT power rotor. Therefore, the purpose of this study was to optimize the HAWT rotor power from rotor blade variations in airfoil shape, angle of attack, and low wind speed.

2. Methodology

BEM (Blade Element Momentum) method has been used in this study to obtain power output. Furthermore, the BEM method is a popular design method for the horizontal axis and vertical axis wind turbines. The main goal of the BEM model is that it is less expensive and has a shorter computing time than the CFD model [19-24]. BEM theory and CFD simulation are the most widely used approaches for predicting wind turbine performance and aerodynamic properties [25]. The mesh developed in the computational domain has a significant influence on the accuracy of CFD simulation

[26] Furthermore, this approach is a model used to analyze wind turbine performance based on mechanical, geometric factors, and features [27]. The BEM is one of the design methods used to simulate and achieve the theoretical analysis of turbine rotors [28].

BEM theory base on the assumption of the forces acting on the two-dimensional blade element so that the lengthwise flow is neglected [29]. Equation 1 and 2 is the equation of thrust and torque on a blade element theory. Figure 1-a is the local element of forces on the blade and figure 1-b is the velocities and flow angles on the blade.

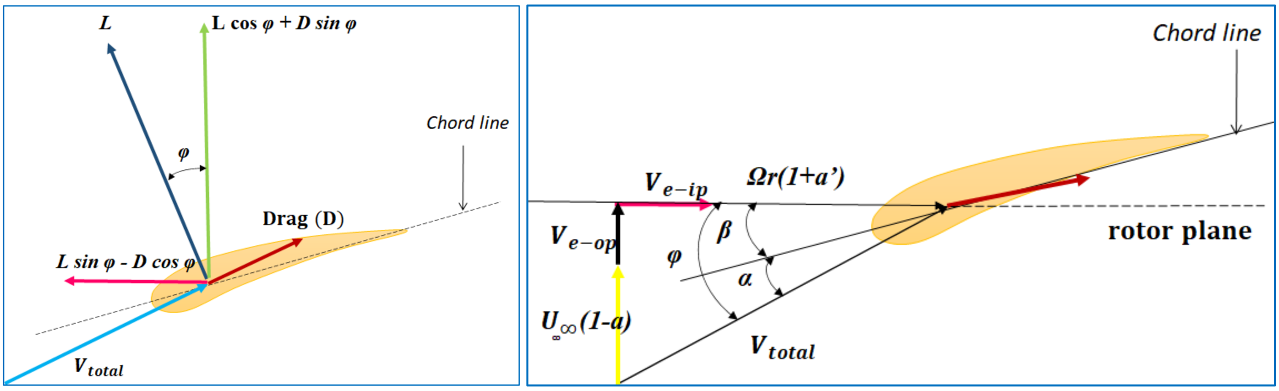


Fig. 1. Local element (a) Forces (b) Velocities and flow angles

$$dT = B\frac{1}{2}\rho V_{total}^{2}(C_l \cos\varphi + C_d \sin\varphi)\, cdr \tag{1}$$

$$dQ = B\frac{1}{2}\rho V_{total}^{2}(C_l \sin\varphi - C_d \cos\varphi)\, crdr \tag{2}$$

Where *dT* is the thrust, *dQ* is the torque on the blade sections, *B* is number of blades, *ρ* is the air density, V_{total} is the resultant velocity, C_l is the lift coefficient, C_d is the drag coefficient, *φ* the inflow angle, *c* is the airfoil chord, and r is the distance of the element from hub.

$$dT = 4\pi r\rho U_{\infty}^{2}(1-a)\, adr \tag{3}$$

$$dQ = 4\pi r^{3}\rho U_{\infty}\Omega(1-a)\, a'dr \tag{4}$$

$$a' = \frac{\omega}{2\Omega} \tag{5}$$

Where *a'* is the axial induction factor, U_∞ is the velocity far downstream, ω is the blade rotation speed, and Ω is the angular speed.

This study focuses on optimizing the power rotor of HAWT (Horizontal Axis Wind Turbine) from the factors of airfoils, angle of attack, and wind speeds. Table 1 shows the specification of HAWT which is simulated using the BEM method.

It is important to predict the power rotor at low wind speeds according to wind conditions in Southeast Asia. As seen in Equation (6), wind power is proportional to the cube of wind speed.

$$P = {}^{1}\!/_{2}\,\rho A w^{3} \tag{6}$$

Where *w* is the wind speed and *A* is the cross-sectional area of blade.

Table 1
Parameter setup of the 1 MW HAWT Model

Specification	Value
Air density (kg/m^3)	1.225
Number of blades	3
Blade length (m**)**	55
Radius of hub (m)	1.25
Tower height (m)	110
Swept Area (m^2)	10,023.67

The optimization method used is the Taguchi method, a methodology in engineering that aims to improve the quality of products and processes, moreover reduce costs and resources to a minimum [30-32]. The target of the Taguchi method is to make the product robust against noise so commonly referred to as Robust Design [23-39].

A two-way analysis of variance used for the data has two or more factors over two or more levels. The analysis table consists of the degrees of freedom calculation, the number of squares, the average number of squares, and the F-ratio. The S/N ratio is used to find the factors that influence the power variance. The characteristics S/N ratio used is larger the better that calculated by Equation 7.

$$S/N_L = -10\ log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y^2}\right) \tag{7}$$

The chosen orthogonal matrix is a matrix that has a degree of freedom value equal to or greater than the experimental degree of freedom value. The degrees of freedom for the matrix $L_{16}(4^3)$. Degrees of freedom $L_{16}(4^3)$ = (many factors) x (many levels = -1) = 3 x (4-1) = 9. So, the chosen orthogonal matrix is matrix $L_{16}(4^3)$. Table 2 is the parameter used in the rotor power optimization. Then Table 3 shows the orthogonal matrix $L_{16}(4^3)$, which has three factors and four levels. Three factors are airfoil, angle of attack, and wind speed. Wind speeds range from 5-8 m/s were classified as low wind speeds according to IEC 61400-1 (International Electrotechnical Commission) [24].

Table 2
Independent Variable and Level Setting

Factor	1	2	3	4
Airfoil (NACA)	4412	2412	4412-2412	4412mod-2412mod
Angle of attack (˚)	3	4	5	6
Wind speed (m/s)	5	6	7	8

Table 3
The Orthogonal Matrix L_{16} (4^3)

No.	Factor Control Airfoil (NACA)	Angle of Attack, α (˚)	Wind Speed, v (m/s)
1.	4412	3	5
2.	4412	4	6
3.	4412	5	7
4.	4412	6	8
5.	2412	3	6
6.	2412	4	5
7.	2412	5	8
8.	2412	6	7
9.	4412-2412	3	7
10.	4412-2412	4	8
11.	4412-2412	5	5

12.	4412-2412	6	6
13.	4412mod-2412mod	3	8
14.	4412mod-2412mod	4	7
15.	4412mod-2412mod	5	6
16.	4412mod-2412mod	6	5

There are two types of main airfoils in this study, namely NACA 4412 (Figure 2) as the 1st variation and NACA 2412 (Figure 3) for the 2nd variation. Furthermore, the 3rd variation uses a combination of NACA 4412 with NACA 2412, then and the last variation is a modification of the lower surface prior to the trailing edge of the two airfoils NACA4412mod-2412mod.

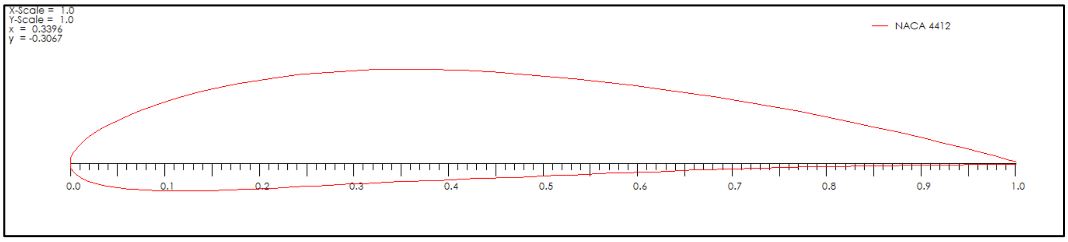


Fig. 2. Airfoil NACA 4412

The form difference of the NACA 4412 and NACA 2412 airfoils before-after modification is found on the lower surface before the trailing edge such as the area marked in circular red (modified form) in Figures 4 and Figure 5. The standard NACA airfoil with NACA modification has a y-coordinate difference of 0.06 for the NACA 4412 airfoil (Figure 6) and 0.0148 for the 2412 airfoil (Figure 7) on the lower surface at points 0.9 to 1.

