Tidal Current Assessment and Design of a Horizontal Axis Tidal Current Turbine for Fiji

by

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A thesis submitted in fulfillment of the requirements for the degree of Master of Science in Engineering

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Suva, Fiji Islands
February, 2012
Declaration of Originality

I hereby declare that this project report is my own work and to the best of my knowledge and understanding, it does not incorporate without knowledge any material previously submitted or published by another person from any university or institute of higher learning. Wherever necessary references, have been provided giving credit, and any individual who has helped in some way or other has been fully acknowledged.

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I hereby confirm that the work contained in this supervised research project is the work of Jai Nendran Goundar unless otherwise stated.

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Acknowledgement

I would like to take this opportunity to express my sincere gratitude and heartfelt appreciation to all individuals who have in some way or the other contributed to the success of this project. Firstly, I would like to express my sincerest gratitude to my supervisor Dr M. Rafiuddin Ahmed for his supervision of this research project and for spending his valuable time providing direction and invaluable guidance whenever and wherever necessary. Secondly, I would like to thank the Taiwan Government and KOICA for providing financial support for doing tidal current assessment for Fiji. I would also like to thank the Fiji Department of Energy (FDoE) for providing financial support and personnel assistance for doing tidal current assessment without which this project would not been a success.

I would like to express my heartfelt gratitude to the technical staff of the Engineering section Mr. Shiu Dayal and Mr. Sanjay Singh for their technical assistance with fabricating hydrofoils and making frames for deploying tidal current profiler and helping throughout the project. Many thanks to Mr. Deepak Prasad for his invaluable help with Ansys-CFX, also to Mr Krishnil Ravinesh Ram and Sandeep Reddy for their great help in Tidal current assessment, and deployment of ADCP’s.

My special thanks to all the staff members of mechanical and electrical engineering for helping me some way or the other, Dr. Daniel Wood, Dr. Rajeshkannan, Mr. Sumesh Narayan, Mr. Mohammed Faizal, Mr. Tazil, Dr. Praneel Chand, Mr. Hamendra Reddy, and Mr. Roneel Sharan.

For their help throughout the project, sharing their kind, critical and useful advice and knowledge, I would like to express my sincere gratitude to my friends Mr. Jeff La’ava, Mr. Sandeep Patel, Mr. Shahil Ram, Mr. Epeli, Mr. Robert Li, Mr. Radesh Lal, Mr. Izzal Sheikh, Mr. Ronit Singh, Mr. Shivneel Prasad, and Mr. Viti Buadromo.

I would like to express my appreciation to my parents and other family members for their kind support and understanding without which I would have not realised my achievements.

I would once again like to say thank you to you all for helping me and for providing invaluable knowledge which have not only helped me to successfully complete the project but have a better understanding of things in life as well.
Abstract

Pacific Island Countries (PICs) have a huge renewable energy potential to meet their energy needs. Limited resources are available on land; however, large amount of ocean energy is available and can be exploited for power generation. PICs have more sea-area than land-area. Tidal current energy is very predictable and large amount of tidal current energy can be extracted using tidal current energy converters. It is important to perform tidal current assessment before designing tidal energy converters, and it is necessary to study the hydrodynamics of such converters. A detailed resource assessment was carried out at two locations in Fiji – known as Wilkes passage and Gun-barrel passage - for 3 months. The Gun-barrel passage was found to have a good marine current and current speeds exceeding 2 m/s many times were recorded. Therefore a turbine can be installed at this site. A 10 m diameter, 3-bladed horizontal axis tidal current turbine (HATCT) was designed. Hydrofoils were designed for different blade location; they are named as HF10XX. The hydrodynamic characteristics of the hydrofoils were analyzed. A thick hydrofoil with a maximum thickness of 24% and a maximum camber of 10% was designed for the root region. The maximum thickness of hydrofoils was varied linearly from the root to the tip for easier surface merging. For the tip region, a thinner hydrofoil of maximum thickness 16% and maximum chamber 10% was designed. It was ensured that the designed hydrofoils do not experience cavitation during the expected operating conditions. The characteristics of the hydrofoils HF10XX were compared with other commonly used hydrofoils. The blade chord and twist distributions were optimized using BEM theory. The theoretical power output and the efficiency of the rotor were also obtained. The maximum power at the rated current of 2 m/s is 150 kW and the maximum efficiency is 47.5%. The designed rotor is found to have good efficiency at current speeds of 1-3 m/s.
Nomenclature

a    axial flow induction factor
a₀   tangential flow induction factor

AOA  angle of attack (α)
C    Speed of sound.
Cₚₐᵣ    Coefficient of power

Cₜₜ    optimum local blade chord length (m)
Cₚₘᵟᵣ    minimum coefficient of pressure

Cₚ₉ᵣ    Critical coefficient of pressure
Cₚ̂    Coefficient of pressure
Cₚ₀    Coefficient of power

f    frequency of rotating turbine
F_d    Change in received frequency (Doppler shift)
F_s    Frequency of transmitted sound
K_s    Velocity profile factor 0.424
K_n    Spring/neap tide factor 0.57
L/D    lift-to-drag ratio
P    Power available in tidal stream
P_Aₜ    Atmospheric pressure
P_v    Saturation pressure of the seawater
P_R    Rotor power
P_o    Pressure at a point on the hydrofoil surface
P_stat    Static pressure of the tidal stream
r    radius of local blade element (m)
R blade radius (m)
Re Reynolds number
TSR Tip speed ratio $\frac{\Omega r}{U}$
T.K.E Turbulence kinetic energy
U free-stream velocity
$U_D$ rated tidal current speed (m/s)
V Velocity of source relative to receiver
$V_r$ relative tidal current velocity $\sqrt{U_o^2(1-a)^2 + \Omega^2r^2(1+a')^2}$
$V_t$ Tangential velocity $\Omega r$
$V_r$ local effective flow velocity (m/s)
Z number of rotor blades
$\rho$ density of sea water (Kg/m$^3$)
$\Omega$ rotational speed $2\pi f$ (rad/s)
$\beta$ Blade pitch angle
$\phi$ Angle between rotating plane and $V_r (\alpha + \beta)$
$\theta$ Twist distribution
$\mu$ Dynamic viscosity of the sea water
$\mu$ Extraction efficiency factor 0.25
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1. Introduction

Rise in electricity demand, depletion of fossil fuels and rising global awareness have motivated researchers to look for alternative methods to provide for the increasing energy demand due to growing population, technology, and rapid growth and development of industry and agriculture [1]. The alternative energy source comes in the form of renewable energy. Renewable energy is considered to be clean energy, because it does not produce toxins or pollutants that are harmful to the environment in the way non-renewable energy does such as coal and fuel. Thus, renewable energy is also known as green or clean energy. Renewable energy recourses are either available on land such as biomass, hydropower, geothermal, solar (photo voltaic) and wind, or in the ocean such as wave, ocean thermal energy and tidal energy.

The world’s population is estimated to double by the year 2050 and the world’s energy demand is also estimated to increase by at least 70% over the next 30 years [2]. Currently about 69% of the world’s electricity needs are met by fossil fuels (oil, natural gas, coal), 13% by nuclear power, 15% by large hydro with the remaining 3% met by various renewable energy resources as shown in Fig. 1.1[3].

![Figure 1.1. Global electricity market overview](image-url)
Global renewable power capacity worldwide reached an estimated 1,230 gigawatts (GW) in 2009, up 7 percent from 2008. Renewable energy now comprises about a quarter of global power-generating capacity (estimated at 4,800 GW in 2009) and supplies some 18 percent of global electricity production. When large-scale hydropower is not included, renewables reached a total of 305 GW, a 22-percent increase over 2008. Among all renewables, global wind power capacity increased the most in 2009, by 38 GW. Hydropower has been growing annually by about 30 GW in recent years, and solar PV capacity increased by more than 7 GW in 2009[3].

In Pacific island countries, imported fossil fuel or petroleum is the primary source for the commercial energy needs. Most isolated islands in the pacific use petroleum for transportation and electricity needs. The total electricity production for Fiji in 2009 was approximately 777 GWh, 39% from diesel and heavy fuel oil (HFO), 58% from hydropower generation, 1% from wind power and 2% provided by independent power producers (IPP) such as Tropic Wood Fiji Ltd and Fiji Sugar Corporation. For 2009, Fiji electricity authority (FEA) burnt a total of 66409 tons of diesel and HFO [4]. Burning diesel and HFO produces carbon dioxide and other toxics which cause environmental issues such as climate change and global warming. The electricity produced by FEA only reaches about 70% of Fiji’s population and is not available to outer islands in Fiji and to many rural settlements. At these places mostly diesel generators are used to meet their electricity needs or kerosene lanterns are used for lighting purposes. Using diesel generators for individual house becomes expensive while kerosene lanterns give out very dim light which is not good for the eyes and also produces lot of smoke because of incomplete combustion of fuel [4].

Renewable energy sources such as tidal current energy are readily available to us and all around the world; with proven technologies one could setup a turbine system to harness energy for electricity. Tidal current energy is being recognized as a resource to be exploited for the sustainable generation of electrical power. The high load factors resulting from the fluid properties and the predictable resource characteristics make marine currents particularly attractive for power generation [5]. If this resource is to be successfully utilized, the technology required could form the basis of a major new industry to produce clean power for the 21st century. The resource is potentially large and can be exploited with little environmental impacts,
thereby offering one of the least damaging methods for large-scale electricity generation [6]. A tidal current turbine rated at 2–3 m/s in seawater can result in four times as much energy per year/m$^2$ of rotor swept area as a similarly rated power wind turbine [5]. Thus, research to determine the tidal current potential in Fiji and design of high performance tidal current turbine is essential to extract tidal energy. The tidal current potential sites around Fiji have to be identified around Fiji and resource assessment needs to done, to see the behavior of tidal current before any turbine can be designed and installed. The designed turbines may not perform well in Fiji condition, a new design turbine approach will be taken, and the hydrofoils most commonly used hydrofoils for HATCT are of NACA foils, which do not have good hydrodynamic characteristics. Therefore, new section will be designed which have better hydrodynamic efficiency and increases the turbine performance. A resource assessment of tidal current potential in Fiji and design of a suitable tidal current turbine was undertaken at the University of the South Pacific (USP), Laucala campus, Suva, Fiji. The designed system can cater for energy needs of Fiji islands.

1.1. Objectives

This study is aimed at tidal current assessment for Fiji and design of tidal current turbine in order to assess the tidal current potential in Fiji and appropriate tidal current system for the location. The specific aims are

- To do initial assessment on tidal current potential in Fiji, at the appropriate locations.
- To measure tidal current velocities at two sites for 3 months.
- To collect and analyze tidal current data.
- To design the turbine blade sections (hydrofoils) and predict the occurrence of cavitation as well as analyzing hydrofoil characteristics using Xfoil and Ansys-CFX (numerical analysis software’s).
- Fabricating and testing of hydrofoil in wind tunnel and comparing the results with Xfoil and Ansys-CFX.
- Design of marine current turbine blade using blade element momentum (BEM) theory, by optimizing blade thickness, taper and twist distribution for maximum efficiency.
1.2. Thesis Structure

This thesis is divided into 5 chapters. The chapters are as follows:

- Chapter 1 (Present one) briefly introduces the topics of tidal current energy and energy demands in Fiji.

- Chapter 2 presents a review of literature in this area. It also describes the theory of tides and tidal current, together with the theory and operation of Horizontal axis tidal current turbines. Describes the brief history and current status of tidal current energy technology together with the review of some tidal current turbine (TCT) design and system around the world.

- Chapter 3 presents the initial assessment of tidal current for various locations in Fiji Islands and full assessment of tidal current for 3 months for 2 locations. Together with assessments methodology, results and analysis, the power density and feasibility of tidal current power is discussed.

- Chapter 4 discusses the design and analysis of hydrofoils for different locations of a 10m horizontal axis tidal current turbine. The design methodology for horizontal axis tidal current turbine (HATCT) is presented. The power optimization for difference tidal current velocities and different pitch is also presented for 10m HATCT.

- Chapter 5 concludes the previous chapters and results providing suggestions for future work.
2. Literature Review

2.1. Introduction

Renewable energy technologies are becoming favorable alternative energy sources in solving fossil fuel related issues[7]. The renewable energy technologies are natural and non-polluting, they can deal with both security of supply concerns and environmental issues [8]. Lots of developments have taken place in the solar and wind energy technologies recently enabling commercial use of these resources. The main disadvantages of most renewable energy technologies are their variations in energy intensity and availability for shorter time.

Tidal energy offers a vast and reliable energy source [9]. Tidal energy is caused by movements of sea water, which derives directly from the gravitational and centrifugal forces between the earth, moon and sun [7]. Tides are a regular and predictable phenomenon caused by the gravitational attraction of the moon and sun acting on the oceans of the rotating earth. Because of the relative position of sun and moon to earth, the moon exerts roughly 2.2 times greater force on the earth’s oceans as does the sun, even though the sun is approximately $2.7 \times 10^7$ times more massive than the moon [10].

Tidal energy consists of both kinetic and potential energy components. The kinetic energy or tidal current energy is the energy present in horizontally moving water caused by tides, and the potential energy is the energy present in the rise and fall of sea level. Therefore tidal power can be extracted from two main technologies called: tidal barrages and tidal current turbines, which extract potential and kinetic energy respectively. A tidal barrage is basically building a dam across a bay or estuary that experiences tidal height deference excess of 5 m [7]. The principle of electricity generation from tidal barrages is similar to that of hydro power generation. The current issues restricting the development of tidal barrage systems are the high construction costs and the environmental impacts. Harnessing the power using barrages requires building strong barrages which requires a vast quantity of materials to withstand the huge loads produced from dammed water. This results in high construction costs and this is a deciding factor whether or not a site is economically viable for tidal energy extraction. Also the energy extracting technology should not harm the environment, the greatest disadvantage of tidal barrages is the environmental
impacts. Building a dam across an estuary may change the flow of the tidal currents, affecting the marine life. Water quality within the basin may also be affected, such as sediment transportation, resulting in changes to water turbidity. The presence of a barrage will also influence maritime traffic. Therefore tidal current energy is more preferable, tidal current turbines are much smaller and rotate with lower rpm which has less environmental impact compared to construction of tidal barrages. In terms of commercial viability, tidal current turbines require less material for construction and less construction and installation costs hence reducing investment cost [7].

2.2. Tides and Tidal Stream

Tides are caused by gravitational force of sun and moon and centrifugal force caused by earth’s rotation. The gravitational pull of moon causes the water to bulge on earths which is greater on the side of the earth nearest to the moon. With earth-moon rotating system, earth also rotates on its own axis producing a centrifugal force, this causes another water bulge on the side of the earth furthest away from the moon as shown in Fig. 2.1 [7]. The side of the earth at which water bulges at earth’s surface is at high tide. At 90° from high tide side, the water at earth’s surface is at low tide. Therefore, one position of earth’s surface is exposed to two high tides and two low tides during each period of rotation of the earth. The tidal phenomenon occurs twice every 24 hours, 50 minutes and 28 seconds, but a single tidal cycle is completed in about 12 hours, 25 minutes and 14 seconds [11]. Since the moon also rotates around the earth, the timing of these tides at any point on the earth will vary, it is delayed by approximately 50 minutes each day [7]. The moon revolves around earth in about 29.5 days called a lunar month; one lunar month is from new moon to new moon or from full moon to full moon. The effect of the phase variation is completed in half of lunar month or about 2 weeks as the moon varies from new to full moon or full to new moon[12].

