Ocean Current Turbine Blade Performance Prediction using the Blade Element Theory

Noor Rahman, Saeed Badshah, Abdur Rafai, Muhammad Adnan, Mujahid Badshah

Abstract— Optimal Design of the ocean current turbine requires analysis of the blade performance to find answer to the question that at specified speed of the ocean current how much torque will produce by the blade. This thesis presents that blade element theory analysis of the ocean current turbine blade. The lift, drag and torque calculations are the important parameters for the blade performance prediction. This paper discussed the blade element theory for the prediction of the lift, drag, torque, theoretical, actual power, and coefficient of power for the NACA 44xx ocean current turbine blade. The length of the blade is 3 meter and is rotating with 24 RPM. The NACA 44xx airfoils coefficients of lift and drag are used for the calculation of lift and drag. The ocean current speed is assumed to be 1.7 m/sc and the ocean water density is 1025 kg/m^3.

Index Terms— CFD, Blade, Ocean, Turbine Blade, Lift, Drag, Torque

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1 INTRODUCTION

T Now a day's the earth inhabitants are facing shortages of energy and the humans are trying to face these shortages with new renewable energies instead of the old ones which produce CO$_2$ and are limited on the earth. In this scenario we have to consider our earth oceans as a good source of clean and inexhaustible energy. Three of four parts of the world's surface are covered by the oceans. It means that most of the energy that arrives from the sun to the earth is retained by the water of the seas. Our oceans are like a very great solar collector.[1] Oceans cover 70 percent of the earth's surface and represent an enormous amount of energy in the form of wave, tidal, marine current and thermal resources.

Though ocean energy is still in a developmental stage, researchers are seeking ways to capture that energy and convert it to electricity. [2]

The ocean currents are the movement of ocean water. [3]Marine currents may represent a renewable energy source characterized by a limited environmental impact. [4] Turbines placed directly in river, ocean, or tidal current generate hydrokinetic power from the kinetic energy of moving water (current).

The available hydrokinetic power depends on the speed of the river, ocean, or tidal current and is a function of the density of the water and the speed of the current cubed.

In order to operate, hydrokinetic devices require a minimum current and water depth. The minimum current required to operate a hydrokinetic device is typically 1–2 m/s, but may be as low as 0.5 m/s, depending on the particular technology approach.

Hydrokinetic devices are ideally installed at locations that have relatively steady flow throughout the year and are not prone to serious flood events, turbulence, or extended periods of low water level. [5]

Ocean Current Turbine is basically a micro hydro kinetic turbine and its main purpose is to transform the kinetic energy of ocean current into electricity. Two main types of ocean current turbines have developed the horizontal and vertical axis ocean current turbines. [6] Recently the researchers are working on the ducted horizontal axis turbine to more efficiently extract energy from ocean current.

The world energy demand is increasing day to day and we will need 45 % additional energy in 2030. [7]

For this purpose ocean energy resources must be extracted to generate electricity for the future. If 0.1% of the total renewable energy is in the ocean, and if converted into electric power then it will be 5 times more than the present electricity demands of the world because ocean are spread on 70% of the earth surface. [8] The ocean hides a huge useful energy more than from the wind energy, because the density of the water is 800 times greater than the air density, it is about 3 times greater than the air/wind density. [9] Obviously the speed of the ocean water is lower that the wind speed but its density makes its kinetic energy greater than the wind kinetic energy. The ducted ocean current turbine will increase the power production from the ocean current energy and

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this will enable us to install this ducted ocean turbine at the site where the ocean velocity is slow and the ordinary turbine does not generate enough power. In ducted ocean current turbine energy is extracted primarily by a pressure Drop. [10] Excelling at renewable energy technology (RET) innovation is an important aspiration for many nations. [11] Many countries are looking for the ocean current power park at their ocean current sites. [12] The researchers predict that in 2050 the electricity production from ocean resources will cross 645 Tetra watts Hour. Technology development remains the critical issue for ocean energy systems. [13] Although the marine and hydrokinetic (MHK) industry is at a relatively early stage of development compared to other renewable energy technologies. [14] Researches and projects the Ocean Current Turbine development is still in the developing phase with a strong promise to the future renewable energy share in the energy sector. But today there are still some problems exist in the commercialization of the ocean current turbine these problems includes the avoidance of drag from cavitation's, this cavitation's decreases the turbine efficiency, other problems are the blade corrosion, prevention of marine growth at the turbine blades, System maintenance and reliability. These problems are the main hurdle in the way of the ocean current turbine commercialization. [15] The research and work is still continued to resolve all the issues that are related with the ocean current turbine. The maintenance of the ocean current turbine is not easy because it is install deep the ocean and which makes its maintenance complex. Research is continued to address all the above problems. The ocean energy is green, renewable, reliable, sustainable and durable and is available on a very large scale. [16]