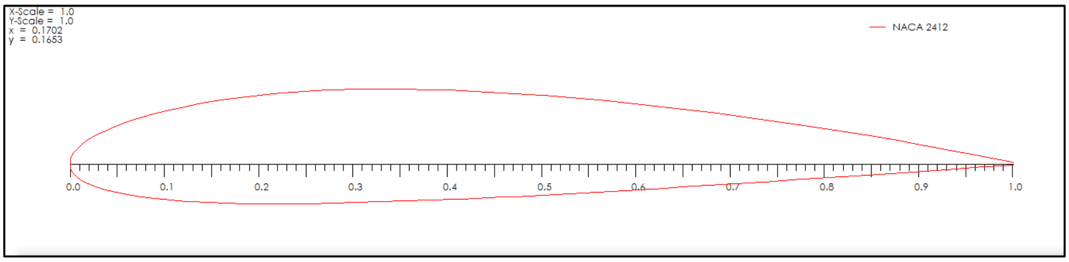


Fig. 3. Airfoil NACA 2412

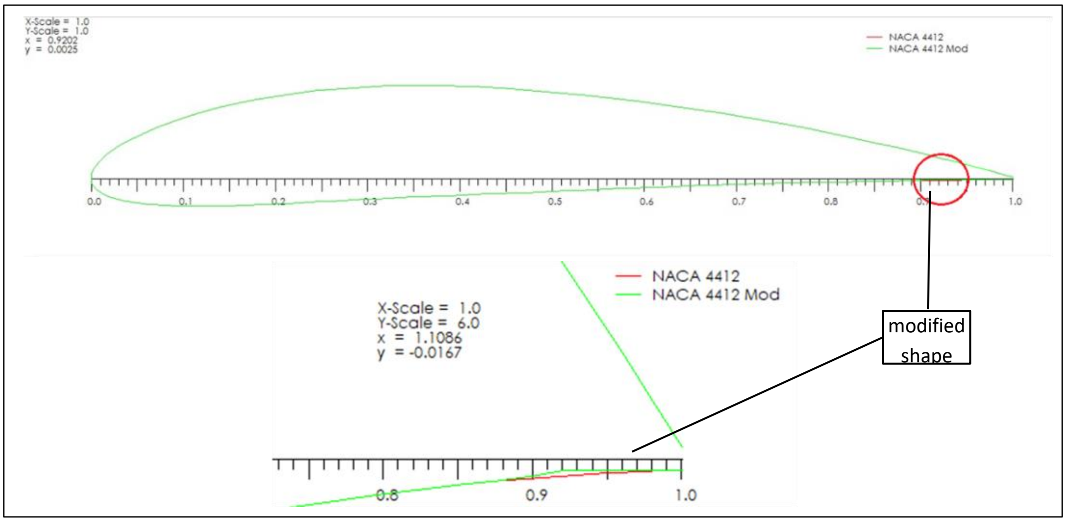


Fig. 4. NACA 4412mod

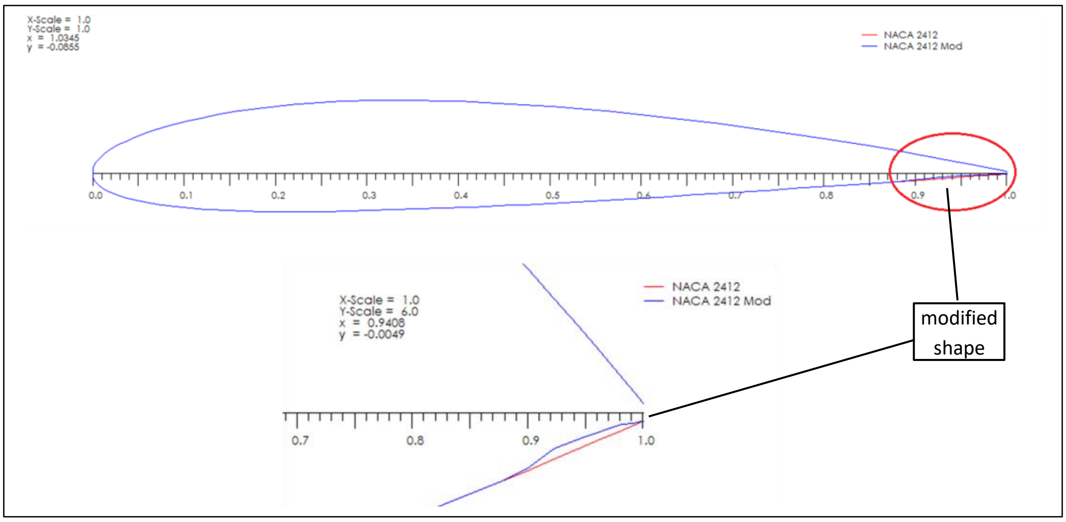


Fig. 5. NACA 2412mod

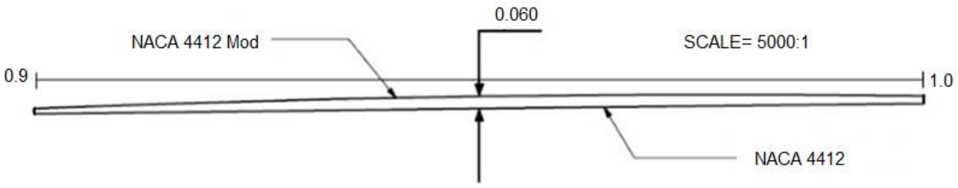


Fig. 6. Differences between Standard Airfoil and Modified NACA 4412

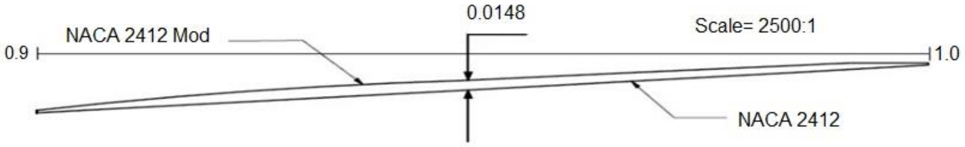


Fig. 7. Differences between Standard Airfoil and Modified NACA 2412

Figure 8 shows the angle of attack on the airfoil and the variations of the angle of attack presented in Table 1. The angle of attack should not be too large caused the air will no longer follow on the airfoil surface. Therefore, airflow will separate above the airfoil, and vortex will occur behind the airfoil leading edge. Consequently, the drag force increases significantly, and the lifting force decreases. This situation is called a stall, and the critical angle at which the transition occurs is called the stall angle of attack.

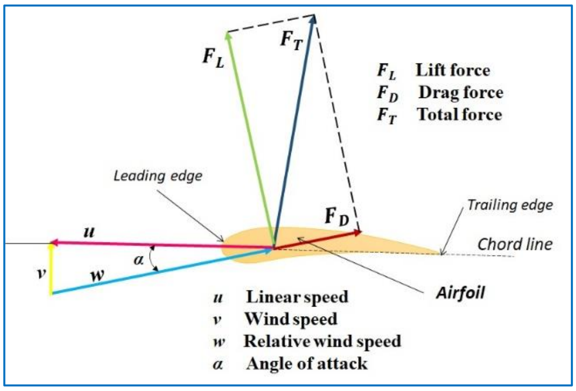


Fig. 8. Angle of attack and relative wind speed

The lift coefficient is very influential on the performance of a turbine. The value of the lift coefficient will change with the change in the value of the angle of attack. Variations of it on the airfoil, the value of C_L will increase as the angle of attack is adjusted until C_L reaches its maximum value. The C_L calculation use Equation (8).

$$C_L = \frac{F_L}{{}^1\!/_2 \rho w^2 A} \tag{8}$$

Where C_L is the lift coefficient and F_L is lift force.

3. Results

The validation has been done by comparing the power output between the CFD method by Oukassou [7] with the BEM method used in the present study. The power rotor has been simulated with the same parameters as the CFD (see Table 4). Hereafter, the power output generated by the BEM method is shown in Figure 9. The difference of CFD-BEM values is not so far apart, which is 0.4%. Therefore, the BEM method was appropriate to use to simulate rotor power accord the boundary conditions. Validation between the two models, namely CFD and BEM Theory, is carried out to verify the results of the turbin performance values are reasonable [40].

Table 4
Validation of BEM method in the present study with CFD methods [7]

Method	Airfoil	*v* (m/s)	Numbers of Blade	TSR	*ρ* (kg/m^3)	N (rpm)	*P*(kW)
CFD	NACA 0012	12	3	7	1,225	12.10	5
BEM	NACA 0012	12	3	7	1,225	12.10	4,98
			% variation				0,4

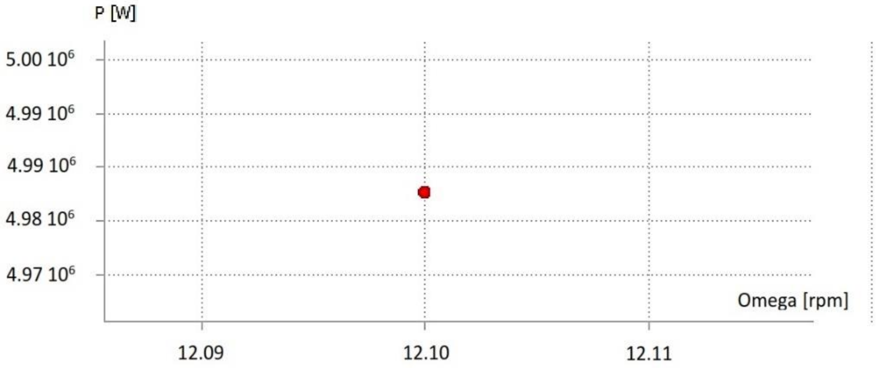
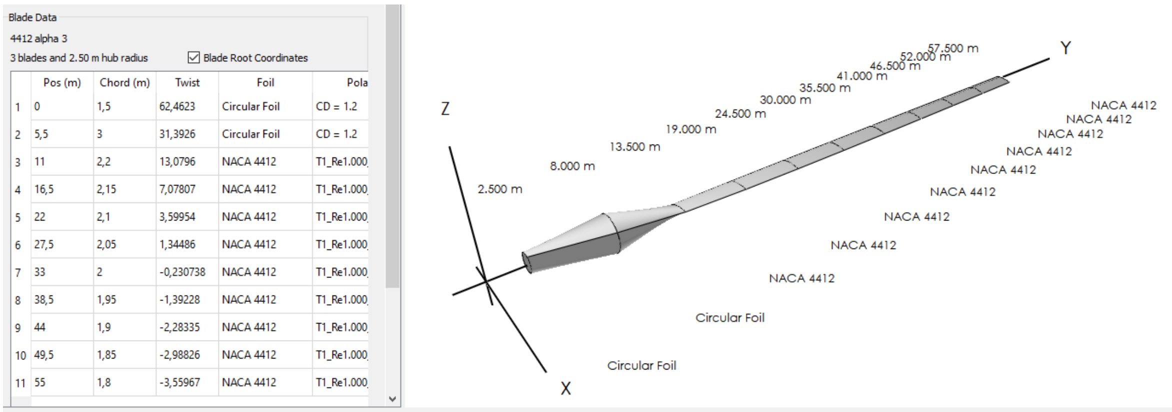


Fig. 9. Graph of power output using the BEM Method

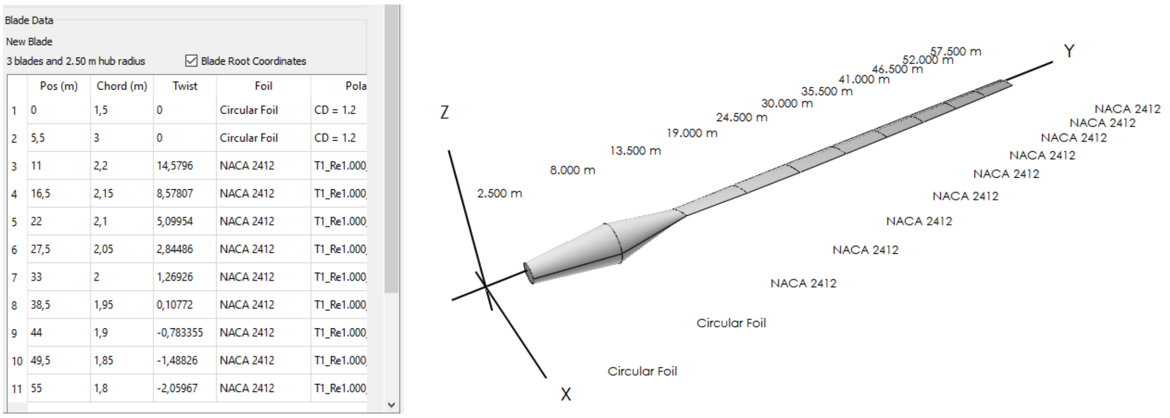
Where *v* is wind speed, *TSR* is a tip speed ratio, *N* is rotor rotational speed, and *P* is the power output of the HAWT. Each rotor blade design consists of 10 segments, wherein segments 1 and 2 use circular foil. Furthermore, the third to the last segment uses either the NACA 2412 or NACA 4412 airfoil design, a combination of both, and the modified combination of the two airfoils. The design and geometry of the blade design as shown in Figures 10 to 13, which are the angle of attack 3˚.



Blade Data
4412 alpha 3
3 blades and 2.50 m hub radius ☑ Blade Root Coordinates

	Pos (m)	Chord (m)	Twist	Foil	Pola
1	0	1,5	62,4623	Circular Foil	CD = 1.2
2	5,5	3	31,3926	Circular Foil	CD = 1.2
3	11	2,2	13,0796	NACA 4412	T1_Re1.000
4	16,5	2,15	7,07807	NACA 4412	T1_Re1.000
5	22	2,1	3,59954	NACA 4412	T1_Re1.000
6	27,5	2,05	1,34486	NACA 4412	T1_Re1.000
7	33	2	-0,230738	NACA 4412	T1_Re1.000
8	38,5	1,95	-1,39228	NACA 4412	T1_Re1.000
9	44	1,9	-2,28335	NACA 4412	T1_Re1.000
10	49,5	1,85	-2,98826	NACA 4412	T1_Re1.000
11	55	1,8	-3,55967	NACA 4412	T1_Re1.000

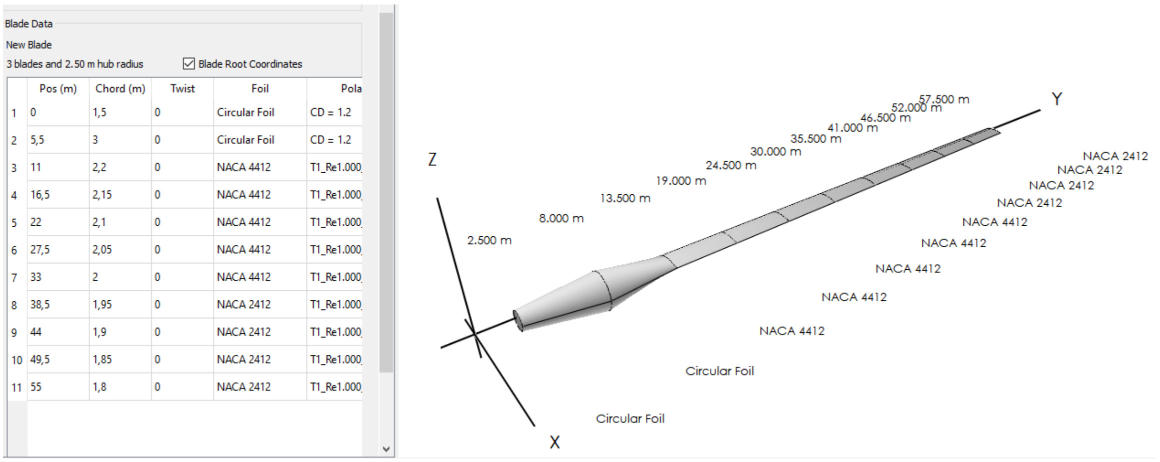
Fig. 10. Rotor blade design use NACA 412 airfoil



