Design and Numerical Simulation of Performance of Horizontal Axis Tidal Turbine with Flow Velocity of 1.3 m/s

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Abstract

Today, the fossil energy is still the main source for energy consumption. But excessive usage of fossil fuel has negative effects for the environment. Because of those reasons the scientists and engineers are looking for new resources that make less negative impact to the environment. In this research, the design process of tidal turbine is done theoretically with sea current velocity of 1.3 m/s. After the design result is considered satisfying, the next process is three dimensional modelling. After that, the model is simulated in computational fluid dynamics software by varying the flow velocity, the turbine rotational speed, and the pitch angle. From the calculation process, it is obtained that the diameter is 13.6 m, airfoil profile is NACA 4412, and angle of attack is 5°. The simulation result showed the torque at the design point is 79 kN.m, power is 83 kW, and the efficiency is 50,3%. From the pressure contour it was known that the lowest pressure happened in the turbine is 163083 Pa. So it could be concluded that the cavitation did not happen. In the simulation of variation of flow velocity, the power increased along with the increase of velocity, but the maximum efficiency was achieved at the design point. In the simulation of variation of turbine rotational speed, the maximum torque was obtained at the design point, but the maximum power was achieved at the rotational speed of 12 rpm. In the simulation of variation of pitch angle the power increased along with the increasing of change in pitch angle.

Key words: tidal turbine, flow velocity, turbine rotational speed, pitch angle

Introduction

One of the parameters of economic development of a country is the demand of electricity. The bigger the economy of a country then the bigger its need for electricity. Indonesia is the 16th largest economy in the world and it needs electricity power as much as 228554.91 GWh in 2014, but the electrification ratio is only 74%. In 2014, the source from fossil fuel to fulfill the electricity demand is 89.5% [1]. This is ironic given that Indonesia is an archipelago country that has vast alternative energy sources, but they are not properly harvested.

Indonesia has coastline length of 54716 km. This is the second longest coastline in the world. The tidal energy potential in Indonesia is 4,8 GW [2]. The tidal turbine is also suitable for remote area application near the coastline.

Objectives

1. Obtain the dimensions from the design process of tidal turbine.
2. Obtain power and efficiency at the design point using numerical simulation.
3. Obtain power and efficiency in variation of operational point of flow velocity, rotational speed and pitch angle using numerical simulation.

Scope of Work

1. The design process is only done in hub and blade. The other components such as nacelle, pole, and mechanical and electrical power transmission system are not designed.
2. Analysis is only done in torque, power, efficiency, and pressure contour of the blade.
3. Numerical simulation is done with varying the flow velocity, rotational speed, and pitch angle. The simulation is done in steady state condition using ANSYS Fluent.

Data used in design process:
Flow velocity (U_∞) = 1.3 m/s
Tip speed ratio (λ) = 5.5
Rotational speed (Ω) = 1.047 rad/s
Number of blades (N) = 3
The following formula is used to calculate diameter.

$$D = \frac{2\,\lambda\, U_\infty}{\Omega} = \frac{2 \times\ 5.5 \times 1.3}{1.047} = 13.6m$$

Based on references, the airfoil profiles commonly used in tidal and wind turbine are NACA 0012, NACA 4412, and NACA 63212. In order to get better performance, it is needed to select airfoil with the highest Cl/Cd. By using QBlade software, the Cl/Cd at various angle of attack can be obtained. The simulation result shown in Figure 2. NACA 4412 is selected because it has higher Cl/Cd than other profiles.