1. MODEL OF OCEAN CURRENT TURBINE BLADE

The model of the blade is generated in Pro-Engineer Software using the NACA 44xx airfoils. The NACA 44xx airfoils are used because its leading edge is round and tailing edge are thicker. Due to these advantages NACA 44xx structures are mostly used in ocean and wind turbine industry.

The two reinforcement webs are passes through the blade are as shown in figure 1. The length of the both the reinforcement is 0.24 m (2400 mm) and they pass throughout the blade. They provide strength to the blade geometry.

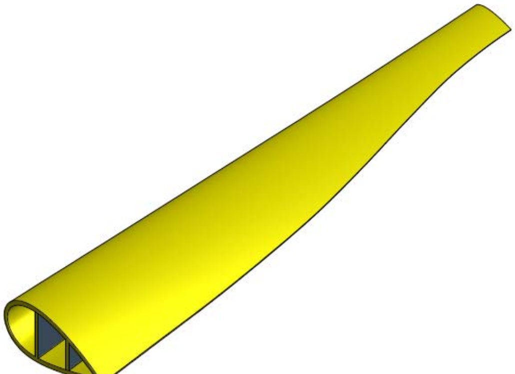


Figure 1 Ocean Current Blade Model

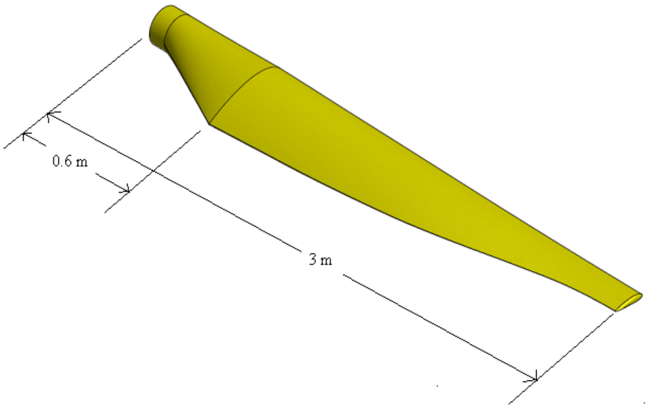


Figure No.2, Complete Blade with Shaft connecting Section

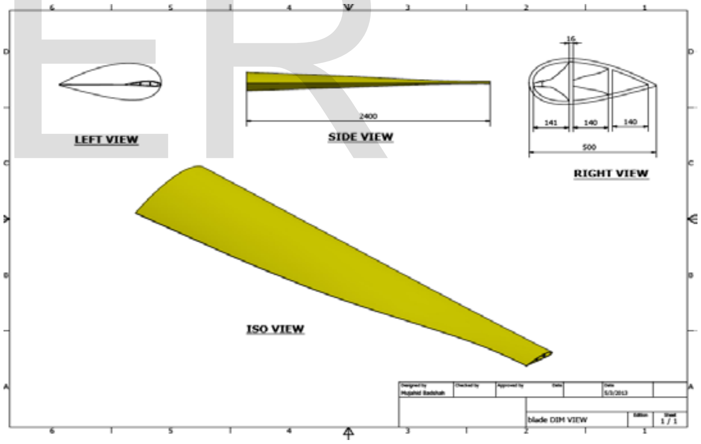


Figure.3, Isometric Views of Ocean Current Turbine Blade

BLADE ELEMENT THEORY:

The Blade element theory is based on the following assumptions.

- No hydrodynamic interactions occur between different blade elements.
- Blade Force are determine using the lift and drag Coefficients [17]

It means that in blade element method every section/blade element is independent from the other sections/blade elements and there is no effect of one blade element on its neighbor's blade element. It enables us to differentiate the whole blade into small independent sections and then solve every section/blade element independently. After solving every section/blade element we integrate all sections/blade over the whole blade span and find the total lift, drag and torque over the blade due to the ocean current speed. The Coefficients of the blade airfoils are available for NACA 44xx airfoils.

