# DESIGN AND OPTIMIZATION OF A HORIZONTAL AXIS MARINE CURRENT TURBINE

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## ABSTRACT

As fossil fuels near depletion and their detrimental side effects become prominent on ecosystems, the world searches for renewable sources of energy. Marine current energy is an emerging and promising renewable energy resource. At the heart of the horizontal axis marine current turbines (HAMCT) are carefully designed hydrofoil sections and optimized blade twist and chord distribution. While there is growing needs to have hydrofoils that provide good hydrodynamic and structural performance, the hydrofoils also have to avoid cavitation due to high suction pressures. This study focuses on designing efficient hydrofoils - HM05XX series; this series has very good hydrodynamic properties and also these sections are thick enough to provide structural strength to the blades. The HM05XX series hydrofoils were used to design and optimize HAMCT. The designed HAMCT has rated operating speed of 1.5 m/s, cut in speed of 0.5 m/s and cut-off speed of 3 m/s. The turbine was optimized using HARP-Opt (Horizontal axis rotor optimization) code that utilizes a multiple objective genetic algorithm and blade-element momentum (BEM) theory flow model to design horizontal-axis wind and hydrokinetic turbine rotors.

## INTRODUCTION

The electricity requirement is met by burning huge amounts of fossil fuels around the globe [1]. The continuous increase in the fossil fuel prices and environmental related problems caused by burning fossil fuels are now global issues [2]. On the other hand, the demand of electricity keeps increasing due to increase in world population, increase in industrialization and industries becoming manual to automated. The demand for electricity is predicted to double by 2053 compared to that in 2008 [3]. This has challenged researchers to look for alternative energy sources; renewable energy is becoming favorable alternative energy source for fossil fuels. Many renewable energy technologies have been exploited over the years, the drawback of renewable energy technology is that limitation of resources available at one location, and it is not viable to store it for longer period of time, therefore, electrical energy from number of sources will be required to feed in to the grid.

Marine current energy a is clean and reliable source of renewable energy; it is one of the alternative energy sources for fossil fuel. Horizontal axis marine current turbine (HAMCT) can be used to generate electricity for commercial use for any locations where the peak marine current velocity exceeds 2 m/s [4]. Developments have been done on HAMCT over the years from increasing the efficiency of prototype to installation. Work of bahaj et al. involves developing, designing and model testing of bi-directional marine current turbines [5, 6]. Hwang et al. designed HAMCT with improved efficiency by developing and designing individual blade control [7]. CFD methods have been developed and now being used to compute and analyze 3D HAMCT performance [8-10]. Sale *et al.* optimized the twist and chord distribution of HATCT blades using genetic algorithm (computation code), this proved to be effective method for optimizing turbine blades with improved hydrodynamic performance [11]. For most cases, airfoils are used as hydrofoils, but this result in high chance of cavitation inception. Using modified airfoils as hydrofoils results in delayed cavitation inception [4, 12] and give better performance. The blade twist and chord distributions need to be optimized so that the turbine gives its optimum performance at given operating conditions.

To maximize the turbine performance, and to make the turbine work over a wide range of operating conditions, the hydrofoils (blade sections) and turbine rotor must be very carefully designed. The hydrofoils must have higher lift-to-drag (L/D) ratio to maximize the turbine performance, lower suction peak to avoid cavitation inception and the hydrofoils must be thick enough to withstand the large hydrodynamic forces. The HAMCT can be optimized using HARP_Opt (Horizontal Axis Rotor Performance Optimization) code. HARP_Opt code utilizes a multiple objective genetic algorithm and blade-element momentum (BEM) theory flow model to design horizontal-axis wind and hydrokinetic turbine rotors [13]. Genetic algorithms solve optimization problems by mimicking the principles of biological evolution. Using rules modeled on biological reproduction and gene modification, genetic algorithms repeatedly modify a population of individuals to create subsequent generation of “superior” individuals.