Blade Data
New Blade
3 blades and 2.50 m hub radius ☑ Blade Root Coordinates

	Pos (m)	Chord (m)	Twist	Foil	Pola
1	0	1,5	0	Circular Foil	CD = 1.2
2	5,5	3	0	Circular Foil	CD = 1.2
3	11	2,2	14,5796	NACA 2412	T1_Re1.000
4	16,5	2,15	8,57807	NACA 2412	T1_Re1.000
5	22	2,1	5,09954	NACA 2412	T1_Re1.000
6	27,5	2,05	2,84486	NACA 2412	T1_Re1.000
7	33	2	1,26926	NACA 2412	T1_Re1.000
8	38,5	1,95	0,10772	NACA 2412	T1_Re1.000
9	44	1,9	-0,783355	NACA 2412	T1_Re1.000
10	49,5	1,85	-1,48826	NACA 2412	T1_Re1.000
11	55	1,8	-2,05967	NACA 2412	T1_Re1.000

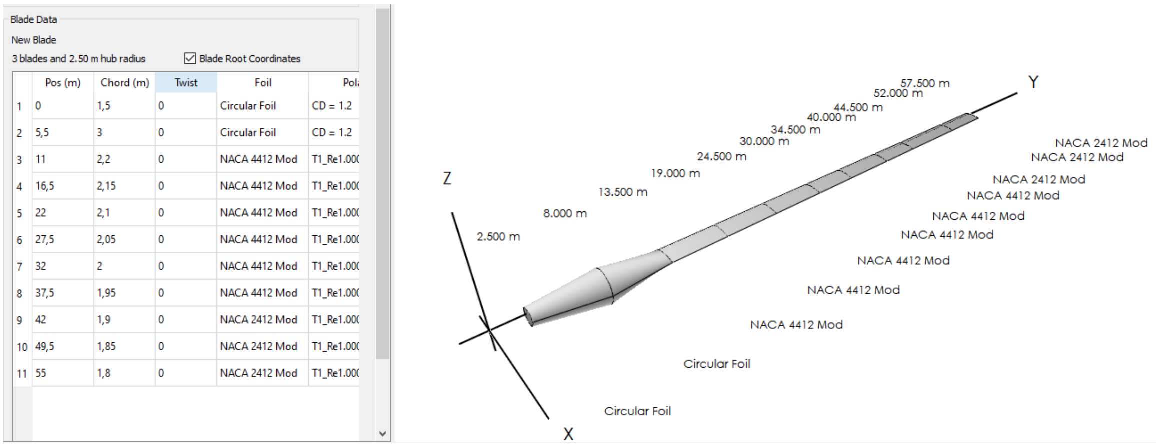
Fig. 11. Rotor blade design use NACA 2412 airfoil



Blade Data
New Blade
3 blades and 2.50 m hub radius ☑ Blade Root Coordinates

	Pos (m)	Chord (m)	Twist	Foil	Pola
1	0	1,5	0	Circular Foil	CD = 1.2
2	5,5	3	0	Circular Foil	CD = 1.2
3	11	2,2	0	NACA 4412	T1_Re1.000
4	16,5	2,15	0	NACA 4412	T1_Re1.000
5	22	2,1	0	NACA 4412	T1_Re1.000
6	27,5	2,05	0	NACA 4412	T1_Re1.000
7	33	2	0	NACA 4412	T1_Re1.000
8	38,5	1,95	0	NACA 2412	T1_Re1.000
9	44	1,9	0	NACA 2412	T1_Re1.000
10	49,5	1,85	0	NACA 2412	T1_Re1.000
11	55	1,8	0	NACA 2412	T1_Re1.000

Fig. 12. Rotor blade design uses a combination of NACA 4412 with NACA 2412



Blade Data
New Blade
3 blades and 2.50 m hub radius ☑ Blade Root Coordinates

	Pos (m)	Chord (m)	Twist	Foil	Pol
1	0	1,5	0	Circular Foil	CD = 1.2
2	5,5	3	0	Circular Foil	CD = 1.2
3	11	2,2	0	NACA 4412 Mod	T1_Re1.00
4	16,5	2,15	0	NACA 4412 Mod	T1_Re1.00
5	22	2,1	0	NACA 4412 Mod	T1_Re1.00
6	27,5	2,05	0	NACA 4412 Mod	T1_Re1.00
7	32	2	0	NACA 4412 Mod	T1_Re1.00
8	37,5	1,95	0	NACA 4412 Mod	T1_Re1.00
9	42	1,9	0	NACA 2412 Mod	T1_Re1.00
10	49,5	1,85	0	NACA 2412 Mod	T1_Re1.00
11	55	1,8	0	NACA 2412 Mod	T1_Re1.00

Fig. 13. Rotor blade design uses modified airfoil NACA 4412 and NACA 2412

The results of the turbine rotor power simulation using the BEM method on the Qblade software are adjusted to the predetermined parameters. The power data the simulation results are shown in Table 5.

Table 5
HAWT Power rotor of L_{16} (4^3).

No.	Factor Control			Power (kW)
	Airfoil (NACA)	Angle of Attack, α (˚)	Wind Speed, v (m/s)	
1.	4412	3	5	366
2.	4412	4	6	626
3.	4412	5	7	975
4.	4412	6	8	1420
5.	2412	3	6	619
6.	2412	4	5	358
7.	2412	5	8	1482
8.	2412	6	7	992
9.	4412-2412	3	7	1045
10.	4412-2412	4	8	1546
11.	4412-2412	5	5	372
12.	4412-2412	6	6	634
13.	4412mod-2412mod	3	8	1564
14.	4412mod-2412mod	4	7	1037
15.	4412mod-2412mod	5	6	646
16.	4412mod-2412mod	6	5	368

ANOVA is used to determine the effect of each factor (airfoil, angle of attack, and wind speed) on the turbine rotor power produced. Table 6 is the analysis of the variance of each factor at each level tested for the rotor power. The analysis (see table 6) shows that the airfoil and wind speed factors significantly affect the turbine rotor power because the analysis value is less than the specified P value (0.05). The largest F value (2,424.3) is found in the wind speed factor so that it is the most influential factor on turbine rotor power compared to airfoil and angle of attack. The table below shows the F and P values for the contribution test of the parameters. Wind speed is the most significant influencing factor in generating power conforms the power output is proportional to the cube of wind speed, according to Equation (6). As the wind speed increases, so does the power extracted by the turbine increased [6].

Table 6
Analysis of Variance on Power Rotor

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
Airfoil	3	9,295	9,295	3.098	7.7	0.02
Angle of Attack	3	5.180	5.180	1,727	4.29	0.06
Wind Speed	3	2,926,710	2,926,710	975.570	2,424.3	0
Error	6	2.415	2.415	402		
Total	15	2,943,600				

S = 20.06 R-Sq = 99.92% R-Sq (Adj) = 99.97%

Calculation of the S/N ratio of roundness through a combination of levels of each factor uses Equation 2. The result of S/N ratio as shown in Table 7.

Table 7
Response of S/N Ratio of Roundness of Effect of Factor

Level	Airfoil	Angle of Attack	Wind Speed
1	57.51	57.84	51.27
2	57.56	57.78	56.00
3	57.90	57.70	60,10
4	57.93	57.58	63.53
delta	0.42	0.26	12.26
rank	2	3	1

Table 7 shows the S/N ratio value of rotor power for each factor. The S/N ratio gets the wind speed factor was ranked 1st or the most significant effect to the power rotor. The data of the S/N ratio was plotted in Figure 13, which shows of each factor affects each level. The airfoil factor at level 4 has a greater influence on the airfoil NACA 4412mod-NACA 2412mod provides a better output of rotor power. Furthermore, to the angle of attack factor, it is known that level 1 has a significant influence over the others (2, 3, and 4). The angle of attack of 3˚ gives a better rotor power output. On another factor, Level 4 of wind speed has a higher effect than levels 1, 2, and 3.

The speed factor has an S/N ratio of 12.26 so this factor has a significant effect on the value of generating rotor power. Based on the plot (Figure 14), the significant influence on the power rotor is the airfoil parameter NACA 4412mod-NACA 2412mod, 3˚an angle of attack, and 8m/s of wind speed. Accordingly, these parameters are the optimum value of the power rotor.

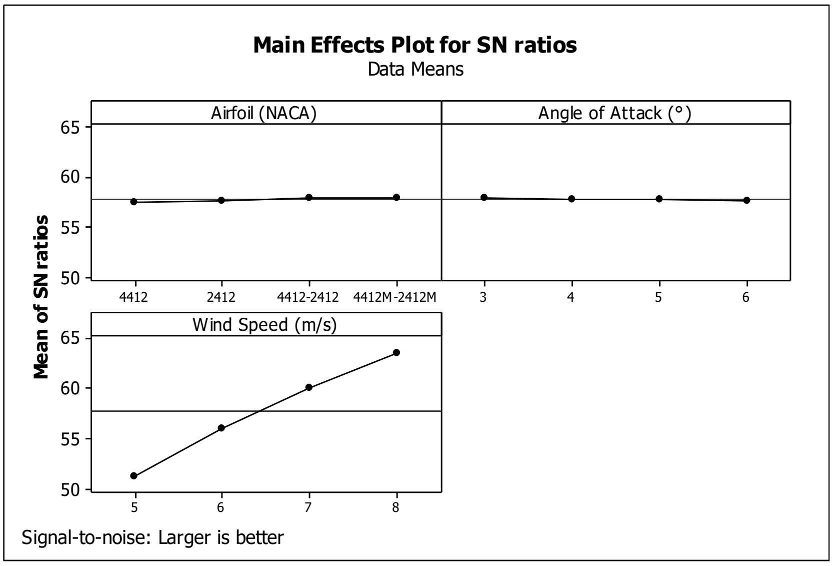


Fig. 14. S/N Ratio Plot Rotor Power

The optimum power was obtained on the NACA airfoil modified. This is because the lift coefficient of the modified NACA airfoil (4412mod-2412mod) is greater than the standard NACA (4412-2412) with the CL value increased by 0.002. These results were obtained from the BEM method simulation as shown in Figure 15. Even though the lift coefficient insignificant increase, but its contributed to an increase in the performance of HAWT.

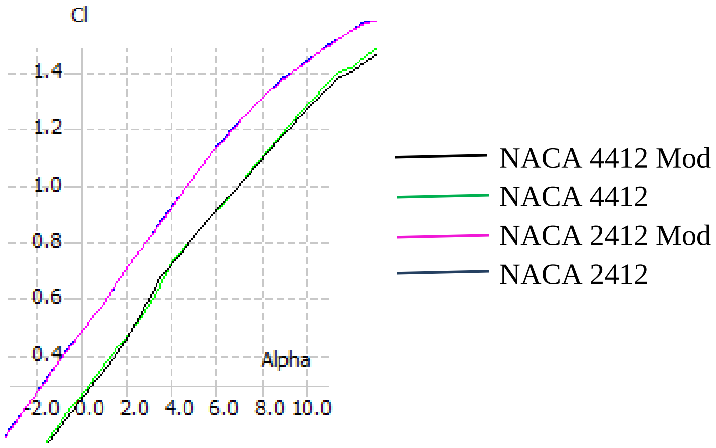


Figure 15. The plot of lift coefficient versus angle of attack of Airfoil in the study

Based on the simulation result (Figure 15), the coefficient of lift of each airfoil increased as the angle of attack increases. Seen at angle of attach of 10˚, the C_L value of at least 1.2 is higher than the C_L limit in this study of 6 ˚, with a minimum CL of 0.6. Due to the obvious unstable character of the flow at high angles of attack, there is a considerable degree of uncertainty in the performance of airfoils and, as a result, in the performance of blades [41]. The angle of attack in this study was 3-6 ˚ further the findings of S/N ratio computation show that the higher the alpha, the lower the value of the S/N ratio. The difference in the decrease of the S/N ratio of 0.26 is too small on the increase in the alpha value, then concluded that the angle of attack factor has no significant effect on the rotor power.