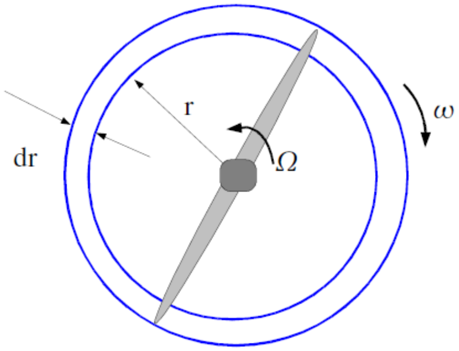


Figure No.4, Rotating Annular Stream tube: notation [17]

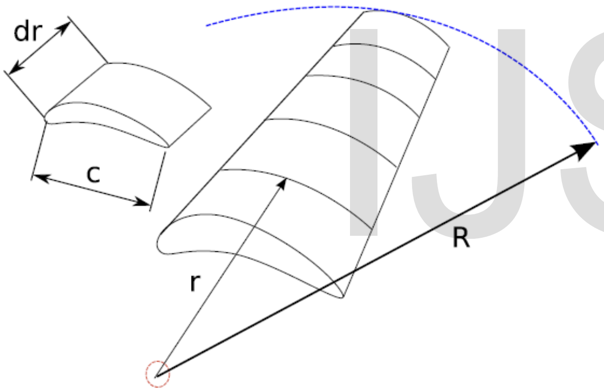


Figure No.5, the Blade Element Model [18]

According to blade element theory blade is divided into N sections/elements. As each element of the blade have a specific chord length, twist angle and rotational speed therefore the flow on each section/element of the blade will slightly different. The ocean current turbine blade have been divided into nine sections/elements each element have a specific chord length, thickness, coefficient of lift, coefficient of drag and angle of attack. After differentiating the whole blade into small element and solving each element the integration of all elements leads to the overall performance of the blade along its whole length.

The forces on the blade element are shown in Figure note that by definition the
lift and drag forces are perpendicular and parallel to the incoming flow. For each blade element one can see:

$$dF_\theta = dL\cos\theta - dD\sin\theta \qquad (1)$$

$$dF_x = dL\sin\theta + dD\cos\theta \qquad (2)$$

F_x is the Axial force and F□ is the Tangential force While dL and dD are the blade element lift and drag forces. dL and dD can be find using the coefficient of lift and drag from the NACA 44xx airfoils. The lift and drag on an element can be found using the below equation no.3 and 4. [17]

Relative Velocity of the Ocean Current on the Blade

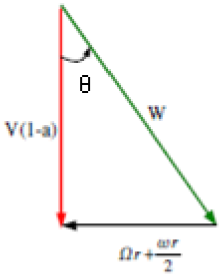


Figure No.6, ocean velocity and relative velocity

$W = V (1-a)/\cos\theta$

a is the axial induction factor
θ is the relative flow angle
$\theta = \alpha + \beta$
V is the ocean velocity and its value is 1.7 m/sec

$$a = 1/[1 + 4\sin^2\theta/\sigma'(C_L\cos\theta + C_D\sin\theta)]$$

σ' is the BladeLocal Solidity
$\sigma' = nc/2\pi r$

n is the number of turbine blades
c is the chord line
r is the local blade radius

Computing values in the above equations and forming the below table for the relative velocity of the ocean current on the turbine blade

Table No.1, For Induction factor (a) and Relative Velocity (W)

l, m	Θ Deg	C, m	CL	CD	σ’	a	W, Relative Velocity m/sec	NACA 44xx
0.6	26.43	0.5	0.868	0.0167	0.064	0.06	1.778625	4441
0.9	20.95	0.48	0.904	0.0168	0.061	0.1	1.6938018	4438
1.2	16.78	0.46	0.954	0.0158	0.059	0.14	1.5276438	4434
1.5	13.46	0.43	0.965	0.0137	0.055	0.2	1.397672	4431
1.8	10.17	0.39	0.946	0.011	0.05	0.33	1.1575201	4427
2.1	9.88	0.33	1.003	0.0107	0.042	0.33	1.1563356	4423
2.4	9.94	0.26	1.075	0.0108	0.033	0.25	1.2944055	4418
2.7	9.35	0.20	1.064	0.0106	0.025	0.25	1.2917025	4416
3	9.32	0.18	1.064	0.0106	0.023	0.25	1.2917025	4416