This paper presents the design of blade sections, HM05XX series hydrofoils. These hydrofoils have higher L/D ratios and lower suction peaks to allow them to operate at changing operation conditions. The maximum thickness t/c (thickness/chord) at the tip is 17% and at the root it is 24%. This will allow the turbine to withstand large hydrodynamic forces. The rotor was optimized using

HARP_Opt code. Rotor performance was computed using BEM theory code. The turbine has maximum efficiency of 48% at the rated speed of 1.5 m/s.

## TURBINE SIZE AND OPERATING CONDITIONS

Mostly 3 bladed HAMCT are used; 3 bladed turbines have less vibrations during operation and the marine streams are not usually wide and deep, therefore, it limits the turbine size, therefore 5 m diameter rotor was selected, the rated speed was set at 1.5 m/s and TSR of 3.5. For this case, average Re is around 1 million at the tip of the turbine. However the Re was calculated at each blade location at different operating conditions designing the hydrofoils and optimizing the blade. The HARP_Opt code was used to optimize blade geometry for optimum turbine performance.

## DESIGN OF HYDROFOILS

The important hydrofoil characteristics that needs to be studied when designing are $C_{Pmin}$ and L/D ratio. A good hydrofoil must have high L/D ratio over a wide range of α with delayed stall, and lower suction peak on the suction side of the hydrofoil to prevent cavitation. For the case of HAMCT, the blade sections need to be thick, so the blade can withstand large hydrodynamic forces.

HM05XX series hydrofoils are designed by modifying E1212 airfoil. This was done after studying the hydrodynamic characteristics of several hydrofoils and some airfoils that can be used as blade sections of HAMCT. Blade sections were designed for different locations along the blade. The maximum thickness and hydrofoil name along the blade are shown in table 1.

Table 1; Hydrofoils along the blade.

| Radial distance r/R | Hydrofoil | Maximum thickness |
|---|---|---|
| 0.2 | HM0524 | 24% |
| 0.314 | HM0523 | 23% |
| 0.428 | HM0522 | 22% |
| 0.543 | HM0521 | 21% |
| 0.657 | HM0520 | 20% |
| 0.771 | HM0519 | 19% |
| 0.886 | HM0518 | 18% |
| 1 | HM0517 | 17% |

All the hydrofoils have maximum camber/chord of 5%. The maximum thickness varies linearly from root to tip. The maximum thickness of the hydrofoil at the tip is 17% and at the root is 24%. The blade section near root at kept thicker, because most of the stress is concentrated at the blade to hub connection.

Figure 1 shows graph of drag polars for hydrofoils HMXX series, from the graph the optimum angle of attack (α) for this series of hydrofoils is around 12º, but the optimum angle is always chosen few degree below, therefore the optimum angle for this series is chosen to be 9º. For the case of HAMCT the local α is not always at optimum angle, it changes with changing operating conditions.

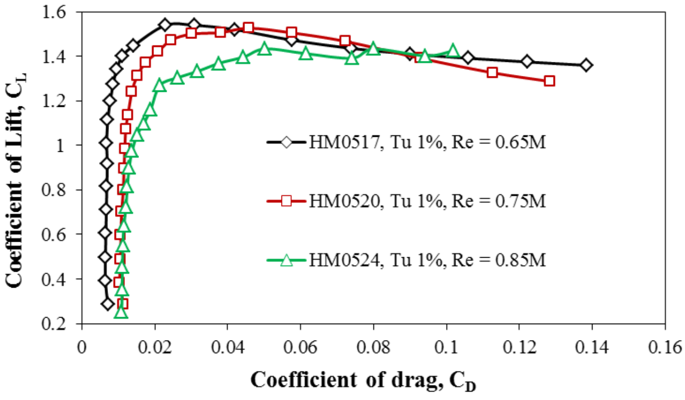


Figure 1. Drag polars for HMXX series hydrofoils at rated speed of 1.5m/s

The L/D ratios of HM05XX hydrofoils are shown in Figure 2. The analyses were done using XFoil. The analyses were done at turbulence intensity (TU) of 1% and at average Re at operating speed of 1.5m/s. HM05XX series hydrofoils have high L/D ratio, HM0524 has slightly lower L/D ratio, but this hydrofoil is for root section, this specially designed to provide strength to blade to hub connection.