4. Conclusions

HAWT rotor blades on several variations of airfoils, angles of attack, and wind speed according to L16(4^3) orthogonal array were simulated to generate output power. The rotor power optimum (1.56MW) obtain on the NACA 4412mod-2412mod airfoils parameters with the angle of attack of 3˚ and wind speed of 8 m/s. Wind speed is the most significant influencing factor based on ANOVA analysis, then was 1st ranked based on S/N ratio analysis. Furthermore, the 2nd rank that influences consecutively is an airfoil, and the last rank is the angle of attack. The higher the wind speed, the greater the rotor power generated. The aerodynamic characteristics of airfoil NACA 4412 and NACA 2412 after being modified on the lower surface near the trailing edge have been simulated with the BEM method produce lift coefficient greater than NACA 4412 and NACA 2412 before modification. The lift coefficient of the NACA 4412 and NACA 2412 after modified was rose by 0.002 for both airfoils types that contribute positively to increasing the power performance of the HAWT rotor.

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Thank you

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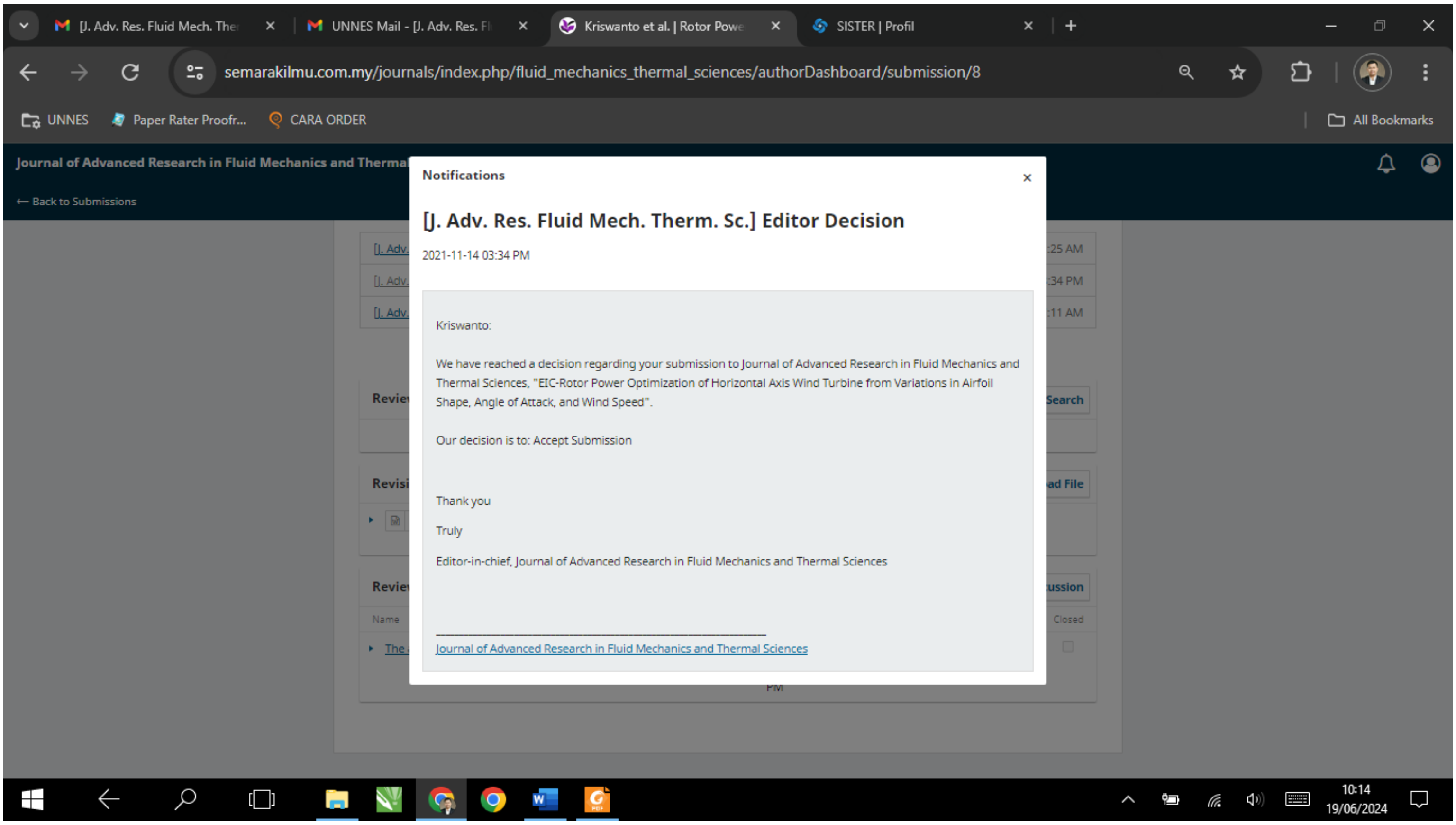

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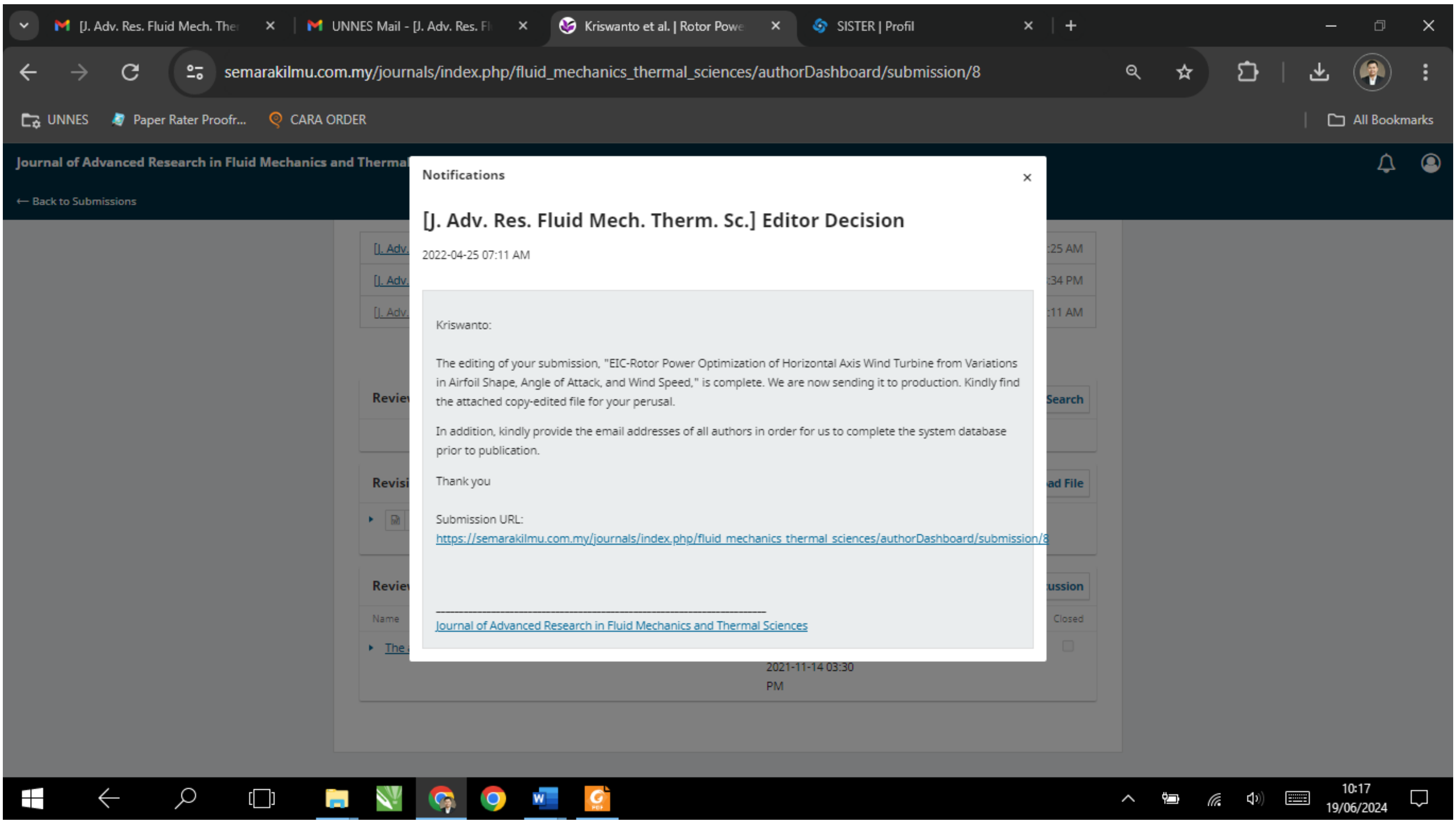

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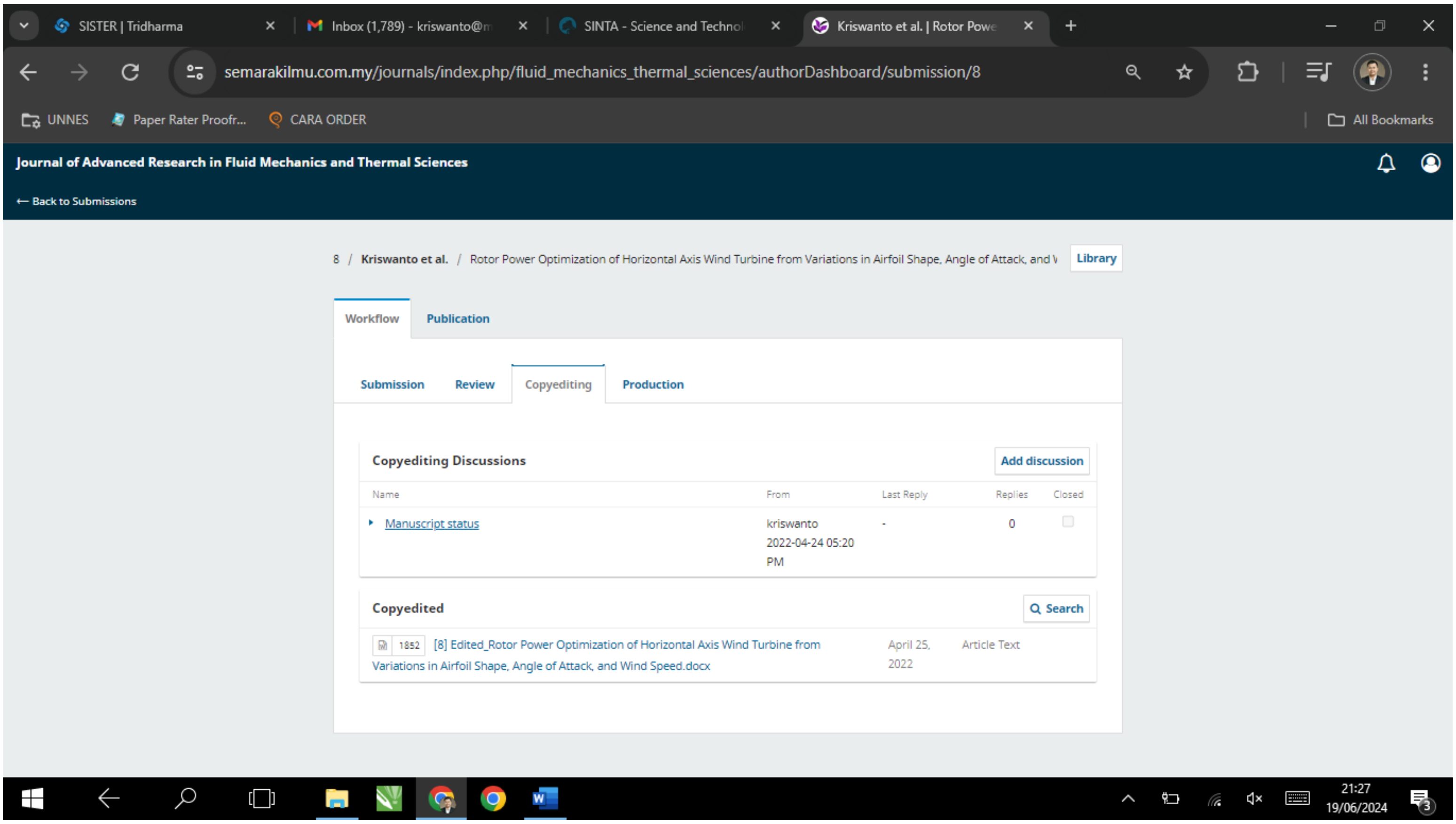