$$dL = C_L \rho 1/2\, W^2 cdr \qquad (3)$$

$$dD = C_D \rho 1/2 W^2 cdr \qquad (4)$$

Lift and Drag coefficients for a NACA 44xx aerofoil are shown in table No.1

Table No.2, for NACA 44xx airfoils Data

l, m	*T, Actual thick-ness, mm*	*C, mm*	*B, deg*	*Θ, deg*	*α, deg*	*Re*	*NACA 44xx*	*CL*	*CD*	*Rip Pitch Dis-tribution mm*
0.6	*16*	*500*	*16.5*	*26.43*	*9.93*	*1106100*	*4441*	*0.868*	*0.0167*	*4.2*
0.9	*16*	*480*	*11*	*20.95*	*9.95*	*1282165*	*4438*	*0.904*	*0.0168*	*3.8*
1.2	*16*	*460*	*7*	*16.78*	*9.78*	*1438808*	*4434*	*0.954*	*0.0158*	*3.2*
1.5	*16*	*430*	*5.5*	*13.46*	*7.96*	*1565234*	*4431*	*0.965*	*0.0137*	*2.8*
1.8	*16*	*390*	*5*	*10.17*	*5.17*	*1623068*	*4427*	*0.946*	*0.011*	*2.2*
2.1	*16*	*330*	*4.5*	*9.88*	*5.38*	*1533421*	*4423*	*1.003*	*0.0107*	*1.6*
2.4	*8.5*	*260*	*4.5*	*9.94*	*5.44*	*1333776*	*4418*	*1.075*	*0.0108*	*0.974*
2.7	*5*	*200*	*4.5*	*9.35*	*4.85*	*1130972*	*4416*	*1.064*	*0.0106*	*0.66*
3	*4.4*	*180*	*4.5*	*9.32*	*4.82*	*1112795*	*4416*	*1.064*	*0.0106*	*0.60*

Graphs showing the lift coefficients and angle of attack for the NACA 44xx airfoils

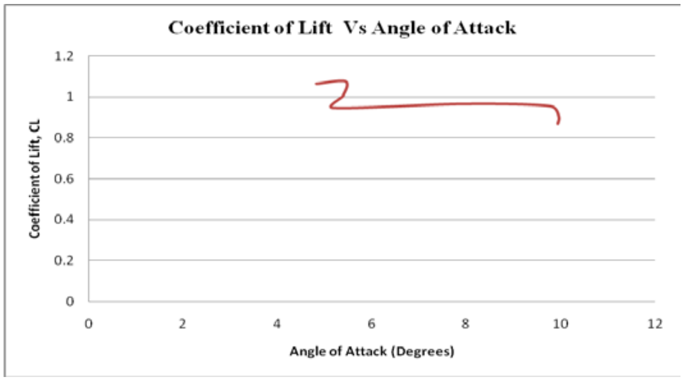


Figure No.7, Coefficient of Lift Vs Angle of Attack

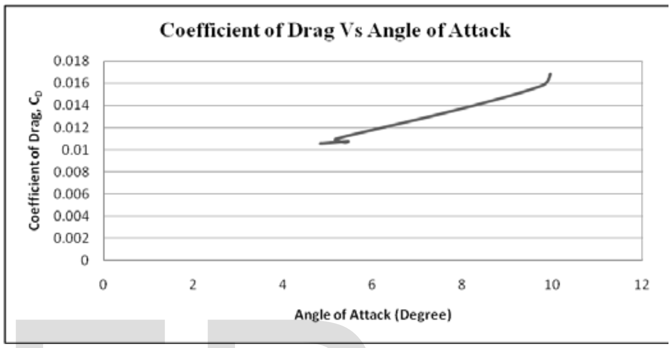


Figure No.8, Coefficient of Drag Vs Angle of Attack

If there are n blades, combining Equation 1 and equation 3 it can be shown that:

$$dFx = n\, 1/2 \rho W^2 (C_L \sin\theta + C_D \cos\theta)\, c\, dr \qquad (5)$$

$$dFq = n\, 1/2 \rho W^2 (C_L \cos\theta - bC_D \sin\theta)\, c\, dr \qquad (6)$$

The torque on the element, dT can be find by multiplying the tangential force by the radius as in the below equation no.7.