In reality the tidal phenomenon is complicated because the earth’s axis of rotation is tilted by 23.5° relative to the moon’s orbit; this causes the difference in height of high and low tides. The two bulges of water are unequal unless the moon is directly over the equator, this height difference is called diurnal inequality and repeats over a 14 day cycle [12].
Figure 2.1 The Effect of the Moon on Tidal Range

Figure 2.2. Sketch of spring and Neap tides
The range of the tide varies according to the intensity of centrifugal force of earth, and gravitational forces of sun and moon at a particular location. Tides have solar and lunar effects according to sun and moon’s gravitational effects. The solar-lunar gravitational force combines when sun and moon are in same direction, this is at the times of new or full moon. The largest tides are known as Spring tides; these occur at the time of new or full moons when the gravitational pull of the sun and moon are aligned as shown in Fig. 2.2. Neap tides are smaller and occur when the moon and sun are at right angle to each other and gravitational forces are not aligned. Neap tides occur when the moon is on its first quarter or last quarter. The spring-neap cycle has a period of approximately 15 days.

Horizontal movement of water is called currents; currents may be either tidal currents or non-tidal current. Non-tidal current includes all currents not due to the tidal movement. Non tidal currents include the permanent currents in the general circulatory system of the oceans as well as temporary currents arising from meteorological conditions.

Tidal currents are experienced in coastal areas and in places where the seabed forces the water to flow through narrow channels such as tidal passages or tidal straits. Tidal currents flow is mostly bi-directional: tidal current moving towards the coast during incoming tides or high tides is called flood current, an ebb tidal current is when receding from the coast during low tide in opposite direction. The zero tidal current speed occurs between the flood and ebb currents; which is also referred to as slack water. The maximum current speed occurs halfway between the slack waters or between two zero currents [7]. For most of the places semidiurnal tidal current is experienced i.e. two flood and two ebb tidal currents.

Like tides, tidal currents are not constant, they vary throughout the day. It varies according to cycles governed by the motion of the Earth and the Moon. It is generally possible to parameterize tidal currents as series of simple sinusoids. If it is assumed that only the semidiurnal and spring–neap cycles need to be considered, then the tidal currents can be simplified to the form [6]:

\[ U_x(t) = (A + (B + C \cos(2\pi t/T_1)) \cos(2\pi t/T_1)) \cos(2\pi t/T_0) \]  
2.1
\[ U_y(t) = F + (D + E \cos (2\pi t/T_1)) \sin (2\pi t/T_0) \]

where \( A \) and \( F \) are related to residual current speeds, \( B, C, D \) and \( E \) are amplitude terms, \( T_0 \) is the period of the semidiurnal variation, \( T_1 \) is the period of the spring–neap cycle, \( U_x(t) \) represents the East–West current speed and \( U_y(t) \) represents the North–South current speed [6].

The resultant of both components can be calculated by:

\[
\left| U(t) \right| = \sqrt{U_x^2(t) + U_y^2(t)}
\]

Tidal currents have periods and cycles similar to those of the tides, and are subject to similar variations, but flood and ebb of the current do not necessarily occur at the same times as the rise and fall of the tide. The speed and strength increases and decreases during the 2 week period, every month, and yearly along with the variations in the range of the tides. Spring tidal currents are stronger, since gravitational forces of Sun and Moon combines to give additional pull on the sea water. Whereas neap tidal currents are weaker, as Sun and Moon’s gravitational forces act at right angles to each other. Tidal currents, like tides, may be semidiurnal where two floods and two ebb currents are experienced, diurnal where one flood and one ebb current is seen, or mixed type tidal current have properties of both semidiurnal and diurnal currents, corresponding to a considerable degree to the type of tide at the place, but often with a stronger semidiurnal tendency. The tidal current flow regime at a particular location has been properly studied for at least 29 days; its variation can be predicted with considerable accuracy over the entire 20 or 30 year life of the project[13].

The current existing at any time is not always purely tidal, but usually includes also a non tidal current that is due to drainage, oceanic circulation, wave and wind. The speed and direction of non tidal current always affect the nature of tidal current. If the direction of non tidal current is same as the tidal current, their velocities add up and further increase the tidal current velocities, if the directions of tidal and non-tidal currents are opposite to each other, then the resultant velocity is usually weak. The non tidal currents can affect the time of occurrence of maximum and minimum current; it can even affect the time and strength of flood, ebb currents and slack water.
The relationship between the times of tidal currents and tides is not the same everywhere. The slack water occurs at local high and low tides. The maximum flood and ebb occur when the tide is rising or falling most rapidly may be approximately true at the seaward entrance. But generally this is not true in other parts of inland waterways. The speed of the current also varies across the channel, usually current is greater in midstream or mid channel than near shore, but in a winding river or winding channel the strongest currents occur near the concave shore, or the outside corner of the curve. Near the opposite (convex) shore the currents are weak [14].

The tidal current velocity varies with depth. Tidal current velocity plotted at different depths is called tidal current velocity profile, and it may not be the same for all the locations. The velocity profile normally depends on the geometry of the tidal current passage. If the channel is wide with good depth then the tidal current profile is close to 1/7th power law or 1/10th power law [6]. These power laws can be used to estimate the tidal current velocity profile. However the tidal current profile may not follow these power laws depending on the geometry of the channels. The general power law relationship for a vertical profile of horizontal fluid flow velocity near a flat solid boundary is as follows:

\[ U(z) = U_o \left( \frac{z}{z_o} \right)^{\frac{1}{10}} \]

2.4

Where \( u(z) \) is the horizontal velocity at same depth \( z \) and \( u_o \) is the reference velocity at a reference depth \( (z_o) \). Depths are measured relative to the bottom, such that the seabed is at \( z = 0 \). Based on the 1/10th power law velocity profile, the depth-average value of velocity is 90.9% of its surface value. The derivation of reference velocity and depth-average velocity is given in appendix A. For some cases 1/7th power law can good approximation for tidal current velocity profile, the 1/7th power law is defined as follows [6]:

\[ U(z) = U_o \left( \frac{z}{z_o} \right)^{\frac{1}{7}} \]

2.5
2.3. Tidal Current Energy Extraction

2.3.1 Tidal current turbines

Tidal current turbines extract kinetic from tidal streams to generate electricity. Tidal current technology is similar to wind energy technology [7]. However, there are several differences in the operating conditions. Under similar operating conditions, water is 832 times more dense than air and the tidal current speed is less than wind speed [15]. Since tidal current turbines operate in water, they experience greater thrust forces. Tidal current turbines must be able to generate during both flood and ebb tides and also should be able to withstand the load during operation. The two most common types of turbines used to extract tidal current energy are: Vertical axis tidal current turbines (VATCT) and Horizontal axis tidal current (HATCT). The VATCT rotates parallel to the direction of flow and HATCT rotates perpendicular to the direction of flow. Example of VATCT is Darries rotor, Gorlov turbine, and Savonious rotor. Although VATCT has its own advantages but it is not as widely used as HATCT. The power output and its speed cannot be controlled by pitching the blades. Difficulty is faced in putting up large scale VATCT mainly with supporting structures. HATCT are most commonly used for tidal current energy extraction. For HATCT, rotor speed and power output can be controlled by pitching the rotor blades about their longitudinal axis (blade pitch controls). The rotor blade shape can be hydrodynamically optimized and it has been proven that it will achieve its highest efficiency when hydrodynamic lift is exploited to a maximum degree [16].

The working principle and design of HATCT is similar to that of Horizontal axis wind turbine (HAWT). A HATCT consists of turbine rotor, gearbox, generator and support structure shown in Fig. 2.3. The turbine rotor consists of turbine blade and hub, the rotor rotates by the force governed by tidal current flowing over the blades, hub is connected to shaft delivering power to generator. The rotor converts tidal current energy to rotational energy called shaft power. The blades are pitched to maximize the turbine efficiency and to extract bi-directional tidal current energy. Pitch control is common in large scale HATCT. Gear box, increases the rotational speed of the rotor to match the speed of the generator, the tip speed ratio of HATCT is usually lower.
Generator converts its shaft energy to electric energy which is transmitted to the shore via a cable on the sea bed.

2.3.2 Support structure
These three parts are mounted to a support structure that is required to withstand the harsh environmental loadings.

![Horizontal axis tidal current turbine components](image)

**Figure. 2.3.** Horizontal axis tidal current turbine components [17].

There are three main support structure options when considering installation of a tidal current turbine. The first of these is known as a gravity structure which consists of a large mass of concrete and steel attached to the base of the structure to achieve stability [7]. The second option is known as a piled structure and the third option is known as a floating structure. The floating structure is usually moored to the seafloor using chains or wire. These supporting structures are shown in Fig. 2.4.
Gravity structures are heavy steel or concrete masses attached to the base of the units to be stable at the seabed by its own inertia. Piled structures are pinned to the seabed by one or more steel or concrete beams. The beams or piles are fixed to the seabed if the ground conditions are sufficiently soft or by pre-drilling. Floating structures are more appropriate solution for deep water locations. In this case, the turbine unit is attached pointing downward, vertically fixed to a barge [17].

2.3.3 Rotor Design
The rotor design is the most important part of HATCT design, the overall performance of turbine depends on rotor design. The design and performance of HATCT is similar to that of HAWT and ship propellers much can be transferred from the design and operation of wind turbines and ship propellers. There are however a number of fundamental differences in the design and operation of the marine current turbine, which will require further investigation, research, and development. Particular differences entail changes in Reynolds number, different stall characteristics, and the possible occurrence of cavitation [19]. Cavitation causes structural damages on turbine blades and adversely affects its performance, cavitation causes lift to decrease and drag to increase, the pressures associated with bubble collapse are high enough to cause failure of metals [20]. However, cavitation inception can be predicted and avoided when analyzing the 2D section of the blade called hydrofoil.
Hydrofoils are sections of HATCT blade; the shape and parts of hydrofoil is shown in Fig. 2.5.

![Figure 2.5. Shape and parts of hydrofoil](image)

The most important features of hydrofoil geometry are the chord, camber, and thickness. Hydrofoils operations are similar to airfoils; water flowing over the hydrofoils causes low pressure on the upper surface of the hydrofoil and higher pressure at the lower surface of the hydrofoil. The shape of hydrofoils is such that it allows water velocity to increase on the upper surface compared to lower surface; the higher velocity on the upper surface creates suction or lower pressure on the upper surface as shown in Fig. 2.6.

The pressure distribution over the airfoil can be expressed as non-dimensional pressure distribution called coefficient of pressure $C_p$ and can be expressed as:

$$C_p = \frac{P_o - P_{stat}}{0.5 \rho U^2}$$

The $C_p$ is usually higher negative on the upper surface and positive on the lower surface at positive angles of attack, as shown in the Fig. 2.6.

The components of the force experienced by the hydrofoil normal to the direction of velocity and in the direction of velocity are called lift and drag forces respectively. The theory of lift generation is known as the flow turning theory. It states that the hydrofoil bends the direction of
the current around it as the water passes over the upper surface, and creates a vertical velocity of water flow past the trailing edge. The effect of the water flow bending is due to the viscosity of a fluid and the Coanda [21] effect. As the hydrofoil bends the water flow near the upper surface, it pulls on the water above it and causes an acceleration of that water. The pulling of the water causes a low pressure system to form over the hydrofoil creating a net force that is lift [22].

The hydrofoil experiences a drag force that opposes the relative motion of the hydrofoil and has a direction parallel to the water flow or perpendicular to lift force [18]. Drag is classified into two main types: Skin friction drag is the friction that occurs between the water molecules and the surface of the hydrofoil and form drag is dependent on the overall shape of the hydrofoil. The lift and drag forces acting on the hydrofoil are shown in Fig. 2.6.

![Figure 2.6. Pressure distribution and forces on a hydrofoil [23].](image)

The lift that a hydrofoil generates depends on the density of the water, the velocity of the water flow, the viscosity of water, the surface area of the hydrofoil, the shape of the hydrofoil, and the hydrofoil's angle of attack. However, dependence on the hydrofoil's shape, the angle of attack (AOA), water viscosity and compressibility are very complex. Thus, they are characterized by a single variable in the lift equation, called the lift coefficient. Due to the complexities of the lift coefficient, it is generally found numerically or experimentally. Lift can be expressed as:

\[
L = 0.5C_L \rho AV_r^2
\]
A is the area of the platform hydrofoil (as viewed from an overhead perspective). Similarly drag is expressed as:

\[ D = 0.5 C_D \rho A V_r^2 \]  

The lift force is basically the summation of y-component of the pressure forces acting on the hydrofoil surface, and drag force is summation of the x-component of pressure forces acting on the hydrofoil surface. The geometry of hydrofoil is an important factor that determines the magnitude of \( C_L \) and \( C_D \), the geometry directs the pressure force which finally gives the lift and drag. Lift and drag both increases as the AOA increases until a critical angle of attack is reached at this angle of attack the flow on the top surface of hydrofoil separates and hydrofoil stalls. Further increasing the AOA will result in a reduction in lift and a significant increase in drag.

The efficiency of HATCT rotors depends on hydrodynamic characteristics and shape of hydrofoils. The most important characteristic of a hydrofoil is the lift-to-drag ratio (\( L/D \)):

\[ L/D = \frac{C_L}{C_D} \]  

The influence of L/D ratio on the rotor performance is shown in Fig. 2.7. As the \( L/D \) becomes smaller, the maximum coefficient of power (\( C_{PR} \)) decreases. When the \( L/D \) ratio is high (\( L/D = 100 \)), the number of rotor blades (\( z \)) has relatively little influence on maximum \( C_{PR} \) value, but when the \( L/D \) ratio is low (\( L/D = 10 \)), the number of blades on rotor becomes important. Therefore few blades can be used, when hydro-dynamically good blade sections are designed.

The complication begins when it comes to comparing hydrofoil characteristics which have different chord length, operating at different velocity and in different fluids. To overcome this complication, a non-dimensional number - Reynolds number (\( Re \)) - number is used to compare different airfoils/hydrofoils, \( Re \) is defined as:

\[ Re = \frac{\rho V L}{\mu} \]  

Where \( V \) is the mean velocity of the object relative to the fluid and \( L \) is the chord length.
Figure 2.7. Effect on power coefficient at changing L/D ratio [23].