Design Calculation

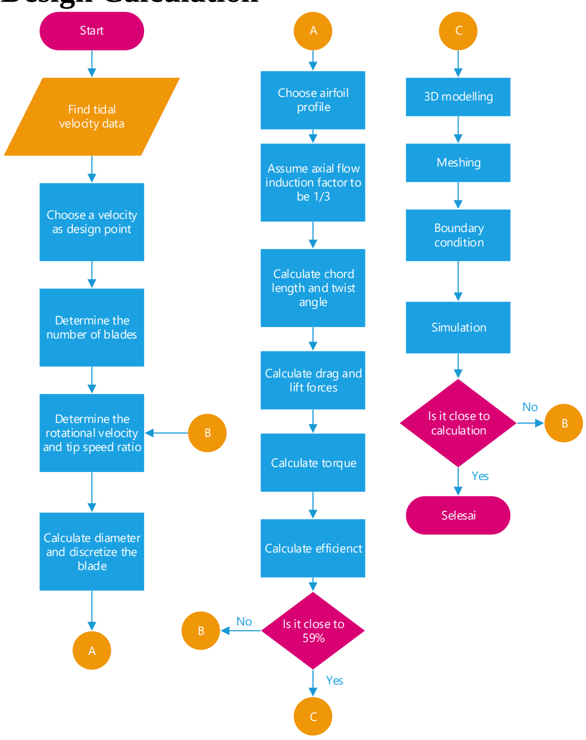

Figure 1 Design flowchart

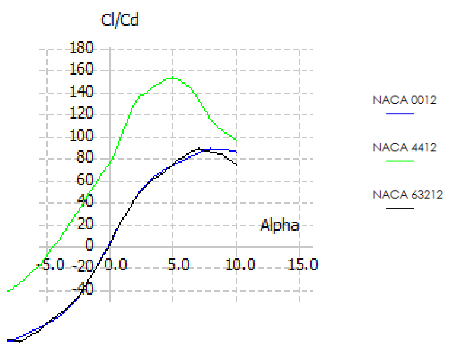

Figure 2 Cl/Cd versus angle of attack

The following formula is used to calculate the fluid relative angle with respect to the blade section.

$$\phi = \tan^{-1}\frac{\Omega r(1+a')}{U_\infty(1-a)}$$

The twist angle of each blade section can be calculated with the following formula.

$$twist\ angle = \phi + \alpha$$

The following formula is used to calculate chord length of each section.

$$c = \frac{8\lambda\mu^2 a'\pi R}{NC_l\sqrt{(1-a)^2 + (\lambda\mu(1+a'))^2}}$$

The calculation result is shown in Table 1.

Table 1 Blade geometry calculation

Segment	Twist angle t (deg)	Chord length (m)
Root	-	-
Section 1	71,5	1,313
Section 2	75,0	1,127
Section 3	77,7	0,980
Section 4	80,1	0,847
Section 5	82,0	0,743
Section 6	83,4	0,661
Section 7	84,6	0,595
Section 8	85,6	0,540
Section 9	86,4	0,495
Section 10	87,1	0,456
Section 11	87,6	0,427
Section 12	88,0	0,402
Section 13	88,1	0,394

After determining the blade geometry, the forces, torque, and power can be calculated with following formulas.

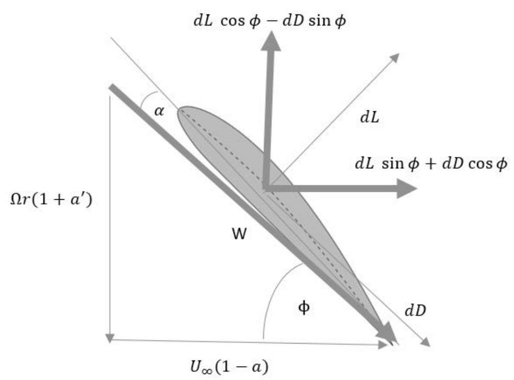

Figure 3 Blade section

$$dL = \frac{1}{2}\rho W^2 c \cos\alpha\, C_l dr$$

$$dD = \frac{1}{2}\rho W^2 c \sin\alpha\, C_d dr$$

$$dT = (dL\ \cos\phi - dD\sin\phi)r$$

The result is shown in
Table 2.

Table 2 Torque calculation

Section	Torsi (N.m)
Section 1	401,0
Section 2	1102,3
Section 3	1324,7
Section 4	1840,6
Section 5	2132,7
Section 6	2420,6
Section 7	2705,3
Section 8	2987,1
Section 9	3266,2
Section 10	3542,8
Section 11	3237,7
Section 12	3437,8
Section 13	1167,8

Total torque:

$$T_{tot} = \sum_{i=1}^{13} T_i = 29.566\ \mathrm{N.m}$$

Power generated:

$$P = N \times \Omega \times T_{tot}$$

$$P = 3 \times 1{,}047 \times 29.566$$

$$\mathrm{P} = 92886\ \mathrm{Watt}$$

Power coefficient or efficiency:

$$C_p = \frac{P}{\frac{1}{2}\rho A_d U_\infty^3} = \frac{92.886}{164.098} = 56{,}6\%$$

Betz efficiency:

$$\eta_{Betz} = \frac{Cp}{0{,}5925} = 95{,}5\%$$

The 3D modelling is done in Inventor Autodesk using loft process from sketches.