$$dT = n1/2rW^2 (C_L \cos\theta - C_D \sin\theta)\, c\, r\, dr \qquad (7)$$

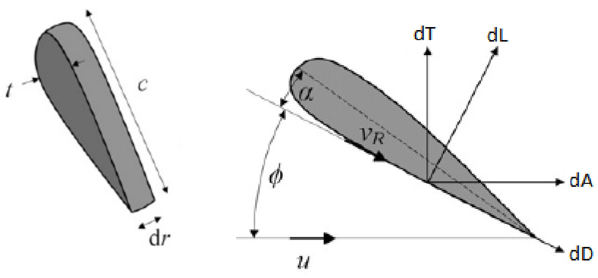


Figure 5. Body Element Theory and Ocean Current Blade Schematic

Putting values in the equation No3 and 4 for the blade section No.1

dL_1 = ½ x 1025 x 0.5 x1.778^2 x 0.868 x 0.3 = 211.093 Newton's

dD_1 = ½ x 1025 x 0.5 x1.778^2 x 0.0167 x 0.3 = 4.061 Newton's

Similarly we can calculate the Lift and Drag for all nine sections aerofoils with the help of the coefficient available for the NACA 44xx airfoils.

Now to find the total lift and drag force over the blade

$L = dL_1 + dL_1 + dL_2 + dL_3 + dL_4 + dL_5 + dL_6 + dL_7 + dL_8 + dL_9$

L = 211.093+ 191.40 + 157.46 + 124.63 + 76.003 + 68.045 + 72.001 + 54.56 + 49.131

L=1004.354 Newton's

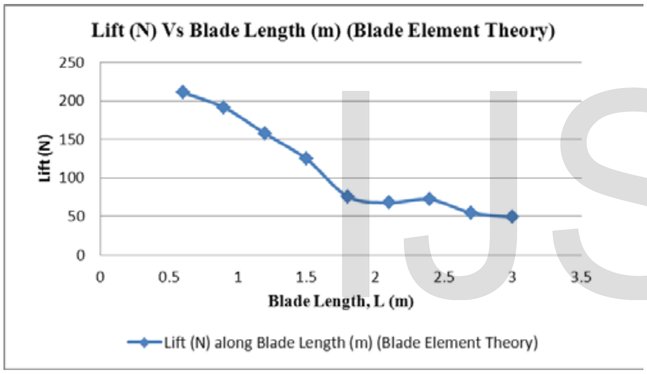


Figure No.9, Lift along blade Length (Blade Element Theory)

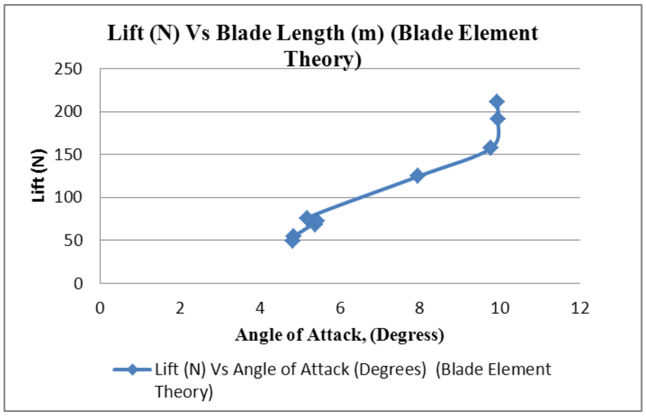


Figure No.10, Lift Vs Angle of Attack (Blade Element Theory)