A single variable Re replaces all other variables, so hydrofoil characteristic can be easily compared. The blade geometry and design is also a very important part of the HATCT, the rotor performance is very sensitive to blade geometry, pitching and blockages, number of blades and rotational speeds in these parameters will affect the rotor performance. It is necessary in the design of HATCT to match the angular velocity of the turbine, to obtain maximum or optimal rotor efficiency. If the rotor of the tidal turbine turns too slowly, most of the water will pass undisturbed through the opening between the blades with little power extraction. On the other hand, if the rotor turns too fast, the rotating blades act a solid wall obstructing the current flow, again reducing the power extraction. Thus tidal turbines must be designed to operate at their optimal tip speed ratio in order to extract as much power as possible from the tidal stream. The relationship between the tidal current velocity and the rate of rotation of the rotor is characterized by a non-dimensional factor, known as the Tip speed ratio (TSR). TSR can be expressed as:

\[ TSR = \frac{\text{speed of the rotor tip}}{\text{free-stream velocity of tidal current}} = \frac{V_t}{U} = \frac{\Omega r}{U} \]  

The optimum operating TSR for any HATCT depends on the particular tidal turbine design used, the blade profile, as well as the number of blades used. In general, a high TSR is desirable since it results in high shaft rotational speed that is needed for the efficient operation of an electrical generator. However, high TSR has several disadvantages - blades rotating at very high speed will
result in erosion of the leading edge from their impact with sand and other particles in water, the chance of occurrence of cavitation increases because the relative velocity on the individual section also increases. It causes vibration, particularly in the cases of single or two bladed rotors\[23\]. The simple Blade element momentum (BEM) theory can be used to predict magnitude of the mechanical power output of the rotor. Using the rotor power coefficient $C_{pr}$, the rotor power can be calculated as a function of the tidal current speed, as follows \[24\]:

$$P_R = 0.5C_{pr}\rho AU^3$$ \hspace{1cm} 2.11

where: $A =$ swept Area of the rotor

The $C_{pr}$ depends on blade geometry, size and number of blades. Torque is also a very important parameter which has significance in characterizing rotor performance. The rotor torque can also be calculated by using torque coefficient $C_T$, and can be expressed as:

$$T = 0.5C_T\rho AU^2$$ \hspace{1cm} 2.12

### 2.3.4 Blade Geometry

Large scale HATCTs normally employs active pitch controls. The rotor performance and occurrence of cavitation in changing tidal current velocity can be controlled by pitching the blades. Power can be extracted from bi-direction tidal streams without yawing the whole turbine that is by pitching the blade 180°. During weak tidal current the blade is highly pitched so the rotor can easily start rotating, then blade pitch is slowly lowered once rotation starts. To maximize the power extraction blade pitching is changed as the tidal current velocity changes. The tidal current normally follows sinusoidal curve with time where very simple control is needed, unlike wind where very precise control is required and very hard to control the blade pitch because wind changes every second.

In rotating blades, blade sections experience the resultant component of free-stream velocity $U$ and tangential velocity $V_t$ the resultant component of $U$ and $V_t$ is relative velocity $V_r$, the
velocity components are shown in Fig. 2.8, where $\alpha$ is AOA of hydrofoil, $\beta$ is the blade pitch and $\phi = (\alpha + \beta)$ is the angle between rotating plane and $V_r$.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig2_8.png}
\caption{Velocity components on a rotating blade section\cite{25}.}
\end{figure}

The relative velocity does not remain constant along the blade, since the tangential velocity is lower at the root and higher at the tip for constant free-stream velocity, therefore $V_r$ also increases from root to the blade tip, as shown in Fig 2.9. The local AOA of hydrofoils is now from chord line to $V_r$. The $U$ and $V_t$ are not in the same direction, changing $V_t$ component causes the change in angle between relative velocity and rotating plane, $\phi$, even when $U$ is constant. The angle $\phi$ is higher at root and lower at the tip as shown in Fig 2.10. To optimize the maximum lift
for better efficiency blade is twisted so $\alpha$ distribution gives higher lift throughout the blade and in order to achieve the optimum reduction in flow velocity over the entire length of the blade.

![Diagram](image)

**Figure 2.10.** Angle between $V_r$ and the rotating plane.

The blade twist is normally designed for one operating condition of turbine. For all other operating conditions, the twist is non-optimal, making power losses unavoidable.

The blade are not linearly twisted, twist is normally determined after cavitation criteria and best rotor performance, however sometimes compromise is to be made to simplify blade manufacturing. Twist distribution can be calculated by the given formulas [26].

\[
\theta = ((R/r) \alpha_t - \alpha_o) - k(1-r/R) \tag{2.13}
\]

\[
\alpha_t = (\phi - \beta) + \alpha_o \tag{2.14}
\]

Where $\alpha_t$ is the angle of attack at the tip and $\alpha_o$ is the angle of attack for hydrofoil giving zero lift. Another equation frequently used to determine overall lift is given as [27].

\[
\theta = a \tan \left( \frac{1}{4\pi x} \right) + \alpha_o \tag{2.15}
\]

The overall twist does not always follow these equations, it is modified to meet the cavitation criteria and twist is optimized to give best rotor performance.

The mechanical power captured by the rotor from the tidal current is affected by the geometrical shape of the rotor blades. Betz’s momentum theory and the strip theory can be applied to calculate the hydro-dynamically optimum shape for turbine blade. The crucial criterion for this calculation is the demand that at each blade radius, the tidal current velocity in the rotor plane is reduced to two thirds of its undisturbed value. This requirement can be met if the local $C_L$ and local chord length follow a hyperbolic course over the blade radius [23]. The $C_L$ is determined from the drag polar curves of the hydrofoil and by considering the local AOA, i.e. the blade pitch angle and the blade twist angle. In other words, the hydrodynamically optimum distribution of
chord and twist of the rotor blades depends on the selection of a particular $C_L$. The $C_L$ should be selected so that at the design TSR of the rotor, the blade is operated at the best possible L/D ratio. The hydrofoil’s local AOA are usually several degrees below the maximum $C_L$, thus providing sufficient margin with respect to flow separation and occurrence of cavitation. As a result, the rotor power characteristics will have the maximum $C_{PR}$ value at the selected design TSR. With certain simplifications, that is by neglecting hydrofoil’s drag and tip vortex losses, a mathematical formula for hydrodynamically optimum chord distribution over the blade length is given as [23].

$$C_{opt} = \frac{2\pi}{z} \frac{8}{C_L} \frac{U_D}{(TSR)V_r}$$

Most of the time the blade chord distribution does not follow above equation, and a modified chord distribution is set to optimize blade at different rotor solidity to have desired TSR and also for strength purposes, depending on turbine operating conditions. Locations with very high tidal current, the turbine requirement is to have thicker and higher solidity blades. For characterizing the geometry rotor blade shape, some important parameters are as follows:

$$\text{Rotor solidity} = \frac{\text{Total blade planform area}}{\text{Rotor swept area}} \text{ (%) } 2.17$$
$$\text{Aspect Ratio} = \frac{(\text{Rotor Radius})^2}{\text{Planform area of rotor blade}} 2.18$$

The blade part near the hub is of less significance for the generation of power. Hence, hydrodynamic aspects can be put aside in favor of higher strength or greater simplicity in manufacturing. However, the part near the hub should not be omitted, this significantly reduces the rotor performance.

The number of rotor blades is important for rotor characteristics and its frequency. Turbines with a small number of blades rotate faster but have a disadvantage of having smaller blade area. Increasing the number of blades increases the maximum power, but more than 3 blades have very less influence on the turbine performance, hence it increases the cost of putting the extra blades. When the number of blades increases from 1 to 2, there is about 10% increase in
maximum power; increasing the number of blades from 2 to 3 blades increases maximum power by about 3-4% and increasing the number of blades from 3 to 4 increases maximum power only by 1-2%. Theoretically, the power coefficient will continue to increase with increase in number of blade, but if the number of blades is very large the power coefficient will start to decrease again. When rotor solidity is very high, the hydrodynamic flow conditions become more complicated (cascade flow) and cannot be described by theoretical models. The optimum TSR decreases with increase in number of blades which is an advantage in regards to cavitation inception; chance of cavitation inception reduces with decrease in TSR. The optimum TSR also depends on choice of hydrofoil, normally $C_{PR}$ values increase, reaches a maximum and then drop, but generally TSR varies with number of blades. Rotor with 2–3 blades is normally a preferred solution for tidal current turbine, as a rule.

The shape of the blade tip influences the tip vortices produced and thus the induced hydrodynamic drag. According to recent investigations, power can be noticeably improved for turbine rotors by optimizing the tip shape. The tip vanes that are frequently used for wind turbines are shown in Fig. 2.11; these can also be employed in tidal current turbines.

![Figure 2.11. Possible tip vanes that are frequently used][23]

**2.4. Development and Progress of Tidal Power**

Tidal current turbine technology is still in its infancy and lots of developments are taking place in this field. Currently major works are being done on the reliability of the technology. Recent advances have translated into down-scaled models and full-scale prototypes and also the first
dedicated test centre, the European Marine Energy Centre (EMEC), based in Orkney, Scotland, which is operational since May 2005 for the testing of tidal current turbines [7].

Tidal energy extraction started by turning water wheels, it is one of the oldest forms of energy used by humans. Indeed, tide mills, in use on the Spanish, French and British coasts, date back to 787 A.D. Tide mills consisted of a storage pond which is filled during incoming (flood) tide through a sluice and emptied during the outgoing (ebb) tide through a water wheel. The mechanical power produced is used to mill grain and power was available for about two to three hours, usually twice a day[28]. Then the tradition of tidal barrages began in 1960s, the first commercial-scale modern-era tidal power plant was built, near St. Malo, France. The highly-efficient hydro-mechanical devices such as the paddlewheel and the overshot waterwheel with hydroelectric turbine generator were built [7].

Building Barrages would require capital cost, has environmental problems such as silting. In 1970s a British mechanical engineer, Peter Fraenkel, used a catamaran raft and vertical axis rotors, a prototype was developed that generated 2–3 kW and pumped up to 50 cubic meters of water a day. This success encouraged Fraenkel to think on using sea, rather than river currents and generating electricity. He was encouraged by the world’s first government sponsored assessment of tidal power potential, by the UK in 1993. A 10-kW prototype, the world’s first tidal current turbine, was developed in the Loch Linnhe inlet the following year[29].

The development and progress on tidal current turbines continued, tidal current turbines are now used commercially. Currently a lot of research is being done in the field of tidal current energy extraction. Some of the most promising progress on tidal current turbines around the world are as follows and the pictures are in appendix A. Delta stream turbine was designed and developed by tidal energy limited in UK, the Evopod tidal turbine was designed and developed by Ocean Flow Energy LTD based in UK, Free Flow turbine was designed and developed by Verdant Power Ltd based in the USA and Canada, Gorlov Helical turbine (GHT) was developed by GCK technology Inc in the USA, Lunar energy tidal turbine was developed by Lunar Energy Ltd based in the UK, Neptune Tidal Stream Device was developed by a Aquamarine Power Ltd based in the UK,
Nereus, solon and dual rotor kong turbines were developed by Atlantis Resources Corporation ltd, the Open Centre Turbine was designed and developed by Open-Hydro Ltd, Sea Flow and SeaGen tidal current turbine were developed by marine current turbine Ltd based in UK, TidEl tidal turbine is a prototype developed by SMD Hydrovision, and Tidal Stream Turbine was developed by Hammerfest Strom AS, a Norwegian company.

There are several other projects under developments by many tidal current turbine manufacturing companies which will be completed in a few years time.

2.5. Summary

Tidal current is a vast and reliable source of energy. Tidal currents are predictable with exceptional accuracy many years in advance. In other words, power suppliers will easily be able to schedule the integration of tidal energy with backup sources well in advance of requirements. Thus, among the emerging renewable energy sources, tidal energy represents a much more reliable energy source than wind, solar and wave, which are not predictable for long time. Many countries are giving incentives and setting targets to meet their energy demands by renewable energy. Due to 800 time’s greater density of water compared to air, tidal current turbines can extract large amount of energy with a smaller swept area. HATCT can be used to extract tidal energy for commercial use. Horizontal axis turbine rotating at lower tip speed ratio has minimum environmental effects compared with capturing tidal energy using tidal barrages. Hydrodynamics and operations of tidal current turbine are very important to fully utilize tidal current turbine for its maximum efficiency.

Designers face challenges in designing blade sections for HATCT as these sections must prevent the occurrence of cavitation and also provide high hydrodynamic efficiency. Tidal turbine technology is still developing and a lot of research and development is needed for large commercial uses. Attention is also given to research on the material used for manufacturing of HATCT blade; manufacturing even a very high efficiency rotor is of no use if it experiences cavitation and bio-fouling. Material used for blade must be strong enough to prevent cavitation erosion, and also prevent or minimize the blade fouling, hence minimizing the maintenance cost. Tidal turbine blades also encounter large thrust forces; again stiff material is required for structural strength.
3. Tidal Current Resource Assessment

3.1. Introduction

Tidal current energy is the most predictable renewable energy resource. Tidal current velocities in tidal streams are often strong, compared to open waters. The velocities differ depending on how the tidal stream interacts with the local geometry of the passage. One important factor is the presence of narrow passages or channels which accelerate the tidal flows. Potential sites for extracting tidal current energy include tidal current passages and tidal current straits and estuaries. At these places tidal current velocity increases due to venturi effects, the mean tidal current speeds are high enough to produce effective power for electricity. These sites are not usually very deep, and it is easier to install a turbine there. However, the flow through a passage is also constrained by the loss of energy due to friction. There is always an upper limit to the energy that can be extracted from such tidal flows.

Another important factor is the phasing of the tidal flows. Very large currents can arise when the tide levels differ on the two sides of a channel. Such phase differences can also generate significant tidal flows near large islands and major headlands. In some cases, strong currents can occur even though the tide range is moderate. Many potential high-energy sites are located at narrow passages between the islands or headlands. The flow velocity within the passage will vary with depth and with position across the channel. For typical sites, the strongest flows tend to occur within the upper half of the water column, and near the centre of the channel. Tidal currents in the open ocean are too weak for economically viable energy extraction using existing or anticipated technologies. For the foreseeable future, development will likely to be restricted to sites with peak flow velocities in excess of 2 m/s [27].

The design of a turbine for tidal power generation is much more complicated compared to the design of a wind turbine. The complication begins with non-uniform tidal velocity profile at different locations of tidal stream, the velocity profile changes along and across the tidal passages. Many factors must be considered when selecting the size of the tidal current turbine for a particular location such as tidal current velocity profile, obstruction from large waves, boats...
and ships crossing the passages, how much blockage is introduced to the passage if very large
turbine is placed in a very small channel. In this case, the tidal current flow may slow down due
to the flow divergence from the channel to either other openings or over the reefs; hence
reducing the power output of the turbine. The changing water depth at different tidal cycle must
also be taken in account while choosing the turbine size. Finally, the interference by turbines
placed in arrays, turbines must be at reasonable distance to allow the flow to get normalized
before striking other turbines.

The available depth of water has an obvious influence on the possible turbine size. It has been
suggested [6] that the maximum turbine size is related to the water depth. The top of the rotor
needs to be at the lowest astronomic tide (LAT) minus 1.5 m for the lowest negative storm surge,
minus 2.5 m for the trough of a 5 m wave and minus a further 5 m to minimize the potential for
damage from shipping and waves. In addition, the bottom tip of the blades must not be within
25% of the water depth at LAT from the sea bed. If shipping is excluded from the vicinity of a
turbine, this needs to be modified. An alternative rule in this case could be simply that the
turbine diameter is 50% of the water depth and the hub should be at the mid water point [6].