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Rotor Power Optimization of Horizontal Axis Wind Turbine from Variations in Airfoil Shape, Angle of Attack, and Wind Speed

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ABSTRACT

This paper presents rotor power optimization of the Horizontal Axis Wind Turbine of various parameters such as airfoil, angle of attack, and wind speed. Simulation of HAWT rotor power uses Blade Element Momentum (BEM). Furthermore, optimization using the Taguchi method with $L_{16}(4^3)$ orthogonal array. The parameters used in this study were: airfoil NACA (National Advisory Committee for Aeronautics) 4412, NACA 2412, NACA 4412-NACA 2412, NACA 4412mod-NACA 2412mod; angle of attack 3˚, 4˚, 5˚, 6˚; and wind speed of 5, 6, 7, 8 (m/s). The simulation uses the general parameter at 1 MW HAWT. Several types of NACA airfoil, angle of attack, and wind speed were simulated, then optimized to obtain optimal parameters for the HAWT output power. The results of this study found the most optimal rotor power, namely the condition of the NACA 4412mod-NACA 2412mod airfoil, 3˚ angle of attack, and 8m/s wind speed. Wind speed is the most significant influence factor based on ANOVA analysis ranked 1st based on S/N ratio analysis, 2nd rank is an airfoil, and 3rd rank is the angle of attack. The higher the wind speed, the greater the rotor power generated.

1. Introduction

Numerous locations in Indonesia have the potential for wind power generation growth, with wind speeds exceeding 5m/s [1]. However, at low wind speeds of the wind power systems at the inland sites, South East Asia does not produce substantial electricity [2]. According to IEC [3], a wind speed of 5 m/s was classed as low wind speed. A rotor blade is an essential part of the advancement of wind power generation. Another component that impacts wind turbine performance is bearings, particularly ones with exceptionally low friction that influences wind turbine performance. Since there's no mechanical contact between the shaft and the rotor blade, studying Permanent Magnetic Bearings (PMB) in wind turbine prototypes to substitute mechanical bearings can enhance rotational speed and torque [4].

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The rotor blade affects wind turbine performance, wherein it is a component that initially receives wind power before converting it to mechanical. Because of the lift and drag forces acting on the blades, wind flowing over the airfoil can cause them to rotate. A minor adjustment in dimensions can have an impact on the blade's efficiency. The High-efficiency of the wind turbines converts the kinetic energy of the wind into electric power optimised so that the blade as the initial component associated with the wind requires selecting chord, alpha (α), twist (β) values that fit, and wind speed.

Many studied have been carried out to improve the rotor shape of Horizontal Axis Wind Turbines to maximize power output. Furthermore, optimize the design of low-speed wind turbine blades by using an NRELS series airfoil with a high aerodynamic performance from the application of the Wilson design method to obtain an average power of 628318W at a wind speed of 7m/s [5]. The study implementing the BEM Method also explains the relationship between wind speed and turbine output power, that the higher the wind speed, the higher power, and then the 1.5 MW of power reached at the wind speed of 14 m/s [6]. Comparison of power, lift and drag coefficients of a wind turbine blade from aerodynamics characteristics of NACA 0012 and NACA 2412 use three simulation models and experimental results getting NACA 2412 airfoils to have higher efficiency at the Tip 7-speed ratio and have a higher maximum power output than NACA 0012. Furthermore, NACA 2412 creates more efficient turbine blades than NACA 0012 [7].

The experimental and numerical comparison of the power coefficient (Cp) and the lift-to-drag ratio of NACA 0012 airfoils with NACA 4412 airfoils revealed that the CP of the NACA 4412 is greater than the Cp of the NACA 0012 [8]. The airfoils (NACA 4412, SG6043, SD7062, and S833) were simulations of QBlade software, and the overall power coefficient (Cp) of NACA 4412 at different ends of the velocity ratio was to be superior to the other three airfoils [9]. The angle of attack is the most crucial element in determining the aerodynamics of a wind turbine revolving blade [10]. Furthermore, it has a significantly influenced performance of a wind turbine blade since it is directly proportional to the forces exerted [11]. The study of unique aerodynamic mathematical models to determine the optimal blade chord and twist angle distributions over the blade span, in which this investigation combines blade design and the airfoil analysis procedure [12].

Numerous studies on the influence of leading-edge airfoils with or without bumps aimed at the airfoil allow it to operate and perform better at higher angles of attack before stalling [13-18]. The study [13-14] [16-18]was for the airfoil on the airplane wing. Furthermore, the study of the airfoil for wind turbines with modifications to the leading edge with a bump gets the lift coefficient of the blade by adding a bump that is higher than the conventional blade [15].

According to the above literature, although research on the performance analysis of HAWT was conduct, the works are focused on certain factors, such as airfoil type, wind speed, or angle of attack. It the necessary knowledge that in HAWT performance, various factors may have distinct and simultaneous effects on the airfoil variation and angle of attack when used at low wind speeds. It emphasizes the necessity of concurrent study on optimizing airfoil type, angle of attack, and wind speed to gain better parameters of the performance of the HAWT power rotor. Therefore, the purpose of this study was to optimize the HAWT rotor power from rotor blade variations in airfoil shape, angle of attack, and low wind speed.

2. Methodology

BEM (Blade Element Momentum) method has been used in this study to obtain power output. Furthermore, the BEM method is a popular design method for the horizontal axis and vertical axis wind turbines. The main goal of the BEM model is that it is less expensive and has a shorter computing time than the CFD model [19-24]. BEM theory and CFD simulation are the most widely used approaches for predicting wind turbine performance and aerodynamic properties [25]. The mesh developed in the computational domain has a significant influence on the accuracy of CFD simulation [26] Furthermore, this approach is a model used to analyze wind turbine performance based on mechanical, geometric factors, and features [27]. The BEM is one of the design methods used to simulate and achieve the theoretical analysis of turbine rotors [28].

BEM theory base on the assumption of the forces acting on the two-dimensional blade element so that the lengthwise flow is neglected [29]. Eq. (1) and (2) is the equation of thrust and torque on a blade element theory. Figure 1-a is the local element of forces on the blade and Figure 1-b is the velocities and flow angles on the blade.

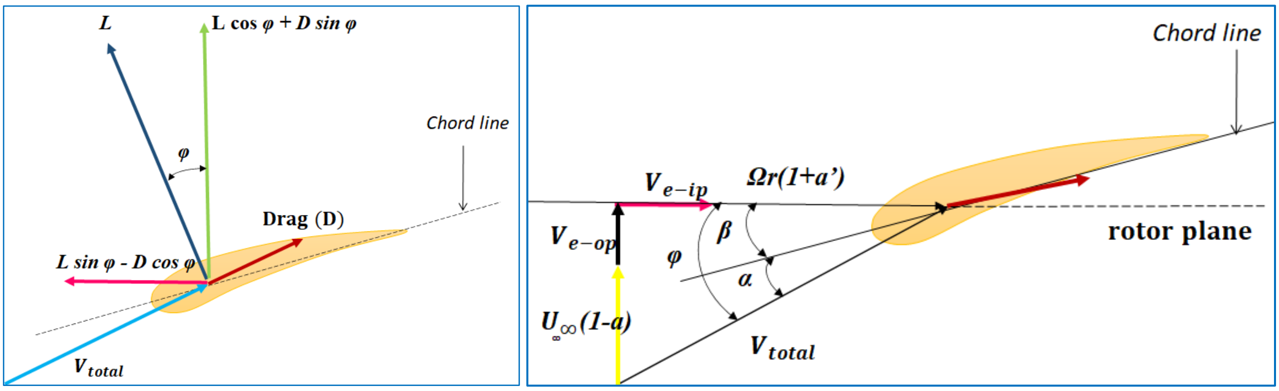


Fig. 1. Local element (a) Forces (b) Velocities and flow angles

$$dT = B\frac{1}{2}\rho V_{total}^{2}(C_l \cos\varphi + C_d \sin\varphi)\, cdr \tag{1}$$

$$dQ = B\frac{1}{2}\rho V_{total}^{2}(C_l \sin\varphi - C_d \cos\varphi)\, crdr \tag{2}$$

Where dT is the thrust, dQ is the torque on the blade sections, B is number of blades, ρ is the air density, V_{total} is the resultant velocity, C_l is the lift coefficient, C_d is the drag coefficient, φ the inflow angle, c is the airfoil chord, and r is the distance of the element from hub.

$$dT = 4\pi r\rho U_{\infty}^{2}(1-a)\, adr \tag{3}$$

$$dQ = 4\pi r^{3}\rho U_{\infty}\Omega(1-a)\, a'dr \tag{4}$$

$$a' = \frac{\omega}{2\Omega} \tag{5}$$

where a' is the axial induction factor, U_∞ is the velocity far downstream, ω is the blade rotation speed, and Ω is the angular speed.

This study focuses on optimizing the power rotor of HAWT (Horizontal Axis Wind Turbine) from the factors of airfoils, angle of attack, and wind speeds. Table 1 shows the specification of HAWT which is simulated using the BEM method.

It is important to predict the power rotor at low wind speeds according to wind conditions in Southeast Asia. As seen in Eq. (6), wind power is proportional to the cube of wind speed.

$$P = {}^{1}/_{2}\, \rho A w^{3} \tag{6}$$

where w is the wind speed and A is the cross-sectional area of blade.

Table 1
Parameter setup of the 1 MW HAWT Model

Specification	Value
Air density (kg/m^3)	1.225
Number of blades	3
Blade length (m)	55
Radius of hub (m)	1.25
Tower height (m)	110
Swept area (m^2)	10,023.67

The optimization method used is the Taguchi method, a methodology in engineering that aims to improve the quality of products and processes, moreover reduce costs and resources to a minimum [30-32]. The target of the Taguchi method is to make the product robust against noise so commonly referred to as Robust Design [23-39].

A two-way analysis of variance used for the data has two or more factors over two or more levels. The analysis table consists of the degrees of freedom calculation, the number of squares, the average number of squares, and the F-ratio. The S/N ratio is used to find the factors that influence the power variance. The characteristics S/N ratio used is larger the better that calculated by Eq. (7).

$$S/N_L = -10\ log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y^2}\right) \tag{7}$$

The chosen orthogonal matrix is a matrix that has a degree of freedom value equal to or greater than the experimental degree of freedom value. The degrees of freedom for the matrix $L_{16}(4^3)$. Degrees of freedom $L_{16}(4^3)$ = (many factors) x (many levels = -1) = 3 x (4-1) = 9. So, the chosen orthogonal matrix is matrix $L_{16}(4^3)$. Table 2 is the parameter used in the rotor power optimization. Then Table 3 shows the orthogonal matrix $L_{16}(4^3)$, which has three factors and four levels. Three factors are airfoil, angle of attack, and wind speed. Wind speeds range from 5-8 m/s were classified as low wind speeds according to IEC 61400-1 (International Electrotechnical Commission) [24].