$D = dD_1 + dD_2 + dD_3 + dD_4 + dD_5 + dD_6 + dD_7 + dD_8 + dD_9$

D = 4.061+ 3.56 +2.61+ 1.77+ 0.88+0.73+0.72+0.54+ 0.49

D = 15.367 Newton's

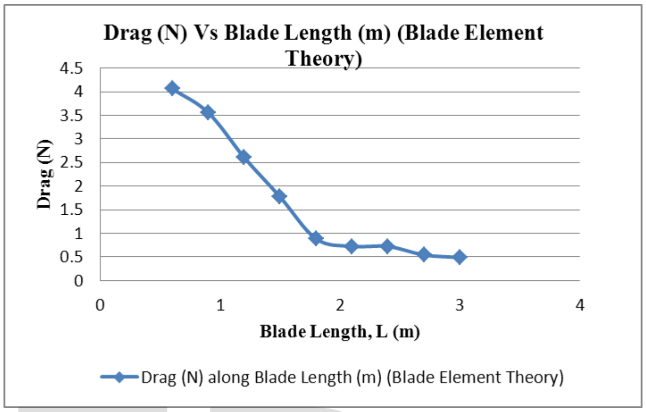
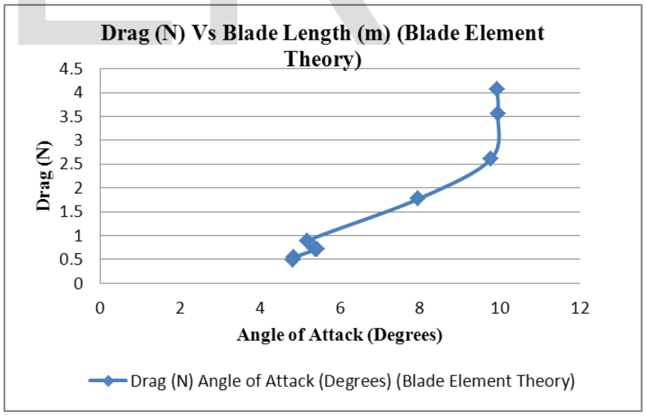


Figure No.8, Drag along blade Length (Blade Element Theory)



No Figure No.11, Drag Vs Angle of Attack (Blade Element Theory)

To find the Torque using the Body Element Theory equation No.7

$dT = n1/2rW^2(C_L \cos\theta - C_D \sin\theta)\, c\, r\, dr$ (8)

T1 = 2093.46 Nm

$T = dT_1 + dT_2 + dT_3 + dT_4 + dT_5 + dT_6 + dT_7 + dT_8 + dT_9$

$T = 2093.464 + 2031.619 + 1674.620 + 1355.443 + 836.237 + 748.810 + + 792.426 + 600.813 + 540.731$

Torque, $T = 10674.166$ Nm

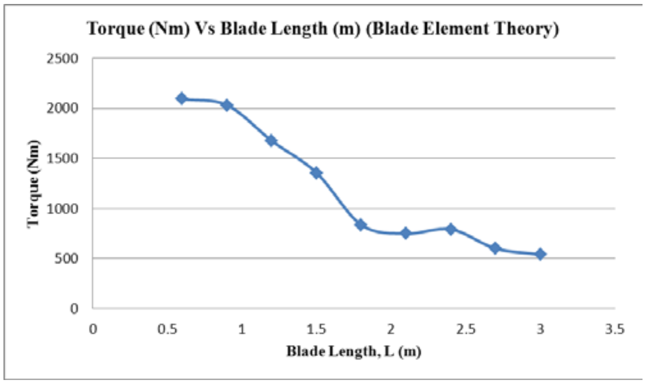


Figure No.12, Torque along blade Length (Blade Element Theory)

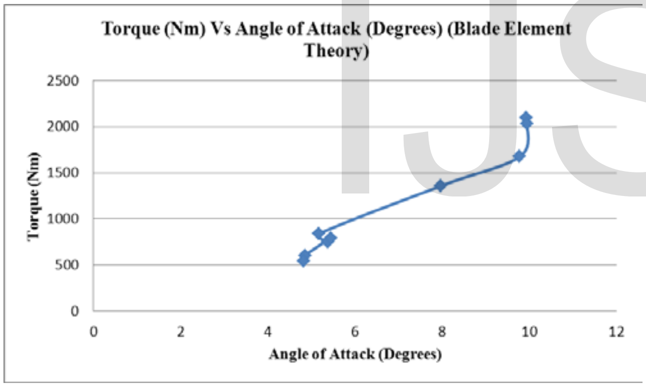


Figure No.11, Torque along blade Length (Blade Element Theory)

The power from the turbine depends on ocean current velocity. The formula for the theoretical power calculation is

$P_{Theoretical} = 1/2\ \rho A V^3$ (9)

A = Turbine Swept Area (m^2)
$A = \pi r^2$
r = Blade Length = 3.75 m
$A = 35.76\ m^2$

$P_{Theoretical} = 90.04$ KW

Where ρ is the density of the ocean water and V is the speed of the ocean current water. The values of ρ are 1025 kg/m3 and V is 1.7 m/sec and it varies from 1.5 to 2.5 m/sec at different locations.