3.2. Theoretical Framework

The tidal current at a site is generally expressed in terms of two orthogonal components, \( U_x(t) \)
and \( U_y(t) \). By convention, \( U_x \) is the east-west component (with eastward flow positive) and \( U_y \)
is the north-south component (with northerly flow positive). The flow speed \( U(t) \) is given by the
vector sum of these two components.

\[
U(t) = \left[ U_x^2(t) + U_y^2(t) \right]^{1/2}
\] 3.1

The direction of the flow is given as:

\[
U_\theta(t) = \tan^{-1} \left[ \frac{U_y(t)}{U_x(t)} \right]
\] 3.2
If the amplitude, phases and frequencies of the dominant velocity constituent is known (either from measurements or numerical simulations) then the $U_x$ and $U_y$ can be easily calculated from

$$U_x(t) = \sum_{i=1}^{M} a_i \cos(\omega_i t - b_i)$$

$$U_y(t) = \sum_{i=1}^{M} c_i \cos(\omega_i t - d_i)$$

where $a_i$, $b_i$ and $c_i$ are the amplitude, phase and frequency of the $i^{th}$ constituent for $Ux(t)$ (equation 3.3), and $c_i$, $d_i$ and $o_i$ are the amplitude, phase and frequency of the $i^{th}$ constituent for $Uy(t)$ (equation 3.4).

The Power ($P$) available in the tidal stream is proportional to the cube of the velocity. The available power increases rapidly with increase in tidal current velocity. When flow speed doubles, the kinetic power increases by the factor of eight. The instantaneous kinetic power density ($p$) of any tidal stream can be expressed as:

$$p = 0.5 \rho U^3$$

The total power in the flow at a site cannot be extracted for energy production. For water flowing through an enshrouded turbine, maximum extraction efficiency occurs when the flow speed at the rotor face is reduced by 1/3 relative to the free-stream velocity, which yields an optimal extraction efficiency of $16/27$ (59%), which is called “Lanchester-Betz limit”. The extractable energy is further limited by channel geometry and environmental considerations, since the channel section cannot be completely filled with turbine rotors.

Another estimation of total available power in square meter, in the channel is given as [30]:

$$P = 0.5 \rho u K_s K_n U^3$$

$$P = 0.3 \rho U^3$$
The available extractable power increases rapidly as the velocity increases as shown in Fig. 3.1. Since the flow velocity is directly proportional to the cube of the power available.

![Figure 3.1. Available power at different tidal current speed](image)

The total available energy density for year can be expressed as:

\[
\text{Available energy density (kWh/m}^2\text{)} = \sum_{W=1}^{52} \sum_{D=1}^{7} \sum_{h=1}^{12} \left[ \frac{1}{2} \rho V^3 \right]_{h,D,W}
\]

3.8

Where \([1/2 \times \rho V^3]\) is the power density per square meter (kWh/m²), and \(V\) is the current velocity in m/s, \(h\) hour of the day \(D\) of week \(W\) in the year.

Annual energy output (KWh) = available energy density (KWH/m²) \(\times\) Cross section area of the channel (m²)
3.3. Methodology

3.3.1. Instrumentation

3.3.1.1. Flow Probe
The picture of the flow probe is shown in Fig. 3.2; it consists of a protected propeller and water bearing for measuring water velocity, coupled to a telescoping probe handle ending in with a LCD display flow computer. Flow handle is made of aluminum and can be extended up to 15 feet and has stainless steel bearings suitable for seawater. Flow probe is a rugged and highly accurate water velocity instrument for measuring flows in open channels and partially filled pipes.

![Flow Probe Image]

**Figure 3.2.** A Flow probe

3.3.1.2. Argonaut – XR 0.750MHz Acoustic Doppler Current Profiler
Argonaut – XR .750MHz is an Acoustic Doppler Current profiler (ADCP) shown in Fig. 3.4 measures the velocity of water using a physical principal called the Doppler shifts. This states that if a source of sound is moving relative to the receiver, the frequency of the sound at the receiver is shifted from the transmit frequency, as shown in equation 3.9.
ADCP can record tidal current at 10 different points for a given depth maximum depth (up to 40 m) when set to profiling mode. The profiling cell can be set to 10 different fixed locations and the 11th cell can be set to dynamic mode which can change its location as the water level changes. ADCP casing is made from Teflon material so it can be used in sea water, the sensor performance is not affected by bio-fouling, and also sensors are painted with anti-bio-fouling paint if fouling occurs. ADCP is in-built with 2 types of dynamic boundary adjustments (DBA). It also has built in compass and sensors, which can correct velocity if ADCP is tilted (maximum tilt ± 50°) and present the velocity in north-south and east-west direction.

The parameters that must be entered for deployments are as follows: water salinity in ppt; a user-supplied value is used for sound speed calculations, this must be correct to ± 1ppt. When dynamic boundary adjustment is enabled the input parameter for 11th dynamic cell are; cell start, the location of the start of the measurement volume and cell end, which is the location of the end of the measurement volume. Both are measured as distance along the axis of the instrument housing. Argonaut is programmed to 1Hz, it takes velocity reading every second. Averaging interval is the period, must be entered in seconds, over which the Argonaut averages data before computing mean velocity. Sample interval is the time between sequential samples, also entered in seconds. This is defined as the time from the start of one sample to the start of the next sample, and must be greater than or equal to the averaging interval or the averaging interval will take precedence. Argonaut can also take burst sampling, this sampling method allows you to record a number of samples in rapid succession, and then place the Argonaut in a low-power state for an extended period. This obtains information about both the short and long term variation of water velocity without the power and memory required for continuous sampling.
3.3.1.3. Nortek Aquadopp Current Profiler (ADCP)

This current profiler works in similar way to that of Sontek Argonaut XR. The picture of current profiler is shown in Fig. 3.6. The material used for ADCP is delrin and polyurethane plastics with titanium screws which is suitable sea water application. The Aquadopp profiler (0.6MHz) uses three acoustic beams slanted at 25°, it has 96 user input cells, the maximum profiling range is 30 - 40m, each cell size can range from 1m to 4m, the minimum blanking distance is 0.5m. The velocity range is up to 10 m/s and can measure tidal currents up to an accuracy of 0.5 cm/s. ADCP has 4 standard sensors which need be verified and/or calibrated for each deployment: these are temperature, Compass, tilt and pressure similar to Argonaut XR. The profiler typically loses data near the surface; this loss is caused by contamination of the near-surface data by side lobe echoes. The near surface contamination of velocity can be approximated using the equation 3.10.

\[ R = H \cos \alpha \]  

3.10

Where \( R \) is limit for good data and \( \alpha \) is 25° for 0.6MHz ADCP.

Some important deployment parameters are: salinity value must be accurate to ± 1 ppt, this is used for sound speed calculation. Blanking distance, maximum distance is 0.5m this is the location from instrument at which cell is located. Number of cells, user input of how many cells has been set above the blanking distance including first cell. Cell size, this is the distance between each cell this should be between 1-4m. Average interval and sample interval is entered in seconds.

3.3.2 Initial Assessment and Site Selection

The most suitable place to do tidal current assessment and install tidal current extracting device are tidal current passages that include openings in reefs, tidal current straits which are passages between two nearby islands and estuaries (river mouths). The tidal flow accelerates at these locations due to venturi effect. At these places area is reduced and water is allowed to pass from larger area through small opening. The overall tidal potential for a particular location depends on the geometry of the location itself, therefore it is very hard to predict tidal current unless measured data are available for that location. Several factors must be considered when choosing
site for Tidal current assessment. The main one is the maximum tidal current velocity - normally a peak velocity above 2 m/s is preferable for full assessment.

Another important factor is the location of the site, which must be close to land where the turbine can be easily connected to the grid and also the installation and transmission cost can be minimized. The appropriate depth for doing assessment is around 20m - 40m, these depths are more convenient for any real time installation of turbines with appropriate cost. There is a very high cost for installing turbines in very deep waters so tidal current assessment in deep oceans is not useful. Even very low depths are not preferable because the diameter of the turbine will be small; the power gets reduced by a factor of 4 if the diameter gets reduced by a factor of 2. The channel width is also important, very narrow channels affect the efficiency of the turbine, for fully blocked channel, the maximum power that can be extracted reduces to 38% from 59% [31].

If there is very large blockage caused by the turbine the water may pass from other openings near the channel hence, reducing the tidal current velocity through the passage.

While doing initial assessment one must take into account for time of high and low tides, and minimize the errors in when taking measurements. The tidal current was recorded using flow probe therefore velocity readings get affected because it is very hard to keep the flow probe straight and vertically down, the boat keeps moving by tidal current and wave action, such movements affect the readings. The best measurement skills were practiced to minimize the errors. Locations were chosen for initial assessments, these locations were selected mainly after consulting with divers who are mostly involved in diving at different locations; some of the locations chosen after getting advice from marine and tidal researchers who were involved with marine research for long time. The locations for which initial assessments were carried out are as follows, and the pictures of these locations are shown in appendix B.

_Votua Passage_ – is very close to the land about 200- 300m, but at this spot it is not very deep, moving further 200-300m the depth increases and is around 20-30m. This passage is 50-60m wide it gets narrower as moving closer to the land. The coordinates of this location are 18°12'54.71"S and 177°42'39.99"E.
**Wilkes passage** - is known to have higher tidal current, the channel has an opening of about 300m, and a semidiurnal tide is experienced at this passage. Wilkes passage is located about 25km from Nadi (Viti Levu) and about 10 Km from Malolo Island. GPS location of the place is latitude 17°50'26.80"S and longitude 177°10'37.67"E, the Google image of the location where measurements were taken is shown in Fig. 3.3. The power generated can be supplied to the grid on Malolo or nearby small islands which are a few hundred meters from this site.

**Navula passage** - is about 6.5Km from Momi, Nadi (Viti levu), this location is close to Wilkes passage but it is a much wider passage compared to the wilkes passage. The Coordinates for this location are: latitude 17°55'41.11"S and longitude 177°13'1.48"E.

**Gau Island** – passages near Gau Island were chosen for assessment of tidal current; the island is surrounded by barrier reefs and has many tidal streams. Gau Island has population of about 2500; there is no major source of electricity for the island except from small hydropower. Gau Island experiences two high tides and two low tides that is semidiurnal tidal condition. The GPS locations of the sites are shown in table 3.1.

**Astrolable reef** - it surrounds most of Dravuni which is located near Kadavu, the tidal current measurement location is very close to Dravuni (about 6.5 km). GPS location of the place is 18°42'23.04"S and 178°30'13.72"E. This place is known for a strong tidal current, the passage between the reefs is not very wide, therefore flow accelerates through the passage.

**Gun-barrel** - is in Sigatoka; it has a very strong current especially when the rip current caused by waves superimposes on tidal current. The resulting flow field is complicated and its analysis becomes difficult. The location of the place is 18°12'1.78"S and 177°38'58.21"E.

**Beqa lagoon** - is about 8km south of Viti Levu; the island is closer to Viti Levu and surrounded by reefs which create a tidal flow in the passage, therefore tidal current accelerates in the tidal passage. The coordinates of the three sites are given in table 3.2, all these locations are very close to Beqa Island.

**Castaway Passage** – is about 7-8 km from Malolo island, is a wide passage of about 2 km and is very deep at the center but depth reduces towards the end of the passage. This site was chosen
with the help of the divers, who experiences very high currents here. The coordinates of this location are 17°44'41.66"S and 177° 3'1.97"E.

3.3.3. Detailed Assessment

Detailed study of tidal current speed for a particular location, gives idea of potential for that location. The study must be done at least for 29 days [13]. There are some factors that must be taken into account, but these can be easily predicted if tidal current is studied for one complete lunar cycle, which is from new moon to new moon or full moon to full moon. The major variation in tidal current velocity occurs within this lunar cycle. The nature of the tidal current depends on the location and geometry of tidal stream. Since major variations in tidal current velocity occur in one complete lunar cycle, therefore tidal current velocity must be measured for at least one month, to get a clear idea of velocities at the channel before any turbine installations are done. After initial assessment, a full assessment was carried out for two locations Wilkes passage and Gun-barrel passage.

The first location chosen for deploying ADCP for detailed assessment was Wilkes passage and the Google image of the location is shown in Fig. 3.3.

![Figure 3.3. Google Image of Wilkes Passage](image)

This location is different from other tidal streams, there is no natural basin where water gets collected – instead, there is deep ocean on both sides of the stream. There is an opening of about
300m in the reef. This location is a few hundred meters from Tavarua Island and about 10 km from Malolo Island. High tidal current velocities are experienced at this location, because of large volume of water moving across due to tidal effect; the passage rapidly increases the tidal current velocity. Tidal current velocity profile from this location will be very useful to compare with the tidal currents recorded from natural basin type tidal streams. This location is ideal for installation of tidal current extracting devices; the depth along the channel is 25-35 m, the installation costs are less for this depth, monopole structures will be appropriate for installing turbines. The power generated from the turbine can be transmitted to nearby small islands instead of connecting it to grid on the mainland to minimize the transmission costs.

Sontek Argonaut XR was deployed at Wilkes passage, the deployment location is shown in Fig. 3.3 and a picture of the deployed instrument (underwater) is shown in Fig. 3.4. It was deployed at an approximate depth of 29 m at the time of low tide and was secured using stainless steel wires and ropes to nearby rocks. The parameters set for this deployment are as follows: salinity value of 33ppt - as this location is away from shores the salinity is higher; average interval of 20 seconds and sample interval of 600 seconds for velocity recording. Dynamic boundary condition was enabled and the cell beginning is at 25m and cell ending is at 33m. The number of cells was set to 10 and all the 10 cells data were used for velocity profiling, the cell size was set as 3m for each cell and blanking distance was set at 0.8m. The date and time was set as 2011/05/13 and 18:00:00. The burst profiling mode was disabled.
The second site for deploying the ADCP was the Gun-barrel passage. The Google image for this location is shown in Fig. 3.5. The coordinates of the location at which ADCP was placed are 18°12'1.78"S and 177°38'58.21"E. The location is about 200 m from land. This is a very narrow passage of 15 -20 m width at the opening to sea. The ADCP was deployed for 3 months, and the parameters set are as follows: the salinity was set at 32 ppt as this location closer to land where salinity values are low. Number of cells was set at 25, cell size was set as 1m and the blanking distance was set as 0.5m. Average interval was set as 20 seconds and profile interval was set to be 600 seconds. The date and time set were 10/09/2011, 6:00:00. The picture of ADCP mounted in the frame is shown in Fig. 3.6; the picture was taken after retrieving the ADCP.
3.4. Results and Discussion

3.4.1. Initial Assessment

The maximum tidal current velocity measured with the flow probe at the Wilkes passage was about 1.8 – 2 m/s. The estimated depth of this location is around 30-40 m. The tidal current measurements were taken around peak tidal current time. The tidal current velocity can even exceed 2 m/s for this location; a detailed assessment can be done to see the power density available for any commercial use installations.