Table 2
Independent Variable and Level Setting

Factor	1	2	3	4
Airfoil (NACA)	4412	2412	4412-2412	4412mod-2412mod
Angle of attack (˚)	3	4	5	6
Wind speed (m/s)	5	6	7	8

Table 3
The Orthogonal Matrix L_{16} (4^3)

No.	Factor Control		
	Airfoil (NACA)	Angle of Attack, α (˚)	Wind Speed, v (m/s)
1	4412	3	5
2	4412	4	6
3	4412	5	7
4	4412	6	8
5	2412	3	6
6	2412	4	5
7	2412	5	8
8	2412	6	7
9	4412-2412	3	7
10	4412-2412	4	8
11	4412-2412	5	5
12	4412-2412	6	6
13	4412mod-2412mod	3	8
14	4412mod-2412mod	4	7
15	4412mod-2412mod	5	6
16	4412mod-2412mod	6	5

There are two types of main airfoils in this study, namely NACA 4412 (Figure 2) as the 1st variation and NACA 2412 (Figure 3) for the 2nd variation. Furthermore, the 3rd variation uses a combination of NACA 4412 with NACA 2412, then and the last variation is a modification of the lower surface prior to the trailing edge of the two airfoils NACA4412mod-2412mod.

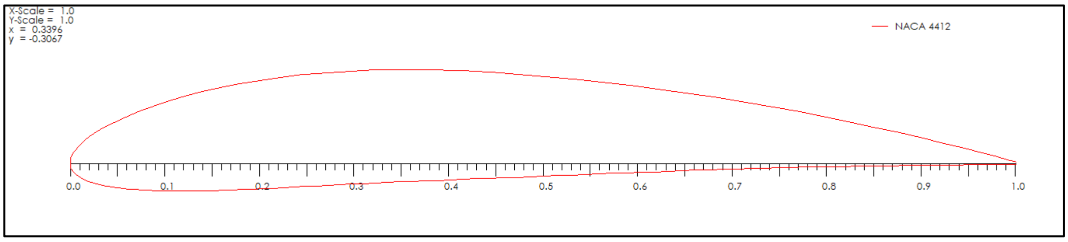


Fig. 2. Airfoil NACA 4412

The form difference of the NACA 4412 and NACA 2412 airfoils before-after modification is found on the lower surface before the trailing edge such as the area marked in circular red (modified form) in Figures 4 and Figure 5. The standard NACA airfoil with NACA modification has a y-coordinate difference of 0.06 for the NACA 4412 airfoil (Figure 6) and 0.0148 for the 2412 airfoil (Figure 7) on the lower surface at points 0.9 to 1.

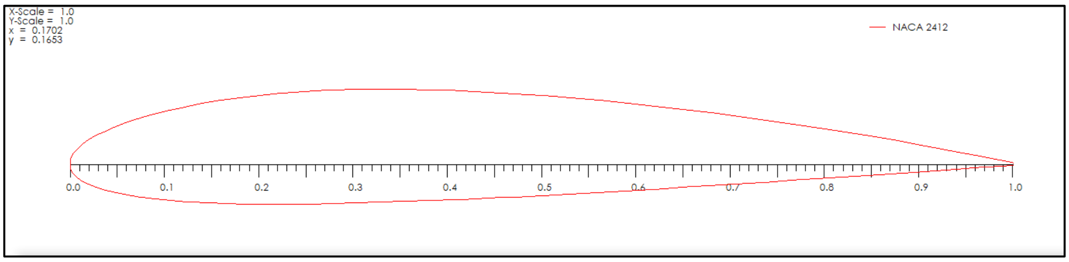


Fig. 3. Airfoil NACA 2412

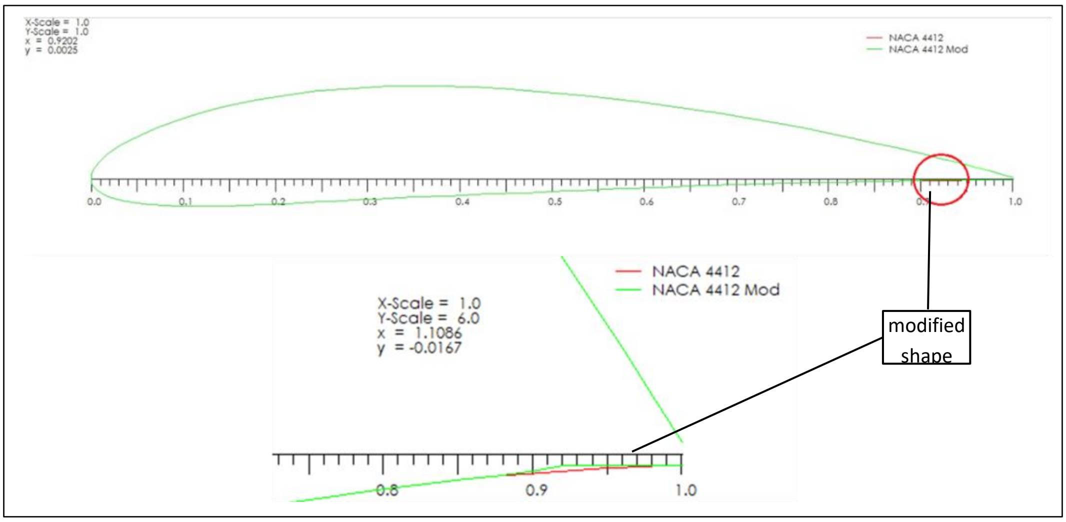


Fig. 4. NACA 4412mod

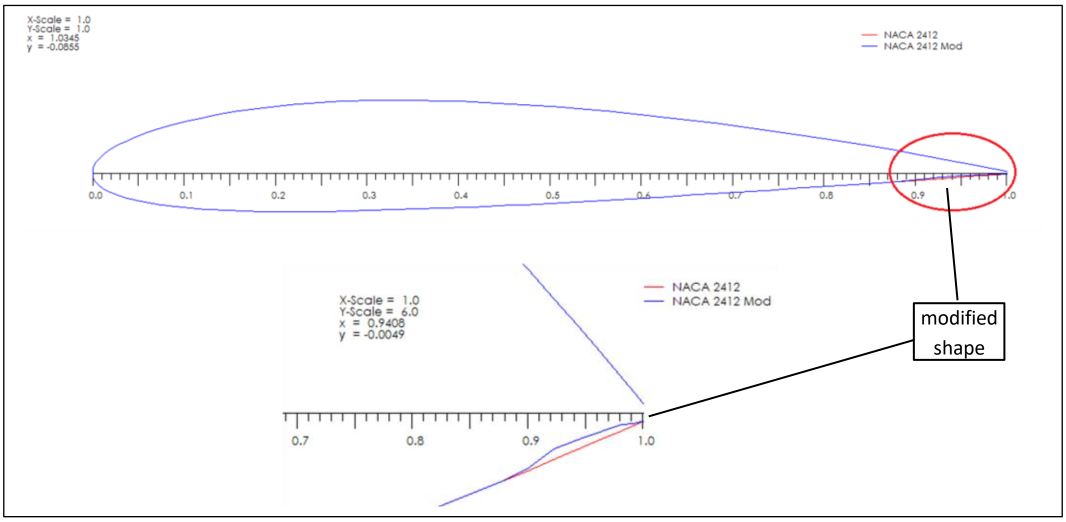


Fig. 5. NACA 2412mod

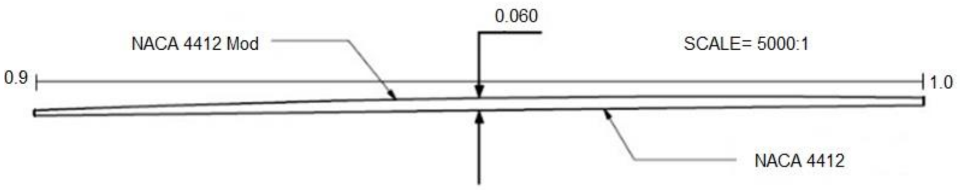


Fig. 6. Differences between Standard Airfoil and Modified NACA 4412

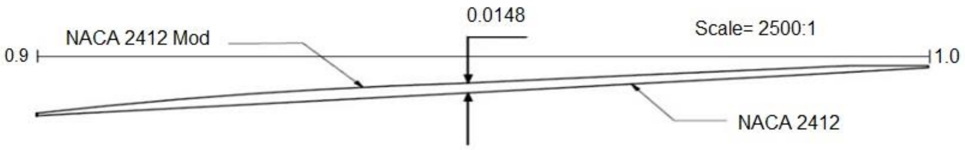


Fig. 7. Differences between Standard Airfoil and Modified NACA 2412

Figure 8 shows the angle of attack on the airfoil and the variations of the angle of attack presented in Table 1. The angle of attack should not be too large caused the air will no longer follow on the airfoil surface. Therefore, airflow will separate above the airfoil, and vortex will occur behind the airfoil leading edge. Consequently, the drag force increases significantly, and the lifting force decreases. This situation is called a stall, and the critical angle at which the transition occurs is called the stall angle of attack.

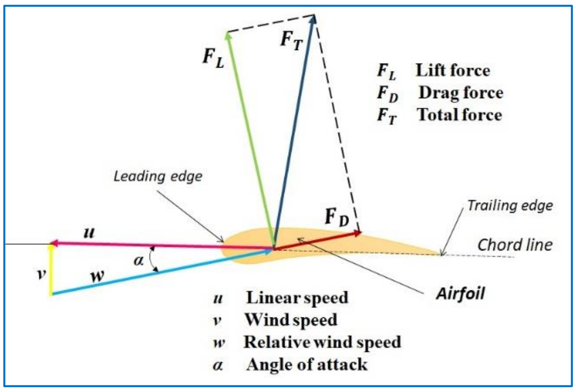


Fig. 8. Angle of attack and relative wind speed

The lift coefficient is very influential on the performance of a turbine. The value of the lift coefficient will change with the change in the value of the angle of attack. Variations of it on the airfoil, the value of C_L will increase as the angle of attack is adjusted until C_L reaches its maximum value. The C_L calculation use Eq. (8).

$$C_L = \frac{F_L}{{}^{1}\!/_{2}\rho w^2 A} \tag{8}$$

Where C_L is the lift coefficient and F_L is lift force.

3. Results

The validation has been done by comparing the power output between the CFD method by Oukassou [7] with the BEM method used in the present study. The power rotor has been simulated with the same parameters as the CFD (see Table 4). Hereafter, the power output generated by the BEM method is shown in Figure 9. The difference of CFD-BEM values is not so far apart, which is 0.4%. Therefore, the BEM method was appropriate to use to simulate rotor power accord the boundary conditions. Validation between the two models, namely CFD and BEM Theory, is carried out to verify the results of the turbin performance values are reasonable [40].