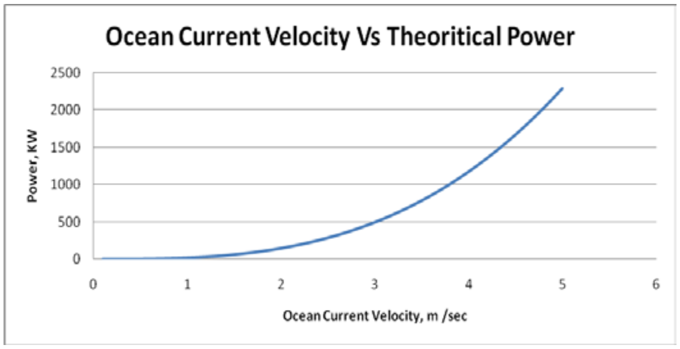


Figure No.13, Theoritical Power (KW) Vs Ocean Current Speed

The theoretical power from the blade at 1.7 m/sec ocean speed is 90.041 KW which is calculated using the above equation.
According to blade element theory the power calculation for the blade is

$P_{actual} = T_r\ 2\pi\ [rpm/60]$ (10)

$P_{actual} = 10674.16 * 2\pi\ [rpm/60]$

$P_{actual} = 26.81$KW

Now we can calculate the coefficient of power, Cp for the blade using the theoretical and actual power calculated from the blade element theory.

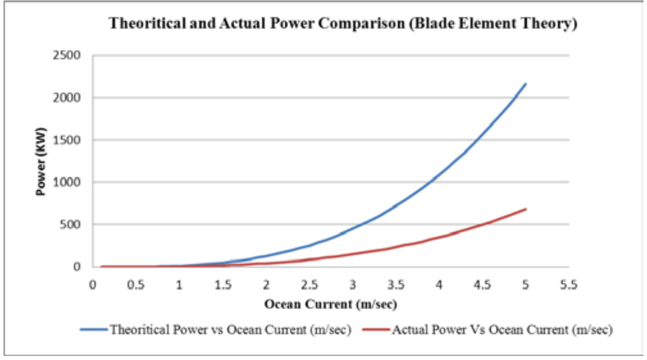


Figure No.14, Theoritical and Actual Power (KW) at different ocean current speeds

Now we want to find the coefficient of power from calculation of Body Element Theory

$C_p = P_{actual}/P_{theoritical} = 26.81/90.04 = 29.77\ \% = 0.2977$

The coefficient of power calculated is 29.77 %.

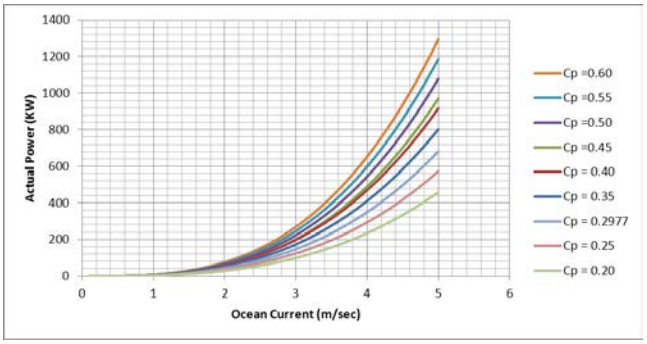


Figure No.15, Actual Power Output at different Coefficients of Power

Conclusions

Performance prediction of the ocean current turbine blade is very important and more economical prior to the fabrication and installation of the turbine. Performance Analysis of Ocean Current Turbine blade can be performed using different methods. Among these methods Blade Element Theory is mostly used for analysis and performance prediction of the ocean current turbine blade because it is the simplest method and is easily implemented. Generally the results of the Blade Element Method are more accurate as compared to other methods for the turbine blade analysis. The accuracy of the Blade Element Theory results depends on the accuracy of the lift and drag coefficient obtained from the NACA 44xx. The Data of the blade element theory can be compared with the ANSYS or Experiment Data to verify the results. Blade Element Theory predicts the blade performance parameter for the ocean current turbine ideal and steady operating conditions. Blade Element Theory calculate the hydrodynamic forces acting on the turbine blade using the NACA 44xx lift, drag coefficients and respective angle of attack for all sections along the blade length. We also calculate torque, actual power and coefficient of the power for the ocean current turbine.

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