Maximum tidal current recorded at Navula passage was around 0.7-0.9 m/s and estimated depth of 30-50m. The tidal currents were measured almost at the peak tidal current velocity time about 1 hour before the peak current. This passage is quite wide therefore the tidal current may not go very high, however a reasonably higher tidal current can be observed.

Very high tidal current of about 2 m/s was observed at the passage near Dravuni, the measurements were performed during peak tidal current. It is narrow channel and depth of about 30-40m. This location may have good potential of tidal energy for commercial installation. It is very close to the island that means low turbine installation and power transition cost.
The maximum tidal current recorded was about 0.5-0.6 m/s at Gun-barrel. This is a narrow channel of about 5-8m width and a depth of around 15-20 m. The measurements were performed during very low tidal current time, mainly the rip current caused by the wave action. Initial measurement from the boat is very difficult because the channel is very narrow and dangerous for boats during maximum tidal current time. However, very high tidal currents were experienced by the divers at this location.

Table 3.1 shows the current velocities, water depth and time when tidal current were recorded near Gau Island.

Table 3.1 Tidal current assessment results for Gau Island

<table>
<thead>
<tr>
<th>Site</th>
<th>GPS location</th>
<th>Current speed</th>
<th>depth</th>
<th>Time (when measured)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>latitude</td>
<td>longitude</td>
<td>m/s</td>
<td>(m)</td>
</tr>
<tr>
<td>1</td>
<td>site 1</td>
<td>17°59'47.862&quot;S</td>
<td>179°12'14.231&quot;E</td>
<td>1.35</td>
</tr>
<tr>
<td>2</td>
<td>site 2</td>
<td>17°59'15.959&quot;S</td>
<td>179°12'57.348&quot;E</td>
<td>0.7 - 0.8</td>
</tr>
<tr>
<td>3</td>
<td>site 3</td>
<td>18°00'156&quot;S</td>
<td>179°12'27.404&quot;E</td>
<td>0.5 – 0.6</td>
</tr>
</tbody>
</table>

The recorded current velocities show that there is a tidal current potential near Gau Island, but the feasibility of the tidal power available and extracted for commercial use cannot be determined, for which a detailed assessment is required. The velocities were recorded during moderate tidal currents.

Table 3.2 shows the current velocities, water depth and time when tidal currents were recorded for tidal current assessment near Beqa Island (Beqa Lagoon).

Table 3.2 Tidal current assessment results for Beqa Lagoon

<table>
<thead>
<tr>
<th>Site</th>
<th>GPS location</th>
<th>Current speed</th>
<th>depth</th>
<th>Time (when measured)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>latitude</td>
<td>longitude</td>
<td>m/s</td>
<td>(m)</td>
</tr>
<tr>
<td>1</td>
<td>site 1</td>
<td>18°19.33&quot;S</td>
<td>178°02.42&quot;E</td>
<td>0.8 - 0.9</td>
</tr>
<tr>
<td>2</td>
<td>site 2</td>
<td>18°21.507&quot;S</td>
<td>178°11.097&quot;E</td>
<td>0.7 - 0.8</td>
</tr>
<tr>
<td>3</td>
<td>site 3</td>
<td>18°22.165&quot;S</td>
<td>178°11.500&quot;E</td>
<td>0.8 – 0.9</td>
</tr>
</tbody>
</table>
Tidal current recorded did not show much tidal potential for commercial installation. However the tidal currents were not measured at the maximum tidal current time.

The tidal current measured at Votua passage was around 2 m/s; the measurements were taken around peak current time. Votua passage is not very wide around 40m and depth of around 20 to 30m. This passage is very close to land about 200m. This location is very good for installation of turbine and grid connection, the turbine installation and power transmission costs will be low.

The tidal current measured at castaway passage was around 0.7-0.9 m/s; these measurements were taken few hours before the peak tidal current. The passage is very deep; this site does not show good potential for tidal current.

From the initial assessment results, the three passages which showed the potential for tidal current energy extraction are Wilkes passage, Votua passage and Gun-barrel passage. These locations were chosen looking at the energy demand at the location, installation and transmission costs, peak tidal current velocity and the size of the passage. Wilkes passage is close to Malolo and Tavarua Island, the major sources of electricity in these two islands is generated using diesel generator, which becomes very expensive, while transporting fuel to the island. Wilkes passage is close to the land therefore turbine installation and power transmission cost will be low. The passage is wide, depth of around 30 - 40m, 4 - 6 turbine of diameter 10-15m can easily be installed, but the number of turbine that needs to be installed also depends on the electricity needs for the island.

Votua passage is also good location for full assessment and installation of tidal current energy extraction devices. Votua passage is very close to the land, the power produced can be transmitted to the grid, hence meeting the electricity demands. The transmission and turbine installation costs will be lower because this location is close to land. The depth is around 20-30m which means a 10-12 m diameter turbine can be installed, however this passage is not very wide, only 2 or 3 turbines can be installed, taking into account the blockage. Similar to Votua passage, the Gun-barrel passage is also very close to land, however this passage is very narrow and only a single turbine installation of diameter 5-8m is possible. At times, this location has a very high marine current.
3.4.2. Detailed Assessment for Three Months

3.4.2.1. Wilkes Passage

The detailed measurements were performed for 3 lunar months (full moon to full moon). This was from 17th May to 13th of August, first lunar month was from 17th May to 15th June, second lunar month was from 16th June to 14th July and the third Lunar month was from 15th July to 13th August. The average depth at which ADCP was placed was about 29m. A 10 cell ADCP was used; therefore it recorded tidal current velocities at 10 different depths. First cell was set at 1m from seabed and the 10th cell was at 28m from the seabed, all other cells were at intervals of 3m. The tidal current velocities recorded at 25m for all the three lunar months are shown in Figs. 3.7, 3.8 and 3.9.

![Figure 3.7](image)

**Figure 3.7.** The tidal current velocity in the Wilkes passage for the first 10 days of the 3 lunar months
Figure 3.8. The tidal current velocity in the Wilkes passage from day 11 to day 20 of the 3 lunar months.

Figure 3.9. The tidal current velocity in the Wilkes passage from day 21 to day 30 of 3 lunar months.
The tidal current flowing in and out of the passage is mostly in north-south direction. However, there was some influence of east-west current caused by interaction of tidal flows on passage wall and from the wave action near the surface.

There were lots of fluctuations in the recorded tidal current velocity. The velocities were stronger during ebb tidal current time. The current velocities were weaker during flood tidal current time. This was because the ADCP was placed about 100-150m away from the passage opening, at this location water leaving the passage has stronger velocity while current into the passage has weaker velocity. The depth right at the passage opening was 8-10m; therefore ADCP was moved further seaward side where mean depth recorded was about 29m. The velocities follow similar trend every month, therefore, one month data could be sufficient to predict the tidal current potential.

The average tidal velocity for first lunar month was 45.6 cm/s, for second was 45.2 cm/s and for third month was 44.8 cm/s; this shows that average velocity of any one complete lunar month can be used for design purposes. The passage is isolated from run-offs caused by rain from the land, there is not much run-off caused by rain in small islands. Therefore tidal current velocities followed similar trend for all the three lunar months.

3.4.2.2 Gun-barrel Passage

The current velocities were recorded for 3 lunar months at this site as well. First lunar month was from 12/09 to 12/10, second lunar month from 13/10 to 11/11 and third lunar month was from 12/11 to 11/12. The current velocities recorded for the 3 lunar months and at the depth of 10.5m are shown in Figs. 3.10, 3.11 and 3.12. The average depth recorded for the location is around 17.5m. The current at this passage is a result of both tidal and non-tidal flows. The non tidal current effect is from water entering the passage from the wave’s breakings at the reefs and go back to sea through the passage. This effect is also called rip current. The rip current at this location is stronger than tidal current. Current is mostly unidirectional near the passage mouth, that is water mostly flows out of the passage. At times when tidal and non tidal current is at same direction, the effect combines to give much stronger current.
The maximum velocity exceeds 2 m/s during the time of large swells. For such a location, the current is unpredictable, where both tidal and non-tidal current exist. However, data for 3 months is good enough to assess the current potential of the site. The current for individual months follows similar trend but the maximum peaks vary for some days. The current is not always strong during spring tide for this location. For the first and second lunar months, the current was stronger during neap tide time, this also depends on waves.

Figure 3.10 The current velocity in the Gun-barrel passage for first 10 days of the lunar month, recorded at 10.5m
Figure 3.11 The current velocity in the Gun-barrel passage from day 11 to 20 of the lunar month, recorded at 10.5m

Figure 3.12 The current velocity in the Gun-barrel passage from day 21 to 30 of the lunar month, recorded at 10.5m
3.4.3 Harmonic Analysis

Harmonic analysis of tidal current velocities can be done using Matlab-based code called *t_tide* [32]. *t_tide* analyzes the tidal constituents of particular location using recorded data and gives the prediction of tidal phenomenon. *t_tide* version 1.3 has other features such as nodal correction and this package is widely used by oceanographers. Up to 146 harmonic constituents may be included by *t_tide* in the least-square solution by *t_tide*. The Rayleigh criterion governs constituent inclusion and is a function of the frequency separation between neighboring constituents recorded and records length. The least square analysis is similar to Fourier analysis, but is preferable because tidal frequencies are not integer multiples of fundamental frequency, which is required for Fourier analysis. The benefit of harmonic analysis is in the use of the derived constituents to predict the current and power density. As observed by Godin [33], such prediction is not very useful, if it is not compared with measured data, which gives the true picture of energy available.

Harmonic analysis gives better prediction of tidal current rather than marine currents. The external effect on tidal current by wave action, the bathymetry and geometry of the channel cannot be predicted using analyzed constituent. The harmonic analysis was done for Wilkes Passage data using *t_tide* for 33 days from the starting date of 13 May 2012. The velocity input was for 30 minutes interval. Linear error estimation or nodal current was set to taking account of phase and amplitude affected by other constituents. The two important constituents that cannot be solved from short term measurements are P1 from K1 and K2 from S2. K2 and P1 are the largest amplitude diurnal and semi-diurnal excluded by the Rayleigh criterion for measurement less than 180 days. The harmonic analysis results of amplitude and phase correction is presented in ref. [34] it shows that there is not much variation over the depth. The comparison of interference property of tidal current is not entirely different from tidal heights estimated by Lavelle et al. [35], the ratio P1/K1 is 0.33 and K2/S2 is 0.23. These parameters are needed in *t_tide* for correction of phase and amplitude inferred by other constituents. The shallow water constituent that can be manually input is ‘M10’[32].

The harmonic analysis of tidal current for Wilkes passage was done for 33 days at an interval of 30 minutes as shown in Figs. 3.13 – 3.15. The current velocity is for 25m from seabed, the direction of velocity is north-south.
The harmonic fit predicted using *t-tide* shows good agreement with the positive velocities measured using ADCP, while the agreement in not so good for the negative velocities. The measured results and harmonic fit do show that tidal sinusoids are in phase, however, harmonic analysis show very poor prediction of tidal current during ebb tide, when water is receding; this
is mainly due to placement of ADCP. The ADCP was placed away from main entrance of the
passage where the current was highly affected by wave breaking over the passage (short of rip
current not so strong) and turbulence flow passing through the passage. This was also the main
cause of non-symmetrical tidal current velocity during ebb and flood tide. Therefore, harmonic
does not give best prediction of tidal current, to analyze the energy potential of particular site,
physical measurements are necessary to see the non-tidal effects on predicted power.

3.4.4. Relation between Tide Height and Tidal Current

3.4.4.1. Wilkes Passage

The tidal velocity is normally dependent on the difference in tide heights, the greater the height
different, the stronger the tidal current. This also varies with geometry of the passage as well not
true for passage which is right inside the land. Figs. 3.16 and 3.17 shows the relationship
between tidal height and tidal current velocity, for 2 days, from 10th July to 11th July, measured
by ADCP at Wilkes passage, measurements were taken at 13m and at 25m. The tidal current
velocity reaches maximum velocity 4 times each day, which is tidal current velocity is maximum
two times during flood tide and two times during ebb tide. The maximum current is right at the
high tide time or right at the low tide time. Between high and low tide the tidal current velocity is
zero also called slack water, at this time the tidal current changes the direction. Tidal current
velocity is zero 4 times every day. The tidal current is not symmetrical during flood and ebb tide
time, it is stronger during ebb tide time although tidal heights are almost symmetrical. This was
because ADCP was placed slightly away from the passage, symmetrical tidal current velocity
during ebb and flood tide time is normally observed right at the passage.
Figure 3.16 Measurement of tidal height for July 10th and 11th at the Wilkes passage

Figure 3.17 Tidal current velocities for 10th and 11th July at the Wilkes passage
3.4.4.2. Gun-Barrel Passage

Figs. 3.18 and 3.19 show the relationship between the tidal height and current at the Gun-barrel passage. The tidal height different for this location is around 1m, but the peak current at this passage exceeds 2 m/s, the flow is the combination of both tidal and non-tidal currents. The non-tidal current is caused by water flowing into the passage, when waves break at the reefs, it is also known as rip current. The combined action of tidal current and rip current have very high current at the passage exceeding 2 m/s. The nature of current at this passage is different from other passages. The current is low during the low tide and increases as the water level increases, and the current reaches maximum during high tide. Higher water level lets more water to flow into the passage over the reef during large swells. The velocity shows lot of fluctuates, because wave height changes regularly.

![Figure 3.18. Tidal heights for 14th and 15th September at the Gun-barrel passage](image-url)
3.4.5. Tidal Current Profile at spring and Neap Tide

3.4.5.1. Wilkes passage

The tidal current velocity changes from the seabed to the surface. This is due to the shear force between the moving water and the seabed, resulting in a boundary layer. The velocity profile is similar to wind profile. For most of the cases the velocity profile follows $1/7^{th}$ or $1/10^{th}$ power laws, but this is not always the case for tidal streams. Mostly the water flow gets turbulent and does not follow power laws. The graphs in Fig. 3.20 show the velocity profile during spring and neap tides, the velocity profile is for single reading. The velocity profiles are compared with $1/7^{th}$ and $1/10^{th}$ power law. The velocity profile of neap tide follows $1/10^{th}$ power law until 35% of the depth, and after that there is a very large increase in tidal current velocity. During spring tide, the tidal current velocity follows $1/10^{th}$ power law until 15% of the depth, then there is a large increase in tidal current velocity. The velocity profile is always interrupted by the wave action at the surface. The tidal current near the surface interacts with the waves; this could be the reason for such high velocities near the surface. The velocities were low near the bottom; this is mostly due to the coral and large rocks at the bottom.
3.4.5.2. Gun-barrel Passage

The velocity profile for a single set of measurements at the Gun-barrel passage is shown in Fig. 3.21, during spring and neap tides. For both the cases, current profile is close to 1/10 power law profile. But the velocities are highly affected at the seabed and near the surface. Gun-barrel passage is quite a narrow passage, the velocity profile is affected by the walls which are rough, and also the bottom is very rough, filled with corals and rocks. These are the reasons which affect the current velocity. For installing any turbine for this location, a clearance of 25-35% from both ends is required. The average depth for this location is about 17.5m; therefore the turbine size that can be installed is about 5-8m.
3.4.6. Tidal Current Velocity and Power Analysis

3.4.6.1. Wilkes Passage

The average tidal current velocity for Wilkes passage is shown in table 3.3, the average tidal current velocity for 3 month was 52.2 cm/s, the average neap tidal current velocity was 34 cm/s and average tidal current velocity during spring for 3 months was 45.2 cm/s. The average tidal current velocities for individual lunar month are very close, even the average spring and neap tidal current velocities are very close. For passages that are away from main land, like Wilkes passage, one month of detailed assessment data are good enough for prediction of the tidal current potential. The maximum tidal current velocity recorded was around 1.5 m/s during spring tide. During spring tide time, the average tidal current velocity is always greater than neap tidal current velocity, hence the power density is greater during spring tide time.