Table 4
Validation of BEM method in the present study with CFD methods [7]

Method	Airfoil	v (m/s)	Numbers of Blade	TSR	ρ (kg/m^3)	N (rpm)	P(kW)
CFD	NACA 0012	12	3	7	1,225	12.10	5
BEM	NACA 0012	12	3	7	1,225	12.10	4,98
% variation							0,4

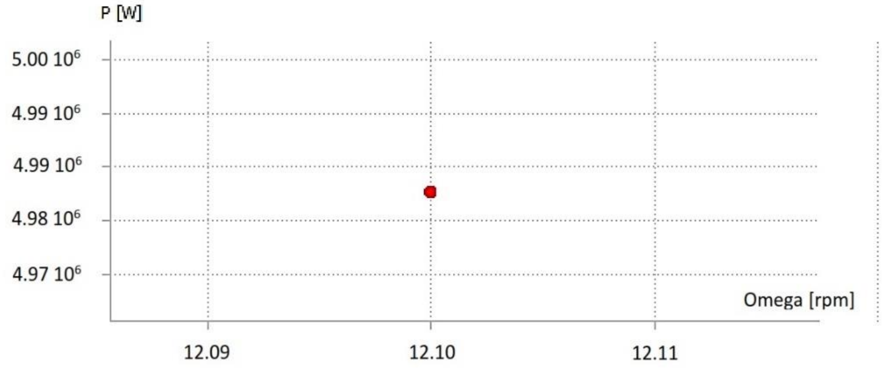
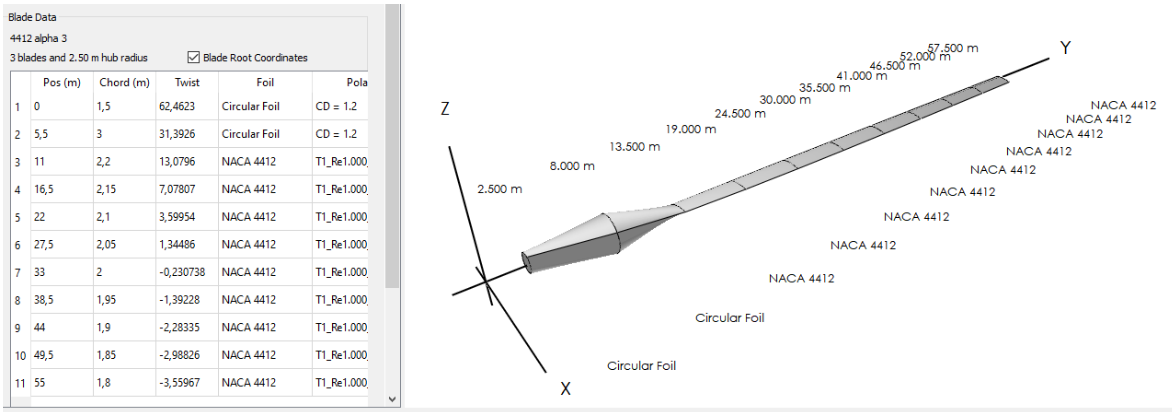


Fig. 9. Graph of power output using the BEM Method

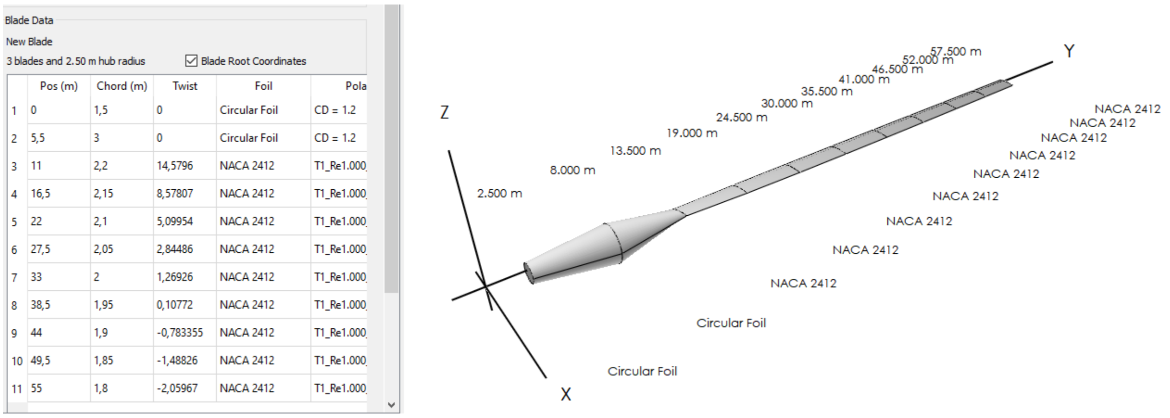
where *v* is wind speed, *TSR* is a tip speed ratio, *N* is rotor rotational speed, and *P* is the power output of the HAWT. Each rotor blade design consists of 10 segments, wherein segments 1 and 2 use circular foil. Furthermore, the third to the last segment uses either the NACA 2412 or NACA 4412 airfoil design, a combination of both, and the modified combination of the two airfoils. The design and geometry of the blade design as shown in Figure 10 to 13, which are the angle of attack 3˚.

The results of the turbine rotor power simulation using the BEM method on the Qblade software are adjusted to the predetermined parameters. The power data the simulation results are shown in Table 5.


Blade Data
4412 alpha 3
3 blades and 2.50 m hub radius ☑ Blade Root Coordinates

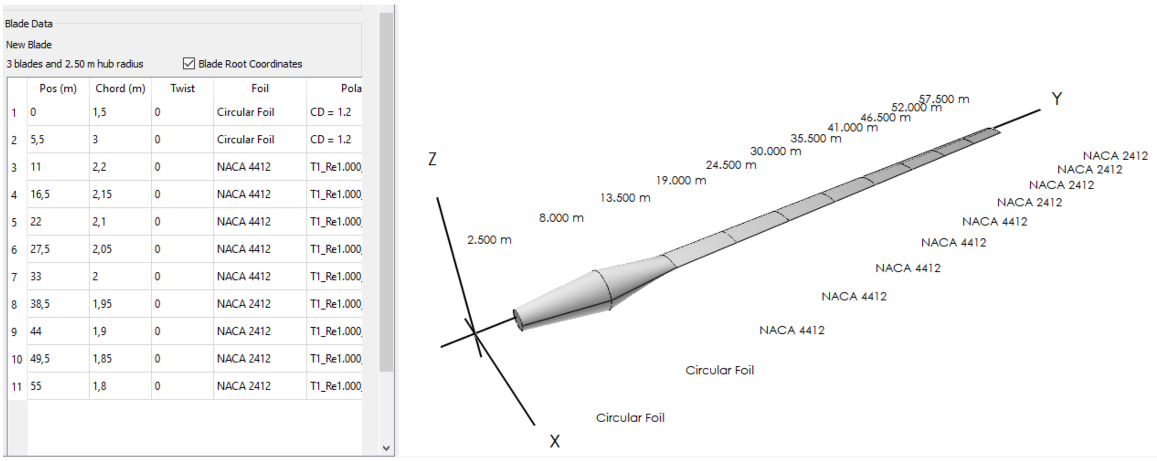
	Pos (m)	Chord (m)	Twist	Foil	Pola
1	0	1,5	62,4623	Circular Foil	CD = 1.2
2	5,5	3	31,3926	Circular Foil	CD = 1.2
3	11	2,2	13,0796	NACA 4412	T1_Re1.000
4	16,5	2,15	7,07807	NACA 4412	T1_Re1.000
5	22	2,1	3,59954	NACA 4412	T1_Re1.000
6	27,5	2,05	1,34486	NACA 4412	T1_Re1.000
7	33	2	-0,230738	NACA 4412	T1_Re1.000
8	38,5	1,95	-1,39228	NACA 4412	T1_Re1.000
9	44	1,9	-2,28335	NACA 4412	T1_Re1.000
10	49,5	1,85	-2,98826	NACA 4412	T1_Re1.000
11	55	1,8	-3,55967	NACA 4412	T1_Re1.000

Fig. 10. Rotor blade design use NACA 412 airfoil


Blade Data
New Blade
3 blades and 2.50 m hub radius ☑ Blade Root Coordinates

	Pos (m)	Chord (m)	Twist	Foil	Pola
1	0	1,5	0	Circular Foil	CD = 1.2
2	5,5	3	0	Circular Foil	CD = 1.2
3	11	2,2	14,5796	NACA 2412	T1_Re1.000
4	16,5	2,15	8,57807	NACA 2412	T1_Re1.000
5	22	2,1	5,09954	NACA 2412	T1_Re1.000
6	27,5	2,05	2,84486	NACA 2412	T1_Re1.000
7	33	2	1,26926	NACA 2412	T1_Re1.000
8	38,5	1,95	0,10772	NACA 2412	T1_Re1.000
9	44	1,9	-0,783355	NACA 2412	T1_Re1.000
10	49,5	1,85	-1,48826	NACA 2412	T1_Re1.000
11	55	1,8	-2,05967	NACA 2412	T1_Re1.000

Fig. 11. Rotor blade design use NACA 2412 airfoil



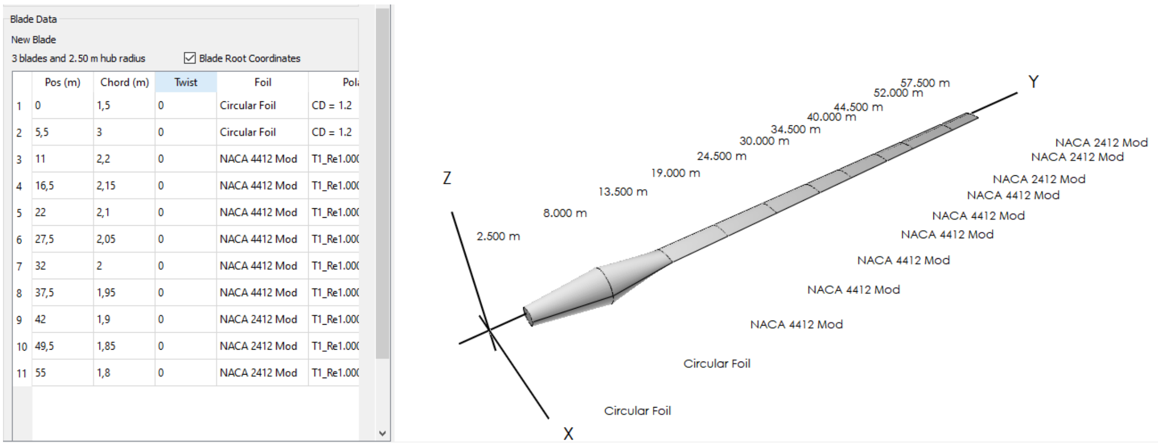
Blade Data

New Blade

3 blades and 2.50 m hub radius ☑ Blade Root Coordinates

	Pos (m)	Chord (m)	Twist	Foil	Pola
1	0	1,5	0	Circular Foil	CD = 1.2
2	5,5	3	0	Circular Foil	CD = 1.2
3	11	2,2	0	NACA 4412	T1_Re1.000
4	16,5	2,15	0	NACA 4412	T1_Re1.000
5	22	2,1	0	NACA 4412	T1_Re1.000
6	27,5	2,05	0	NACA 4412	T1_Re1.000
7	33	2	0	NACA 4412	T1_Re1.000
8	38,5	1,95	0	NACA 2412	T1_Re1.000
9	44	1,9	0	NACA 2412	T1_Re1.000
10	49,5	1,85	0	NACA 2412	T1_Re1.000
11	55	1,8	0	NACA 2412	T1_Re1.000

Fig. 12. Rotor blade design uses a combination of NACA 4412 with NACA 2412



Blade Data

New Blade

3 blades and 2.50 m hub radius ☑ Blade Root Coordinates

	Pos (m)	Chord (m)	Twist	Foil	Pol
1	0	1,5	0	Circular Foil	CD = 1.2
2	5,5	3	0	Circular Foil	CD = 1.2
3	11	2,2	0	NACA 4412 Mod	T1_Re1.00
4	16,5	2,15	0	NACA 4412 Mod	T1_Re1.00
5	22	2,1	0	NACA 4412 Mod	T1_Re1.00
6	27,5	2,05	0	NACA 4412 Mod	T1_Re1.00
7	32	2	0	NACA 4412 Mod	T1_Re1.00
8	37,5	1,95	0	NACA 4412 Mod	T1_Re1.00
9	42	1,9	0	NACA 2412 Mod	T1_Re1.00
10	49,5	1,85	0	NACA 2412 Mod	T1_Re1.00
11	55	1,8	0	NACA 2412 Mod	T1_Re1.00

Fig. 13. Rotor blade design uses modified airfoil NACA 4412 and NACA 2412

Table 5
HAWT Power rotor of L$_{16}$ (4^3)

No.	Factor Control			Power (kW)
	Airfoil (NACA)	Angle of Attack, α (˚)	Wind Speed, v (m/s)	
1.	4412	3	5	366
2.	4412	4	6	626
3.	4412	5	7	975
4.	4412	6	8	1420
5.	2412	3	6	619
6.	2412	4	5	358
7.	2412	5	8	1482
8.	2412	6	7	992
9.	4412-2412	3	7	1045
10.	4412-2412	4	8	1546
11.	4412-2412	5	5	372
12.	4412-2412	6	6	634
13.	4412mod-2412mod	3	8	1564
14.	4412mod-2412mod	4	7	1037
15.	4412mod-2412mod	5	6	646
16.	4412mod-2412mod	6	5	368

ANOVA is used to determine the effect of each factor (airfoil, angle of attack, and wind speed) on the turbine rotor power produced. Table 6 is the analysis of the variance of each factor at each level tested for the rotor power. The analysis (see table 6) shows that the airfoil and wind speed factors significantly affect the turbine rotor power because the analysis value is less than the specified P value (0.05). The largest F value (2,424.3) is found in the wind speed factor so that it is the most influential factor on turbine rotor power compared to airfoil and angle of attack. The table below shows the F and P values for the contribution test of the parameters. Wind speed is the most significant influencing factor in generating power conforms the power output is proportional to the cube of wind speed, according to Eq. (6). As the wind speed increases, so does the power extracted by the turbine increased [6].