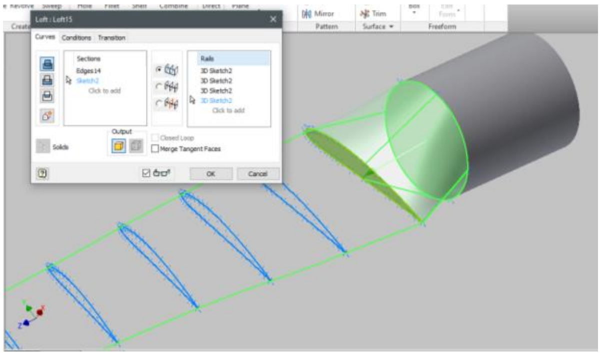

Figure 4 3D modelling

Result and Analysis

From the simulation result, the torque at the design point is 79 kN.m and the power is 83.3 kW. But from the calculation process the power is 92 kW. The result obtained from the simulation process is more close to the physical representation because in theoretical calculation there are many assumptions. In theoretical calculation the axial flow induction flow factor is assumed to be 0.33, which is an ideal value. But in reality this value depends on the geometry and flow velocity. In theoretical calculation, it is also assumed that in the same section, the chord length and twist angle are constant. In theoretical calculation, the blade tip loss phenomenon is neglected. Blade tip loss is the loss in lift force due to vortex that happens as a result of the pressure difference between pressure and suction side of the airfoil.

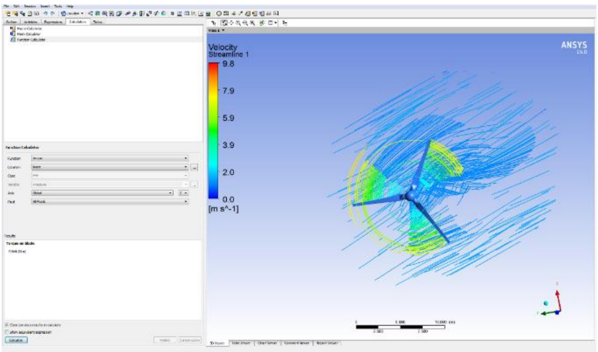

Figure 5 Streamline velocity

In pressure contour from simulation result, it is shown that the lowest pressure in the turbine is 164083 Pa. The saturated pressure of water at temperature of 30oC is 4159 Pa. Because the lowest pressure in the turbine is higher than the water saturated pressure, it can be concluded that cavitation does not occur.

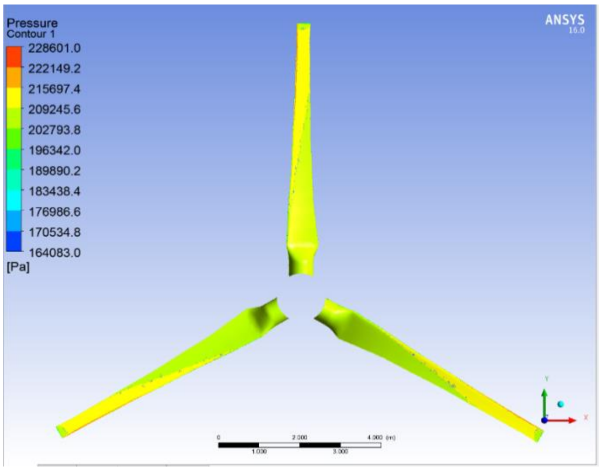

Figure 6 Pressure contour on pressure side

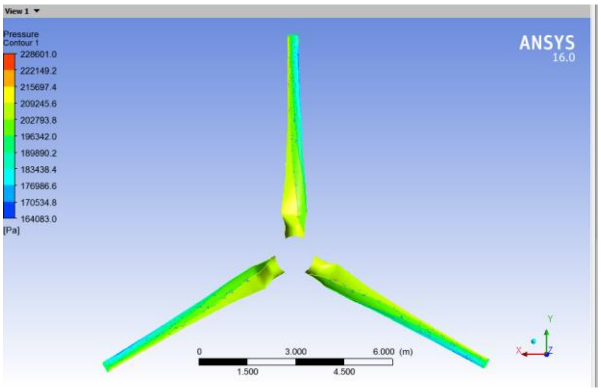

Figure 7 Pressure contour on suction side

The simulation result with variation of flow velocity is shown in Figure 8. Figure 8 shows that with increasing in velocity, the power is also increasing. But Figure 9 shows that the efficiency is decreasing at the velocity that far from the design point. This happens because the relative angle of the fluid into the blade is changing. The change in the angle makes the angle of attack changes and not in its optimum angle.