Figure 3.21. Tidal current profiles for Guns Barrel passage during spring and neap tide
Table 3.3 Velocity and power summary for Wilkes Passage

<table>
<thead>
<tr>
<th>Days</th>
<th>1st month</th>
<th>2nd month</th>
<th>3rd month</th>
<th>Average for 3 months</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring tide average velocity (C/m/s)</td>
<td>54.2</td>
<td>52.2</td>
<td>50.2</td>
<td>52.2</td>
</tr>
<tr>
<td>Neap tide average velocity (C/m/s)</td>
<td>35.2</td>
<td>34.5</td>
<td>32.5</td>
<td>34.1</td>
</tr>
<tr>
<td>Average velocity (C/m/s)</td>
<td>45.6</td>
<td>45.2</td>
<td>44.8</td>
<td>45.2</td>
</tr>
<tr>
<td>Total average power available (W/m²)</td>
<td>98.32</td>
<td>92.35</td>
<td>86.35</td>
<td>92.35</td>
</tr>
<tr>
<td>Power available per month (kWh/m²)</td>
<td>70.8</td>
<td>66.5</td>
<td>62.2</td>
<td>66.5</td>
</tr>
<tr>
<td>Total average power extractable (W/m²)</td>
<td>58.992</td>
<td>55.41</td>
<td>51.81</td>
<td>55.41</td>
</tr>
</tbody>
</table>

The average velocity data for at least 29 days can be used to successfully predict the average available power density. The extractable available power is always lower; according to the Betz limit the total extractable power is 59% of the total available power. But the extractable power decreases once the blockage is introduced into the stream. For fully blocked tidal stream, the maximum extractable power is about 38% [31]. Table 3.3 shows the total average available and extractable power for Wilkes passage. The maximum total power density for one year is around 92.35W/m², but the maximum average power that can be extracted is around 55.41W/m². HATCT operates at higher tidal current, which is not appropriate to install at this location. For this location other tidal current energy converters which have lower installation and maintenance costs can be installed.

Table 3.4 Velocity and Power summary for Gun-barrel passage

<table>
<thead>
<tr>
<th>Days</th>
<th>1st month</th>
<th>2nd month</th>
<th>3rd month</th>
<th>Average for 3 months</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring tide average velocity (m/s)</td>
<td>0.75</td>
<td>0.78</td>
<td>0.75</td>
<td>0.76</td>
</tr>
<tr>
<td>Neap tide average velocity (m/s)</td>
<td>0.95</td>
<td>0.92</td>
<td>0.75</td>
<td>0.88</td>
</tr>
<tr>
<td>Average velocity (m/s)</td>
<td>0.92</td>
<td>0.85</td>
<td>0.7</td>
<td>0.85</td>
</tr>
<tr>
<td>Total average power available (W/m²)</td>
<td>667.71</td>
<td>556.57</td>
<td>308.02</td>
<td>525.08</td>
</tr>
<tr>
<td>Power available per month (kWh/m²)</td>
<td>480.1</td>
<td>400.7</td>
<td>221.8</td>
<td>378</td>
</tr>
<tr>
<td>Total average power extractable (W/m²)</td>
<td>400.63</td>
<td>333.94</td>
<td>184.81</td>
<td>315.05</td>
</tr>
</tbody>
</table>
Velocity summary for the Gun-barrel passage is shown in table 3.4. Average current for three months is about 0.85 m/s. For individual lunar months the average current velocities are different, the maximum was for the first month at 0.92 m/s, decreases to 0.85 m/s for the second lunar month and further decreases to 0.7 m/s for the third lunar month. The average current during neap tide time was greater than spring current for the first two lunar months, but for the third lunar month, the current was stronger during neap tide time. The nature of the tidal current is affected by the non tidal current at the passage, therefore it is different from the other tidal current passage.

The total average available power at the Gun-barrel passage for one year is around 525.08W/m² and average extractable power for this location is around 315.05W/m². However, the velocity and power will reduce when moving along the channel, because rip current is stronger near the passage opening to the sea. This site shows good potential for marine current. HATCT can be installed at this site, which will have good performance and power output.

3.5. Summary

Detailed tidal current assessments were carried out at two locations; Wilkes passage and Gun-Barrel passage. These two locations were selected after initial assessments for various places around Fiji. The detailed assessment was carried out for 3 lunar months; one lunar month is of 29.5 days from new moon to new moon or from full moon to full moon. The average tidal current velocity for the Wilkes passage was around 45.2 cm/s, the average velocities for individual lunar months were close, therefore, one lunar months data is enough to predict the tidal current potential. The total average power available at Wilkes passage is 92.35W/m². The harmonic analysis of tidal current velocity was also done using $t_{\text{tide}}$, the predicted results does show good agreement with the positive velocities measured using ADCP, while the agreement in not so good for the negative velocities, therefore, it is better to have measured data along with predicted data, to analyze power density of any location.

Installation of HATCT is not appropriate for Wilkes, because tidal current velocities for these sites are not so high. Therefore other tidal current energy converters which have lower initial installation cost and maintenance costs can be designed for this location. The other site, the Gun-
barrel passage shows potential of marine current power generation, the peak current velocity exceeds 2 m/s, two times a day. This was because of superimposition of non-tidal current velocity over tidal velocity. The average current velocity for 3 months was around 0.85 m/s, but the average velocity for the first month reached 0.92 m/s, because of larger in this month. The total average available power for this location is around 525.08W/m², and 315.05W/m² of this can be extracted. A HATCT can be installed at this location to capture energy from ocean current available in the stream.
4. Horizontal Axis tidal current (HATCT) design

4.1. Introduction

There are plenty of tidal streams near Pacific coasts, with good energy potentials. Tidal current energy is the most predictable energy source compared to other renewable energy sources such as solar and wind energies. The challenge is in extracting this large amount of energy with good efficiency. Horizontal axis tidal current turbine (HATCT) is frequently used for tidal current power extraction. For peak tidal current velocities above 2 m/s, HATCT can be used for extracting power for commercial use [19]. With developments in technology, HATCT are becoming more efficient, even in tidal current velocities lower than 2 m/s. The successful utilization of HATCT requires an understanding of the hydrodynamic characteristics of tidal current turbines. A lot of design criteria and operation of HATCT are same as Horizontal axis Wind turbine (HAWT) and ship propellers. However, there are some differences in the design and operation of HATCT which needs further research and investigation. These differences include the change in Reynolds number, different stall characteristics, possible occurrence of cavitation [36], variation in speed, non-uniform speed and direction of current, the shear profile in the tidal flow, and the influence of the free depth and the free surface.

The hydrodynamic design parameters basically include choice of diameter, pitch or twist distribution, chord distribution choice of blade sections which has predicted cavitation criteria and study of stall characteristics. The basic performance of HATCT can be modeled successfully using blade element momentum (BEM) theory, same as for wind turbines [37]. The BEM theory is well established for modeling rotor dynamics including marine propellers and wind turbines. BEM theory can successfully predict the span-wise loading on narrow blades, such as wind or marine turbines; it does not provide information on 2-D loading. Other methods, such as the 2D panel methods, can be used to predict the chord wise pressure distributions and loadings, which are of particular relevance to the study of stall characteristics and the occurrence of cavitation [37]. For numerical calculation of 2-D sections, such as $C_L$, $C_D$ and of the occurrence of cavitation, the 2-D panel code Xfoil can be used [38]. Xfoil is a linear vorticity stream function panel method with viscous boundary layer and wake model, and is found to be suitable for
predicting cavitation criteria at the primary design stage [36], more details on Xfoil, the associated theory and the Xfoil manual can be found in ref. [39]. Once the cavitation is avoided then the BEM theory is assumed to be valid for HATCT [40].

The general BEM theory is based on a combination of momentum and blade element theories. The momentum theory is used to derive the axial and circumferential inflow factors, with the tip loss factor to take into account the finite number of rotor blades. The blade element theory is used to model the section drag torque by dividing the rotor blade into a number of elemental sections. By the combination of these theories, the rotor thrust loading and rotor power loading at each blade radius are determined by matching the fluid momentum changes to blade forces based on lift and drag coefficient at operating angles of attack at different blade sections. Allowance for the finite number of rotor blades is made using an approximation to the Goldstein tip loss factor [41]. The integration of the loadings across the blade gives the torque, drag and power coefficient for the rotor.

The performance of a small strip of the rotor between radius r and radius (r+dr) can be analyzed by matching the blade forces generated by the blade elements to the momentum change occurring in the fluid flowing through the rotor disc between the radii. The directions of blade forces, velocities and the angles are shown in Fig. 4.1; \( \phi \) is the angle between the rotating plane and the relative velocity of the tidal current and the rotating blade, \( \alpha \) is the local angle of attack of hydrofoil. The derivation of equation is presented in reference [19] and described briefly below.
Figure 4.1. Direction and angles of forces and velocities on a hydrofoil

**Momentum Considerations**

Equating the thrust on an element of the blade to the axial momentum change, the torque on an element to the angular momentum change and introducing a Goldstein factor \( k \) to take into account the finite number of blades leads to the following equations for the thrust (T) and torque (Q) gradients:

\[
\frac{dT}{dr} = 4\pi \rho r [U_0^2 a (1 - a) \kappa + (a' \Omega r \kappa)^2] \tag{4.1}
\]

\[
\frac{dQ}{dr} = 4\pi r^3 \rho U_0 \Omega a' (1 - a) \kappa \tag{4.2}
\]

**Blade element consideration**

The local lift and drag gradients are defined by:

\[
\frac{dL}{dr} = \frac{1}{2} \rho c B V r^2 C_L \tag{4.3}
\]

\[
\frac{dD}{dr} = \frac{1}{2} \rho c B W V r^2 C_D \tag{4.4}
\]
Where \( c \) is the local blade chord, \( B \) is the number of blades. The rotor thrust and torque gradients are then defined by:

\[
\frac{dT}{dr} = \frac{dL}{dr} \cos \phi + \frac{dD}{dr} \sin \phi
\]

\( 4.5 \)

\[
\frac{dQ}{dr} = r \left[ \frac{dL}{dr} \sin \phi + \frac{dD}{dr} \cos \phi \right]
\]

\( 4.6 \)

Combining equations 4.1, 4.2, 4.5 and 4.6 yields equation for axial (a) and tangential (a') inflow factors.

These equations are solved by iteration for \( \phi \).

\[
\frac{a}{1 - a} = \frac{\sigma_k}{4\pi kx \sin^2 \phi} \left[ C_x - \frac{\sigma_k c^2}{4\pi x \sin^2 \phi} \right]
\]

\( 4.7 \)

\[
\frac{a'}{1 + a'} = \frac{\sigma_k C_y}{4\pi kx \sin \phi \cos \phi}
\]

\( 4.8 \)

Where \( x = r/R, C_x = C_L \cos \phi + C_D \sin \phi, C_y = C_L \sin \phi - C_D \cos \phi \), and solidity ratio \( \sigma_k = cB/2R \).

**Power and Thrust**

The application of equations 4.1 and 4.8 gives the solution for power and thrust gradients:

\[
\frac{dC_p}{dx} = \frac{2\text{TSR}(1 - a)^2 \sigma_k x C_y}{\pi \sin^2 \phi}
\]

\( 4.9 \)

\[
\frac{dC_T}{dx} = \frac{2(1 - a)^2 \sigma_k C_x}{\pi \sin^2 \phi}
\]

\( 4.10 \)

The integration of these gradients will give the solution for the power and thrust.
Tip loss factor

The Goldstein momentum averaging factor $k$ has been used to evaluate tip losses. The following equations provide a good fit to the Goldstein charts used in the marine propellers:

\[
\kappa = \frac{2}{\pi} \cos^{-1}\left(\frac{\cosh(yf)}{\cosh(f)}\right)
\]

\[
f = \frac{B}{2x \tan \varphi} - \frac{1}{2}
\]

4.2. Methodology

4.2.1. Instrumentation

4.2.1.1. Wind tunnel

An open circuit wind tunnel made by Engineering Laboratory Design, Inc was used for the experimental work. Air is drawn into the inlet, through a honeycomb and screen pack and is accelerated through the contraction into the test section. The system air regains static pressure after passing through the diffuser. Flow continues through the fan and is discharged to the atmosphere. The wind tunnel components include: flow duct, flow straighteners, test section, fan, motor, motor controller and supporting frames. The test section is made from clear GM grade, acrylic and the dimensions of the test section are: length 1 m, height 12 inches (30.48cm) and width 12 inches (30.48cm). The free-stream velocity at test section can reach up to 48.8 m/s. A standard airfoil of chord length 100 mm can be tested at a maximum Re of up to 300000. However, placing the airfoil at the test section introduces solid blockage and significantly increases the velocity and hence increasing the Re. The velocity can be corrected after placing the airfoil by the giving equations 4.13 and 4.14 [42]:

\[
V = V_U \left(1 + \varepsilon^{ch}\right)
\]

\[
\varepsilon^{ch} = \frac{k_1 (m_{\nu})}{\frac{3}{csa} \bar{c}}
\]
Where $V_u$ is uncorrected free-stream velocity (m/s), $\varepsilon_{sb}$ solid blockage correction factor, $K_1$ is wind-tunnel correction constant for solid blockage effects (0.74), $M_v$ is model volume ($m^3$) and $csa$ is the cross-sectional area of the wind tunnel test section. The schematic of wind tunnel is shown in Fig. 4.2 below.

**Figure 4.2. Schematic of wind tunnel**

### 4.2.1.2 Dynamometer

The dynamometer is a two component force balance that measures lift and drag forces. It is arranged to mount on the external floor of the test section. Forces generated by the model under test are conveyed to the dynamometer via a stiff strut resulting in the deflection of the beam assemblies. These deflections are proportional (within range) to the magnitude of the applied forces. It can take force reading to 0.01 N resolutions. Before taking the readings the dynamometer must be calibrated. The dynamometer is shown in Fig. 4.8.

### 4.2.1.3 Micro-manometer

The FCO510 Micro-manometer is a microprocessor-based precision measuring instrument for low-range differential pressures. In addition, through its unique features and advanced software, it can display air velocity, volume flow, temperature and absolute pressure on its large dot matrix backlit liquid crystal display. This Micro-manometer comprises a highly sensitive low-range differential pressure transducer capable of resolution down to 0.001 Pa. The instrument displays
the pressure in one of 12 different measuring units as selected from the menu. The picture of the Micro-manometer is shown in Fig. 4.7.