Table 6
Analysis of Variance on Power Rotor

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Airfoil	3	9,295	9,295	3.098	7.7	0.02
Angle of Attack	3	5.180	5.180	1,727	4.29	0.06
Wind Speed	3	2,926,710	2,926,710	975.570	2,424.3	0
Error	6	2.415	2.415	402		
Total	15	2,943,600				

S = 20.06 R-Sq = 99.92% R-Sq (Adj) = 99.97%

Calculation of the S/N ratio of roundness through a combination of levels of each factor uses Eq. (2). The result of S/N ratio as shown in Table 7.

Table 7 shows the S/N ratio value of rotor power for each factor. The S/N ratio gets the wind speed factor was ranked 1st or the most significant effect to the power rotor. The data of the S/N ratio was plotted in Figure 13, which shows of each factor affects each level. The airfoil factor at level 4 has a greater influence on the airfoil NACA 4412mod-NACA 2412mod provides a better output of rotor power. Furthermore, to the angle of attack factor, it is known that level 1 has a significant influence over the others (2, 3, and 4). The angle of attack of 3˚ gives a better rotor power output. On another factor, Level 4 of wind speed has a higher effect than levels 1, 2, and 3.

Table 7
Response of S/N Ratio of Roundness of Effect of Factor

Level	Airfoil	Angle of Attack	Wind Speed
1	57.51	57.84	51.27
2	57.56	57.78	56.00
3	57.90	57.70	60,10
4	57.93	57.58	63.53
delta	0.42	0.26	12.26
rank	2	3	1

The speed factor has an S/N ratio of 12.26 so this factor has a significant effect on the value of generating rotor power. Based on the plot (Figure 14), the significant influence on the power rotor is the airfoil parameter NACA 4412mod-NACA 2412mod, 3˚an angle of attack, and 8m/s of wind speed. Accordingly, these parameters are the optimum value of the power rotor.

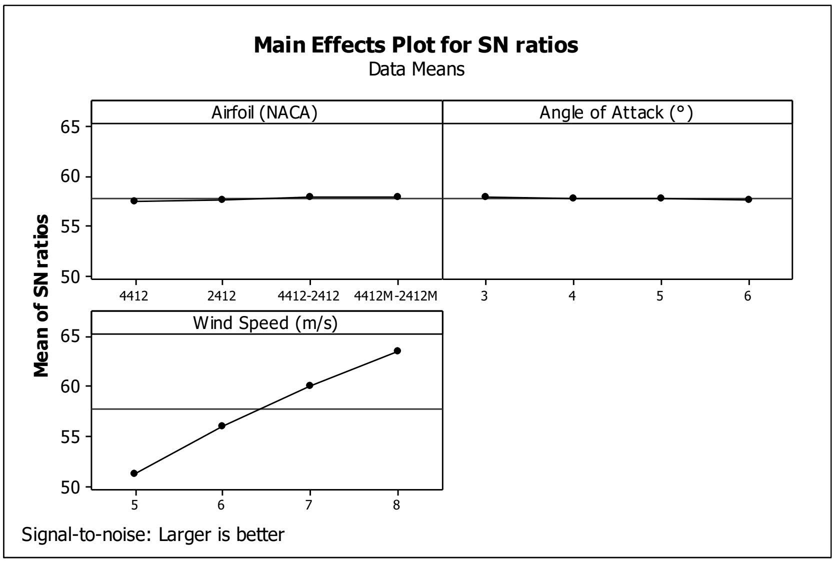


Fig. 14. S/N Ratio Plot Rotor Power

The optimum power was obtained on the NACA airfoil modified. This is because the lift coefficient of the modified NACA airfoil (4412mod-2412mod) is greater than the standard NACA (4412-2412) with the CL value increased by 0.002. These results were obtained from the BEM method simulation as shown in Figure 15. Even though the lift coefficient insignificant increase, but its contributed to an increase in the performance of HAWT.

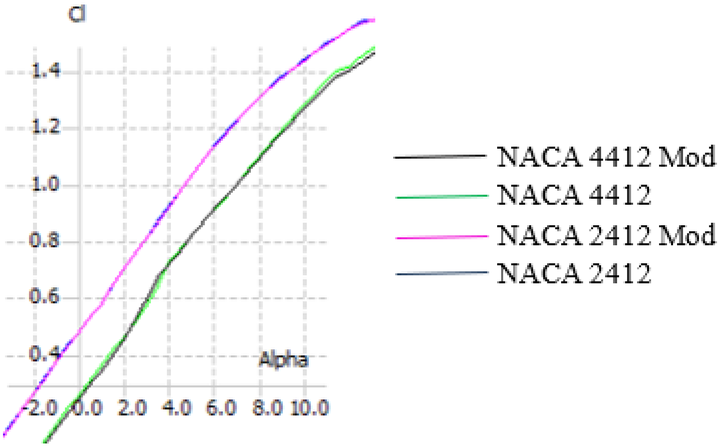


Fig. 15. The plot of lift coefficient versus angle of attack of Airfoil in the study

Based on the simulation result (Figure 15), the coefficient of lift of each airfoil increased as the angle of attack increases. Seen at angle of attach of 10˚, the C_L value of at least 1.2 is higher than the C_L limit in this study of 6 ˚, with a minimum CL of 0.6. Due to the obvious unstable character of the flow at high angles of attack, there is a considerable degree of uncertainty in the performance of airfoils and, as a result, in the performance of blades [41]. The angle of attack in this study was 3-6 ˚ further the findings of S/N ratio computation show that the higher the alpha, the lower the value of the S/N ratio. The difference in the decrease of the S/N ratio of 0.26 is too small on the increase in the alpha value, then concluded that the angle of attack factor has no significant effect on the rotor power.

4. Conclusions

HAWT rotor blades on several variations of airfoils, angles of attack, and wind speed according to L16(4^3) orthogonal array were simulated to generate output power. The rotor power optimum (1.56MW) obtain on the NACA 4412mod-2412mod airfoils parameters with the angle of attack of 3° and wind speed of 8 m/s. Wind speed is the most significant influencing factor based on ANOVA analysis, then was 1st ranked based on S/N ratio analysis. Furthermore, the 2nd rank that influences consecutively is an airfoil, and the last rank is the angle of attack. The higher the wind speed, the greater the rotor power generated. The aerodynamic characteristics of airfoil NACA 4412 and NACA 2412 after being modified on the lower surface near the trailing edge have been simulated with the BEM method produce lift coefficient greater than NACA 4412 and NACA 2412 before modification. The lift coefficient of the NACA 4412 and NACA 2412 after modified was rose by 0.002 for both airfoils types that contribute positively to increasing the power performance of the HAWT rotor.

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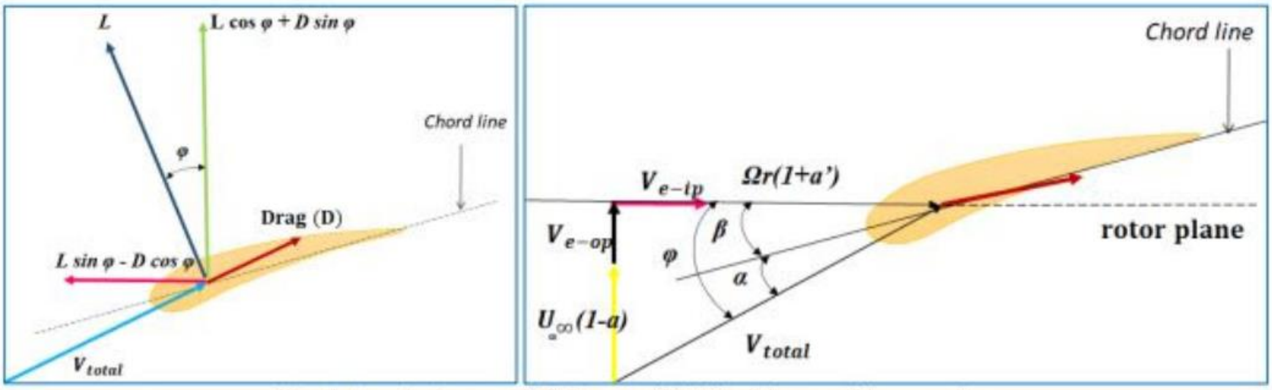

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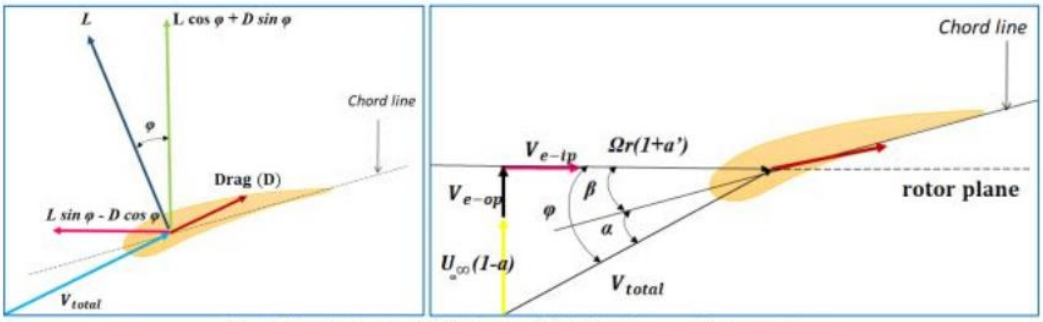

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Rotor Power Optimization of Horizontal Axis Wind Turbine from Variations in Airfoil Shape, Angle of Attack, and Wind Speed

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ABSTRACT

This paper presents rotor power optimization of the Horizontal Axis Wind Turbine of various parameters such as airfoil, angle of attack, and wind speed. Simulation of HAWT rotor power uses Blade Element Momentum (BEM). Furthermore, optimization using the Taguchi method with $L_{16}(4^3)$ orthogonal array. The parameters used in this study were: airfoil NACA (National Advisory Committee for Aeronautics) 4412, NACA 2412, NACA 4412-NACA 2412, NACA 4412mod-NACA 2412mod; angle of attack 3˚, 4˚, 5˚, 6˚; and wind speed of 5, 6, 7, 8 (m/s). The simulation uses the general parameter at 1 MW HAWT. Several types of NACA airfoil, angle of attack, and wind speed were simulated, then optimized to obtain optimal parameters for the HAWT output power. The results of this study found the most optimal rotor power, namely the condition of the NACA 4412mod-NACA 2412mod airfoil, 3˚ angle of attack, and 8m/s wind speed. Wind speed is the most significant influence factor based on ANOVA analysis ranked 1st based on S/N ratio analysis, 2nd rank is an airfoil, and 3rd rank is the angle of attack. The higher the wind speed, the greater the rotor power generated.

1. Introduction

Numerous locations in Indonesia have the potential for wind power generation growth, with wind speeds exceeding 5m/s [1]. However, at low wind speeds of the wind power systems at the inland sites, South East Asia does not produce substantial electricity [2]. According to IEC [3], a wind speed of 5 m/s was classed as low wind speed. A rotor blade is an essential part of the advancement of wind power generation. Another component that impacts wind turbine performance is bearings, particularly ones with exceptionally low friction that influences wind turbine performance. Since there's no mechanical contact between the shaft and the rotor blade, studying Permanent Magnetic Bearings (PMB) in wind turbine prototypes to substitute mechanical bearings can enhance rotational speed and torque [4].

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