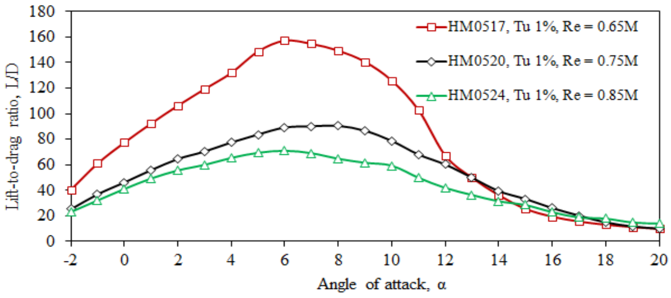


Figure 2, Lift-to-drag ratio for HMXX series hydrofoils at the rated speed of 1.5 m/s

## CAVITATION INCEPTION

For hydrofoil design stage, the 2D panel method XFoil can be used [4]. XFoil is a linear vorticity stream function panel method with viscous boundary layer and wake model, and is found to be a suitable tool for predicting cavitation criteria and hydrofoil characteristics at the preliminary design stage [14]. It is very important to avoid cavitation on blade surfaces. Cavitation causes structural damage and reduces turbine performance, the pressures associated with bubble collapse are higher enough to cause failure of metals [15]. Cavitation inception will occur when the minimum local pressure on the blade surface falls below the vapour pressure of the fluid at that temperature. Cavitation inception can be predicted by comparing the local minimum $C_P$ with the cavitation number σ [4]. Hydrofoil will encounter cavitation if the $C_{Pmin}$ is lower than – σ or $C_{Pmin}$ is lower than $C_{Pcrit}$ ($C_{Pcrit}$ = – σ). The cavitation number is defined as

$$\sigma = \frac{p_O - p_V}{0.5\rho W^2} = \frac{P_{AT} + \rho g h - p_V}{0.5\rho W^2} \quad [1]$$

The risk of occurrence of cavitation is higher on the blade towards the tip of the turbine blade due to low immersion depth near the tip and the highest relative velocity experienced near the tip of the blade. An important parameter in predicting cavitation on hydrofoils is its Re, information of turbine geometry and turbine operating conditions is required for calculating Re. To predict cavitation $C_{Pcrit}$ was determined at different locations on the blade using above blade geometry and operating conditions. The $C_{PCrit}$ at the blade location (r/R) of 0.6 to 1.0 and for tidal current velocities of 2 m/s, 2.5 m/s and 3 m/s are shown in Figure 3.

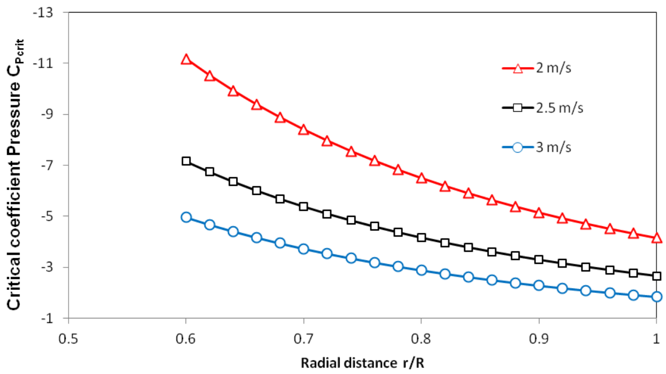


Figure 3, $C_{PCrit}$ for the rotor at different operating free stream velocities

The $C_{pcrit}$ for blade tip at tidal current velocities of 1 m/s and 1.5 m/s is around -16 and -8; therefore, the chances of cavitation are almost zero, as the velocity increases above 2 m/s, the chance of cavitation increases at r/R of 0.6 to 1.0. The cavitation may occur on the outer 10% of the blade if the $C_{Pmin}$ drops below -4.0, -2.7, and -1.8 for velocities of 2m/s, 2.5m/s and 3m/s respectively.