4.2.2 Blade Design and Turbine Operation Parameters

The basic hydrodynamic design parameters for HATCT include diameter, pitch, twist and chord distributions across the blade span, the stall characteristics, choice or design of blade section and also prediction of occurrence of cavitation at individual blade sections at different operating conditions. This design is further complicated by changing tidal current velocity, shear profile of tidal flow and changing water depths.

Most of the design conditions are similar to wind turbines, but there are some differences in its design and operating conditions; these include, Reynolds number, density of water is about 830 times compared to air, low flow speed and TSR, tidal current does not usually exceed 3.5 – 4 m/s for most of the locations and HATCT usually have low TSR usually between 4-6 to reduce cavitation inception. Also blade performance significantly reduces at higher TSR, if it is bio-fouled. The twist and chord distributions of HATCT are also different from wind turbines. The blade loading and performance can be predicted using BEM theory; however cavitation criteria must be predicted in 2-D design stage. For analyzing 2-D section characteristics and predicting cavitation criteria Xfoil was used [27]. Cavitation inception occurs on the section when the local pressure on the section falls below the vapour pressure of the fluid, and can be predicted from the pressure distribution on hydrofoil surface with cavitation number $\sigma$ [43]. The cavitation number is defined as:

$$\sigma = \frac{p_o - p_v}{0.5 \rho V_r^2} = \frac{P_{AT} + \rho gh - p_v}{0.5 \rho V_r^2}$$

Where $P_o$ is the local pressure on the hydrofoil surface and, $h$ is the local immersion depth of the individual blade section; the sea water property was taken salinity of 32ppt and temperature of 40°C, it is assumed that temperature of sea water will not go above 40°C. Cavitation will occur if $P_L$ is greater than $P_v$, or the minimum negative pressure coefficient – $C_p$ is greater than $\sigma$ or $C_P$ is greater than $C_P$ critical ($C_{PCrit}$), $C_{PCrit}$ is - $\sigma$. The chances of cavitation occurring on the blade
section increase towards the tip of the turbine blade due to the low immersion depth of the tip and the highest relative velocity experienced at the blade tip. Higher free-stream velocity is experienced near the sea water surface compared to seabed shear profile of tidal current; also the temperature of sea water is higher at the surface. Higher seawater temperature is expected in hot countries like Fiji and other South Pacific countries throughout the year.

The turbine rotor diameter is chosen as 10 m, it has 3 blades; 3-bladed turbines are stable and do not cause much vibration, hence reducing fatigue failures [23]. Also 3-bladed turbines can have lower TSR ratios giving the advantage of reduced chance of cavitation inception. Each blade is 4m; the hub and the connection to blade is 2m. The curve CD in Fig. 4.11 represents the chord distribution for the HATCT blade, the curve is similar to that produced using a Genetic algorithm code[40]. The rated tidal current speed is 2 m/s, but the turbine is designed to operate in tidal current velocity ranging from 1 m/s – 3 m/s, maximum speed of 3m/s is chosen, so turbine could operate in unpredictable conditions.

The operational TSR is chosen as 4, the TSR of tidal current turbines are always lower - usually between 4 – 6 [19, 27, 36, 40, 44, 45]. Lower TSR is preferable for HATCT to delay the cavitation inception in turbine blade. The tidal current measurements completed and currently being carried out in Fiji waters at average depths around 30 m; for the turbine design the last 25% of the total depth from the seabed is left out, since the tidal current velocity is lower at the seabed and the flow is highly turbulent. A clearance of 7 m is given from sea surface for large wave clearance and clearance for speed boats passing through the way. Therefore a turbine with diameter 10 – 12 m is appropriate for this depth, hence 10 m diameter was chosen.

The Re variations along the turbine blade for different tidal current velocity are shown in Fig. 4.3. The Re for tidal current speed of 1 m/s is between 1x10^6 and 1.2x10^6 for speed of 2 m/s the Re is between 2x10^6 and 2.4x10^6 and speed of 3 m/s the Re is between 3x10^6 and 3.5x10^6.
For the cavitation criteria, the $C_{PCrit}$ at different blade locations and tidal current velocities were determined. The $C_{PCrit}$ at locations on the blade 0.6 to 1 of $r/R$ and for tidal current velocities of 2 m/s, 2.5 m/s and 3 m/s are shown in Fig. 4.4. 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 cavitation cannot occur at these velocities, but once the tidal current velocity increases above 2 m/s the chances of cavitation increase from $r/R$ of 0.6 to the tip. The cavitation may occur for tidal current speed of 2 m/s on the last 10% of the blade if the minimum $C_p$ drops below -4. The minimum $C_p$ should not fall below -2.7 for the last 10% of the blade for tidal speed of 2.5 m/s and $C_p$ should fall below – 1.8 for last 10% of the blade for tidal speed of 3 m/s. For these cases, it is necessary to pitch the blade to avoid cavitation.
4.2.3. Designing of a Hydrofoil

Hydrodynamic design parameters for hydrofoil include studying the pressure distribution on the hydrofoil surface, study of minimum coefficient of pressure ($C_p$), coefficient of lift ($C_L$), coefficient of drag ($C_D$), and lift to drag ratio (L/D). Further design parameters include pitch, twist, and taper distribution of the blade and the performance characteristics on a rotating blade. The hydrodynamic design is further complicated due to non-uniform speed and direction of the current, the shear profile in the tidal flow, and the influence of water depth and the free surface. To study the section performance of the hydrofoil, the 2D panel code Xfoil was used. A challenge in designing hydrofoils is to avoid cavitation, while maintaining higher L/D ratio and delayed stall characteristic for HATCT. Delayed stall is important since turbulence and higher relative velocity at different angles can be experienced on rotating turbine.

To make the HATCT perform well over a wide range of conditions, a wide range of high $C_L$ is needed, with delayed separation and stall. For better efficiency of the HATCT, a lower $C_D$ is required. For structural requirements, a thick section near the root is needed. For the case of marine current turbines it is important to have a section profile such that cavitation inception is...
delayed. This is achieved by having a lower minimum suction pressure i.e. $C_P$ should be higher than $C_{P\text{crit}}$ or $-\sigma$.

Airfoils are mostly used as blade sections for HATCT - either they are modified or without any modification. Some of airfoils used as hydrofoils are from NACA 44XX series\cite{46}, Risø - A1-XX \cite{40}, NACA 63-2XX, NACA 63-8XX \cite{27}, NACA 63-4XX series \cite{42}, NACA 00XX series\cite{48, 49}, FX631XX series \cite{50}, S8XX\cite{44, 45}. For the present design of blade sections of 10m HATCT, the characteristic of these hydrofoils and airfoils were studied - also including the airfoil sections from NACA 44XX, 63-2XX, 63-4XX and NACA63-8XX, FX631XX, Risø - A1-XX, Eppler e1XX, e2XX and e3XX series, Selig S8XX, S12XX, S20XX, S30XX, S40XX, S70XX and S80XX series, Selig/Donovan series Sd20XXseries, Sd80XXseries, Martin Herpperle series MhXX series. The 2-D section analysis was done using Xfoil, the ones which showed good characteristics and that can be used as hydrofoils for HATCT were chosen and modified by changing their nose radius, maximum camber and maximum thickness to improve their hydrodynamic characteristics, the main focus was to increase L/D ratio and reduce the maximum suction peak.

The blade sections were designed for different blade locations from these modified sections. Around 70 - 80\% of the power is extracted from the outer half of the blade, therefore thinner hydrofoils with good hydrodynamic characteristics are used for this section and thicker hydrofoils are used for sections near the root to provide strength to the blade. The hydrofoils for different sections were designed from existing S1210 airfoil by modifying the maximum camber and maximum thickness. The camber thickness was increased to increase the blade strength and camber was increased to improve the hydrodynamic characteristics of hydrofoils. It was found that increasing the camber and maximum thickness for S1210 reduces the minimum suction pressure and increases $C_L$ and L/D. The hydrofoil profiles are shown in Fig. 4.5 and the maximum thickness and the names are given in table 4.1.
Table 4.1 Hydrofoils designed for different sections of the blade, and their maximum thickness and maximum camber.

<table>
<thead>
<tr>
<th>Turbine Section r/R</th>
<th>Hydrofoil</th>
<th>Maximum Thickness t/c (%)</th>
<th>Maximum Camber (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>HF1024</td>
<td>24</td>
<td>10</td>
</tr>
<tr>
<td>0.4</td>
<td>HF1022</td>
<td>22</td>
<td>10</td>
</tr>
<tr>
<td>0.6</td>
<td>HF1020</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>0.8</td>
<td>HF1018</td>
<td>18</td>
<td>10</td>
</tr>
<tr>
<td>1</td>
<td>HF1016</td>
<td>16</td>
<td>10</td>
</tr>
</tbody>
</table>

Figure 4.5. Hydrofoils for the HATCT
A thick hydrofoil of maximum thickness 24% and maximum camber of 10% was designed for the root region; it is named as HF1024. Maximum thickness of hydrofoil varied linearly from the root to the tip for easier surface merging. For the blade tip a thinner hydrofoil was designed, it has a maximum thickness of 16% and a maximum camber of 10%. This hydrofoil is named as HF1016. Thin hydrofoils have good hydrodynamic characteristics which are necessary for tip to mid section of the blade. All the hydrofoils have maximum camber of 10%. The HF1018 has a maximum thickness of 18%, similarly HF1020 has a maximum thickness of 20% and HF1022 has a maximum thickness of 22%. The hydrofoils HF1016, HF1018, HF1020 and HF1022 were designed to give higher $C_L$ and $L/D$ for wide range of AOA. A thick hydrofoil HF1024 was designed for the root region, as described earlier, to give strength to the hub to blade connection.

4.3.2.1. Experimentation

Hydrofoil HF1020 was fabricated for experimentation and pressure taps were placed on top and bottom surfaces to record the local pressure on hydrofoil surface. Fig. 4.6 shows the pressure tap locations on the hydrofoil surface, 18 pressure taps on the top surface and 19 pressure taps on the bottom surface. The fabricated hydrofoil has a chord of 100 mm and a span of 300 mm. The hydrofoil was placed in the test section touching both ends of test section to avoid 3-D flow.

![Pressure Taps](https://example.com/pressure-taps.png)

**Figure 4.6.** Hydrofoil HF1020 showing location of pressure taps.

The hydrofoil was tested in an Engineering Laboratory Design (ELD) Inc., low speed open circuit wind tunnel at a Re of 190000 at an air velocity 30.53 m/s; equivalent to tidal current velocity of 2 m/s. Air-flows with velocities below 100 m/s are considered to be incompressible and if the free-stream velocity in the wind tunnel does not exceeds 50 m/s, the flow is always
considered as incompressible flow. The fabricated hydrofoil to record pressure distribution and the experimental setup for measuring the pressure distribution are shown in Fig. 4.7. The Coefficient of pressure ($C_P$) was calculated for $6^\circ$ and $10^\circ$ angles of attack (AOA, $\alpha$) using pressure readings taken from the pressure taps.

![Image of hydrofoil and experimental setup]

**Figure 4.7.** The fabricated hydrofoils and experimental setup for pressure distribution test.

Solid blockage caused by the walls of the test section increases the flow velocity in the test section. The solid blockage was corrected using the equations 4.13 and 4.14.

Another model of HF1020 hydrofoil was fabricated to measure the lift and drag forces, the hydrofoil and experimental setup for the lift and drag measurements are shown in Fig. 4.8. The hydrofoil has a clearance of less than 1 mm from both the walls of the test section to avoid 3-D flow and at the same time to avoid the hydrofoils from touching the walls of the test section. Hydrofoil was mounted on the dynamometer which gives the Lift and Drag forces caused by the hydrofoil. Lift and drag were measure for Re of 190000 equivalent to tidal current velocity of 2m/s and angles of attack from $0^\circ$ to $16^\circ$ at intervals of $2^\circ$. 
4.3.2.2. Computational fluid dynamic (CFD) studies

CFD analysis was carried for HF1020 hydrofoil to compare the computational results with experimental and Xfoil results. The hydrofoil’s geometry and the far field were created in Unigraphics (NX4); the chord length was 100 mm and the far field was 1250 mm in front of hydrofoil and 2000 mm behind the hydrofoil. The chosen far field was large to avoid any solid blockage effects. The geometry was imported in Ansys ICEM-CFD for meshing. Very fine meshing was done close to the hydrofoil and coarse meshing was done away from the hydrofoil; the geometry and meshing are shown in Fig. 4.9.
The mesh was then converted to unstructured mesh and the mesh and the geometry were imported to Ansys-CFX for fluid-dynamic analysis. The boundary conditions (shown in Fig. 4.10) set were as follows: for the inlet; boundary type was inlet, inlet flow velocity was set at 2m/s for Re 190,000 and 21.07m/s for Re 2000,000, velocities were at relative flow angle reference to angle of attack for hydrofoil; the working fluid was water at 25°C. The exit boundary type was outlet and reference pressure at the outlet was set to zero. On the top and bottom, the boundary types were ‘wall’ with no slip boundary condition. The boundary types for Wall 1 and Wall 2 were also ‘wall’ with free slip condition. On the Hydrofoil, the boundary type was wall and no slip boundary condition. Other conditions for the Domain were: the free-stream turbulence was 1%; maximum iterations 1000. For convergence, residual type of RMS and the residual target value of $1 \times 10^{-6}$ were set as the criteria.
Figure 4.10. The boundary conditions around the hydrofoil and in the far field for CFX computations.

The CCL (expression for solver) are as follows: AOA = 6° – this was varied for difference solving, U\(\infty\) (inlet velocity) = 2 m/s – for Re 190,000 and 21.07 m/s for Re 2000,000.

The CFD analysis were done for Re of 190,000 to compare with experimental results and at Re 2000,000 which is average Re on the blade section under actual operating conditions, these results were compared with XFOil results. The values of C\(P\), C\(L\) and C\(D\) were computed at AOA between 0° to 16°.

4.2.3. Turbine design

4.2.3.1. Hub Design

The hub size frequently used for HATCT is 20% of the turbine diameter, as recommended in references [51] and [52]. The hub holds the blades rigidly and firmly during rotation, this means
that blades cannot move in flap-wise or edgewise direction. There is usually teetering between
the hub and the blade to pitch the blade at different angles. The picture of the hub is shown in
Fig. 4.15.

4.2.3.1. Blade Design

Chord distribution

Equation 2.20 is mostly used for calculating the chord distribution of wind turbine blades, but for
tidal turbines the chord distribution is normally modified to have lower blade TSR and also to
increase blade strength for the extreme sea conditions. The chord distribution was studied for
various HATCT which are shown in Fig. 4.11. The curves represent the chord distribution - CD1
is the chord distribution that was used to model Contra-Rotating Marine Current Turbine[45]; the
turbine diameter was 0.81 m and was designed to operate at a TSR of 6. CD2 is the chord
distribution that was used for 20 m HATCT rotor, a model 800 mm rotor was designed,
manufactured and tested in towing tank and the model performance used to predict the
performance of 20 m rotor other details are available in ref [19]. Both turbine uses linear twist
distribution, a similar linear chord distribution was used in ref [53] a 0.7 m diameter model
turbine was constructed and tested in towing tank. Another model of 11 m rotor has linear chord
distribution is presented in ref [44] a 1.5 m model turbine was constructed and tested in towing
tank at the velocity of 2 m/s.