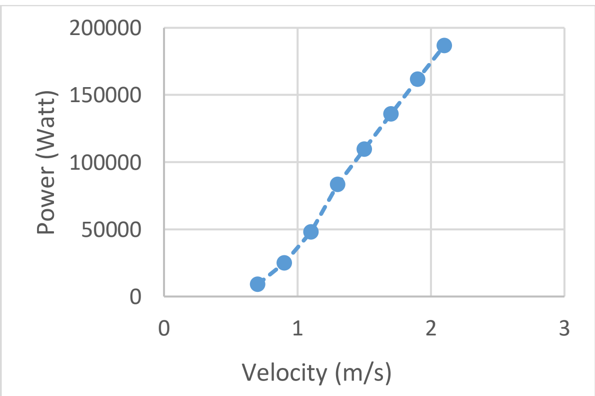

Figure 8 Power versus flow velocity

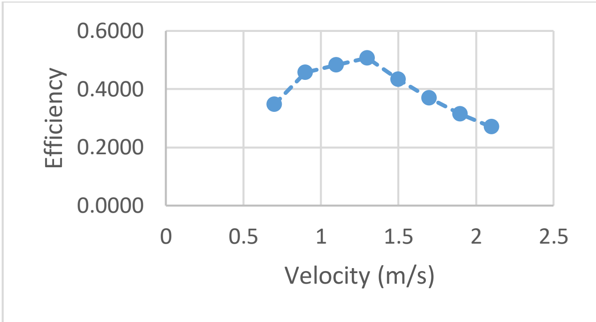

Figure 9 Efficiency versus flow velocity

The simulation result with variation of rotational speed is shown in Figure 10and Figure 11. The maximum torque happens at rotational speed design point. When the rotational speed increases, the torque is decreasing. Maximum power and efficiency are obtained at 12 rpm and starts to decrease at 15 rpm.

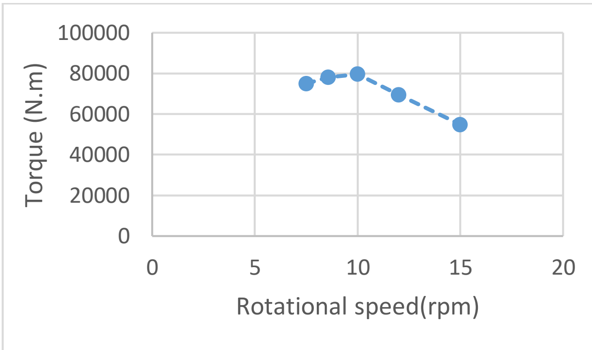

Figure 10 Torque versus rotational speed

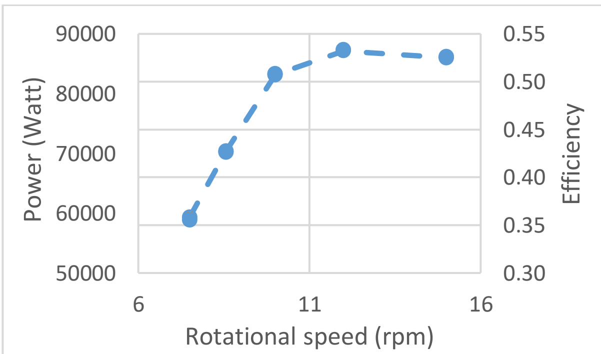

Figure 11 Power versus rotational speed

The simulation result with variation of pitch angle is shown in Figure 12. The graph shows that with increasing the angle, the power is also increasing. But if the angle is increased furthermore, stall will happen and the power will decrease.

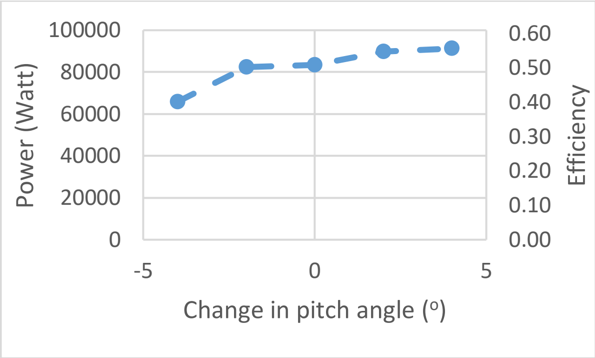

Figure 12 Power versus change in pitch angle

Summary

1. Design results
   - Number of blades: 3
   - Turbine diameter: 13,6 m
   - Airfoil profile: NACA 4412
2. Performance obtained at the design point:
   Torque: 79.5 kN.m
   Power: 83.3 kW
   Efficiency: 50.7%
3. Performance at various operational point:

- Variation of velocity: the power is increasing along with the increasing of velocity. But at the velocity far from the design point the efficiency is decreasing.
- Variation of rotational speed: the maximum torque is achieved at the design point and decreasing along with the increasing of rotational speed. Maximum power is obtained at 12 rpm.
- Variation of change in pitch angle: the power is increasing along with the increasing of pitch angle.

Reference

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