Figure 4, shows the minimum coefficient of pressure $C_{pmin}$, at operating Re, for maximum speed of 3m/s, for HM05XX series are shown. These sections are for blade tip region, the chance of cavitation is maximum at the tip. These hydrofoils has lower suction peek, ideal for HATCT, to avoid cavitation inception. The local α at the tip at free stream velocity of 3m/s is around 4º, minimum $C_P$ is around -1.6, this promises no cavitation inception at maximum free stream velocity of 3 m/s.

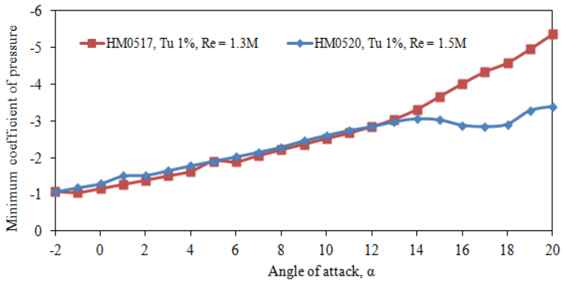


Figure 4, $Cp_{min}$ for HM05XX series hydrofoils at cut off velocity of 3 m/s.

## ROTOR OPTIMISATION AND PERFORMANCE

The blade twist and chord distributions were optimized using HARP_Opt. The HARP_Opt optimizes the twist and chord distribution to maximize the turbine performance and checks for cavitation inception for the limiting operating conditions. The factor of safety for cavitation inception was set to 1.5. The rotor performance analysis was done using BEM Theory equations. Figure 5 shows the rotor performance at different operating conditions.

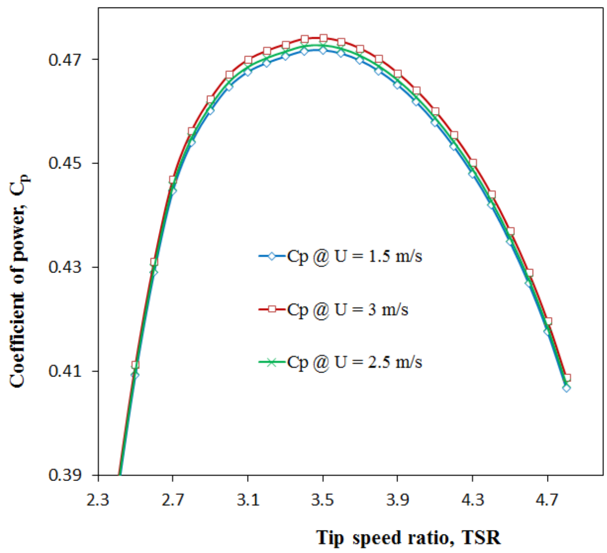


Figure 5, Rotor performance at different operating conditions.

The maximum efficiency of the rotor is around 48% at TSR of 3.5. The maximum power at cut in speed of 0.5 m/s is 600 W, 16.2 kW at rated speed of 1.5 m/s, and 130 kW at cut off speed of 3 m/s. The turbine performs very well at changing conditions and no cavitation inception is found at changing operating conditions.

## CONCLUSION

Blade sections and rotor were successfully designed to have superior performance at changing operating conditions. The hydrofoils have higher L/D ratio, lower suction peaks and are thick enough to withstand large hydrodynamic forces. The rotor has maximum Coefficient of Power of 48% and can deliver rated power of 16.2 kW.

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