Many turbines have linear chord distribution which is preferable for manufacturing point of
view. However a best design for higher rotor performance, the chord distribution follows
hyperbolic curve. The chord distribution curves optimized by Genetic algorithm (GA) code for
best optimized rotor performance are presented in ref [40] and are shown in Fig. 4.11. CD4 is
chord distribution was used for Verdant power 35 KW Gen4 turbine and was verified with GA
code. The same GA code was used to optimize chord distribution curve for Risø and NACA
hydrofoil rotor, CD4 is chord distribution for NACA 44XX hydrofoil 5 m diameter rotor and
CD5 is the chord distribution for Risø - A1-XX hydrofoil. A similar chord distribution but
slightly modified was produced for 10 m HATCT with HF10XX hydrofoil blade sections, Chord
distribution was produced taking into account the Re at different section and variation in
cavitation number, the curve CD represent chord distribution is shown in Fig. 4.11.
Figure 4.11. Chord distributions for various HATCT

Figure 4.12. The chord distribution of blade

**Twist distribution**

The angle between rotating plane and blade $\varphi$ always change with variable TSR and free-stream velocity, but there is large variation in $\varphi$ in along the blade length, this result in large variation in angle of attack for an untwisted blade. The blade twist is calculation for one optimum condition for which the angle of attack for hydrofoils along the blade is almost constant. The twist distribution was optimized for 10 m HATCT blade to give the best performance under its
operating contestations. The optimized twist distribution curve is shown in Fig. 4.13 and the picture is shown in Fig. 4.14.

**Figure 4.13.** Optimized twist distribution for 10 m HATCT.

**Tip vane**

Tip vanes are mostly used for HATCT turbines to reduce the tip losses on the blade tips. The types of tip vanes used are shown in Fig. 2.11. The tip vane “straight trailing edge” was used for the blade tip as shown in the Fig. 4.15.
**Turbine Geometry**

The geometry of the 10 m HATCT and the parts are shown in the Fig. 4.15 below.

![Turbine Geometry Diagram](image)

**Figure 4.15.** Geometry of 3 bladed, 10 m tidal current turbine rotor

### 4.4. Results, Analysis and Discussion

#### 4.4.1 Hydrodynamics of Blade Section

##### 4.4.1.1. Comparison of Hydrofoil Characteristics Obtained with Ansys-CFX, XFOil and Experiments

Xfoil is frequently used to predict hydrodynamic characteristics of hydrofoils. Hydrofoils normally operate at very high Re such that experimentally testing the characteristics becomes difficult. Multiple testings need to be done and results need to be analysed for experimental and Ansys-CFX which takes longer time compared to Xfoil. However numerical results need to be validated with experimental results. The Xfoil results of pressure distribution and $C_L$ for HF1020 were validated with Experimental and Ansys-CFX. Figs. 4.16 and 4.17 shows the $C_P$ plot at 6° and 10° AOA, and of Re 190,000 (0.19M, also represented as 0.19M in the graphs) and Re 2,000,000 (2M, also represented as 2M in the graphs). Looking at the $C_P$ plot it shows good agreement between Xfoil, Experimental and Ansys-CFX results at Re of 0.19M for both the AOA, however, the minimum suction peak predicted by CFX is slightly lower compared to
experiments and Xfoil results at both the AOA. For Re of 2M both Xfoil and CFX follows the similar trend to that at Re 0.19M, there is good agreement between XFOIL and CFX for 6° and 10° AOA.

The graphs in Fig. 4.18 compares the Xfoil results of $C_L$ with Ansys-CFX and experimental, for HF1020 at AOA, and for Re of 0.19M and 2M. There is good agreement between Xfoil and experimental results at Re 0.19M, however $C_L$ slightly underpredicted by CFX. Similar treads is seen for $C_L$ values at Re of 2,000,000. Both the results pressure distribution and $C_L$ shows good agreement between Xfoil, experiment and CFX for Re 0.19M and also for higher Re, that is for Re 2M, the graphs at Re of 2M follows similar trend to that of Re of 0.19M. Therefore Xfoil can be used to predict hydrofoils hydrodynamic characteristics at higher Re, Re is always higher for tidal current turbines.

![Figure 4.16. Graphs of pressure distribution for Re 190,000 and Re 2,000,000 for 6° angle of attack.](image-url)
Figure 4.17. Graphs of pressure distribution for Re 190,000 and Re 2,000,000 for 10° angle of attack.

Figure 4.18. The $C_L$ values for HF1020 at different angles of attack for Re 190,000 and 2,000,000.
4.4.1.2 Hydrodynamic Characteristics of Hydrofoils HF10XX

The hydrodynamic characteristics of HF10XX hydrofoil series at Re = 2M were obtained from Xfoil. The average Re is around 2M at turbine operating condition. The most important characteristic that needs to be looked at is the turbine design stage that are $C_{p_{\text{min}}}$ to see the cavitation criteria, $C_L$ and L/D for the efficiency point of view. Before the characteristics of any hydrofoils can be compared, a optimum AOA for each hydrofoils needs to be determined. The optimum AOA is usually determined using drag polar of $C_L$ and $C_D$. Cavitation criteria also needs to be considered while choosing the optimum AOA, there should not be occurrence of cavitation at hydrofoil operation at optimum AOA.

The drag polar of $C_L$ and $C_D$ for hydrofoils HF10XX series are shown in Fig. 4.19 were used to choose the optimum AOA for hydrofoils HF10XX series. There should be good balance between $C_L$ and $C_D$, so the L/D ratio will be higher at the optimum AOA. From the drag polar the optimum AOA for HF10XX series hydrofoil is around 12°. The drag polar shows increasing $C_L$ with small increase in $C_D$ from 0 -12 degrees, and there is large increase in drag after 12° and slight increase in drag, but taking into account for variation in tidal current velocity and direction, also turbulence flow in tidal current passage can alter the local AOA of hydrofoil, for these case the actual optimum AOA are always few degrees below this point. Therefore the optimum operation angle of attack for hydrofoils HF10XXX can be around 9°.
The graphs in Fig. 4.20 show the values of $C_{P_{\text{min}}}$ for all the designed blade sections at different AOA. The $C_{P_{\text{min}}}$ plot at different AOA are important to determine the cavitation criteria of hydrofoils for various operating conditions. Cavitation prediction is very important at the turbine design stage, because cavitation does structural damage to the blade and significantly reduces the blade performance. The $C_{P_{\text{min}}}$ of blade sections are compared with $C_{P_{\text{crit}}}$, the $C_{P_{\text{min}}}$ should never fall below $C_{P_{\text{crit}}}$, otherwise there will be cavitation on the blade surface.

The optimum AOA may be altered if there is cavitation inception at optimum AOA under operating conditions. For extreme conditions if the $C_{P_{\text{min}}}$ is below the $C_{P_{\text{crit}}}$ at operating AOA, then blade needs further pitching so local AOA decreases and $C_{p_{\text{min}}}$ increases above the $C_{P_{\text{crit}}}$. The $C_{P_{\text{min}}}$ for hydrofoils HF10XX at Re 2,000,000 and for different AOA are shown in Fig. 4.20. The $C_{P_{\text{min}}}$ at operating AOA of 9° is greater than -2.9 for all the blade sections that were designed. Comparing this with $C_{p_{\text{crit}}}$ from Fig. 4.4, for tidal current velocities of 2 m/s and below the $C_{p_{\text{crit}}}$ is above -4.2; this indicates that there will not be any cavitation inception on the surface of the blade sections at tidal current velocities of 2 m/s and below. However, there can be cavitation inception for tidal current velocities above 2 m/s. If the operating AOA is 9° for 2 m/s,
the turbine blade needs to be slightly pitched, so the local AOA of hydrofoils are below 9° and hence increasing the minimum $C_p$.

Figure 4.20. The minimum coefficient of pressure for hydrofoils HF10XX at Re 2,000,000.

Lift plays a significant role for HATCT, the torque on the rotating blade is a component of the lift force, and the rotor power is proportional to the torque. It is very complicated to control or determine the component of lift force contributing towards the torque force for blade operating under changing flow condition. Therefore, the overall focus is to increase the lift force and reduce the drag force, maintaining a high lift/drag (L/D) – as high as possible, especially for the outer half of the blade, because this part of the blade contributes 70-80% of the total power developed by the rotor. The $C_L$ for hydrofoils HF10XX at different angles of attack and for Re of 2 million is shown in Fig. 4.21. All the HF10XX series hydrofoils have higher $C_L$ values over a wide range of AOA.

All the hydrofoils HF10XX have high $C_L$ at optimum AOA of 9°; hydrofoils HF1019 to HF116, which are used from $r/R$ of 0.5 to 1 have $C_L$ values around 2.0 at 9°. The $C_L$ slightly decreases for
hydrofoils near the root which are around 1.8 – 1.9 for hydrofoils HF1020 – HF1023 and 1.6 for HF1024. The hydrofoils used near the root are thick to provide enough strength to the blade structure, large tangential force is experienced when the turbine operates in extreme conditions, therefore root sections are designed to have higher strength to operate at extreme conditions. The maximum strength is required right at the root of the blade, at the blade to hub connection, because maximum stress is concentrated at this point. HF1024 has the maximum thickness of 24%, it is mainly designed to sustain the hydrodynamic forces on the blade to hub joint. All the blade sections have higher $C_L$ even at lower AOA. Therefore pitching blade at tidal current velocity above 2 m/s will still give the rotor good efficiency. The $C_L$ is above 1 for AOA between 0 – 9 for hydrofoils HF1016 – HF1019, around 0.9 for hydrofoils HF1020 – HF1023 and around 0.8 for HF1024.

![Graph](image)

**Figure 4.21.** The $C_L$ values for HF10XX series at different angles of attack for Re 2,000,000.

Lift to drag L/D ratio is very important in design of HATCT, for good performance of the turbine, the L/D ratio of hydrofoils are always maximized for better turbine performance. The graph on Fig. 2.7 shows that turbine performance is significantly reduced when L/D gets lower. The hydrofoils must have higher L/D for a wide range of AOA so the rotor performance is not
affected in changing tidal flow and turbine operating conditions. The L/D ratios for all the hydrofoils at different AOA are shown in Fig. 4.22. At the operational AOA of 9°, the L/D is between 100 – 130 for all the hydrofoils except for HF1024 which is around 90. The L/D is higher even for lower AOA; at AOA between 1° to 9° it is around 90 -100 for all hydrofoils except for HF1024 which is around 75. Therefore, these sections will have good performance when the blade is pitched at tidal velocity above 2 m/s to reduce the local AOA of hydrofoils.

![Figure 4.22](image.png)

**Figure 4.22.** The L/D ratio for HF10XX series at different angles of attack for Re 2,000,000.

### 4.4.1.3 Contours of Turbulence Kinetic Energy for HF1020

The contours of turbulent kinetic energy obtained with Ansys-CFX were plotted; these plots basically show the level of turbulent kinetic energy in the fluid flow over the hydrofoil surface.
The turbulent kinetic energy per unit mass was estimated using the relation

$$T.K.E. = \frac{1}{2}(u'^2 + v'^2)$$

The rise in the turbulence level, the approximate location of transition and the location of flow separation from the surface can be determined from these contours. The flow separates from the upper surface if the flow does not have enough mean kinetic energy to overcome the adverse pressure gradient. If the flow has high mean kinetic energy from the leading edge to the trailing edge, the flow will remain attached till the trailing edge, whereas if the mean kinetic is less, the flow will separate.

Flow separation from the upper surface of the hydrofoil affects the blade performance. If the $C_{p_{\text{min}}}$ increases too much at upper surface near the leading edge of hydrofoil, then the flow does not have enough kinetic energy to withstand the high pressure after passing $C_{p_{\text{min}}}$ and as a result the flow separates. Early flow separation creates thicker wake region at the back of the hydrofoil, which results in high pressure drag. The point of flow separation will move towards the leading edge as AOA is increased, but if there is early separation at optimum AOA then the flow separation can be delayed by shifting the transition point more towards the leading edge. Transition point can be clearly seen in $C_p$ plot, it is denoted by a kink in $C_p$ curve at the upper surface. When the transition point is shifted towards the leading edge, the flow separation is delayed, this reduces the pressure drag, but usually increases the skin friction drag because turbulent flow has a larger skin friction drag.

Pressure drag is always greater than skin friction drag at higher AOA; therefore, shifting the transition point reduces the overall drag, hence, increasing the L/D ratio. The separation point can be determined from $C_p$ plot or from turbulent kinetic energy plot. If the $C_p$ at the upper surface becomes constant (fails to recover after an initial recovery), it indicates low energy in the flow and flow separation. The separation point can also be seen from Contours of kinetic energy plot, at the separation the energy in the flow will reduce. The contours of kinetics energy HF1020 hydrofoil were obtained using CFX for 6° and 10° at Re of 0.19M and 2M and are...
shown in Figs. 4.23, 4.24, 4.25 and 4.26 to show the separation point. The separation and transition point can also be seen from Cₚ plot, the Cₚ plot for hydrofoil HF1020 at 6° and 10° at Re 0.19M and 2M are shown in Figs. 4.14 and 4.15. From Xfoil Cₚ plot transition point of HF1020 at 6° and Re 0.19M is around 0.4 of X/C but from experimental Cₚ plot the transition point is around 0.42 of X/C, and the flow separates at around 0.85 of X/C. Experiments show slightly delayed flow separation around at 0.9 of X/C, and slightly early separation from contours of turbulence of kinetic energy around 0.85 of X/C.

The transition point shifts towards leading edge when Re is increased for the same AOA, the transition point shifts to 0.35 X/C shown in Cₚ plots obtained with Xfoil and from experiments at 6 degrees at Re 2M. The shifting of transition point results in attached flow till the trailing edge as can be seen in the contours of kinetic energy, however, Cₚ plot of Xfoil shows flow separating at 0.99 of X/C. Both Xfoil and Experimental Cₚ plots show the transition point at 0.35 of X/C at 10° AOA and Re of 0.19M, and also early flow separation at 0.75 of X/C from Xfoil Cₚ plots, flow separates at 0.78 of X/C from experimental Cₚ plots and contours of kinetic energy plot shows flow separating at 0.8 of X/C. For Re of 2M, the transition point was shifted to 0.3 of X/C from Xfoil, and as a result there was attached flow till the trailing edge seen in both Cₚ plots of Xfoil; the contours of turbulent kinetic energy show attached flow till the trailing edge. At higher Re there is always delayed flow separation, therefore L/D ratio is higher at higher Re. Looking at the L/D values for all the other blade section, it can be said that all other sections also have delayed flow separation.
Figure 4.23. Turbulent kinetic energy distribution on HF1020 at 6° AOA and Re of 190,000.

Figure 4.24. Turbulent kinetic energy distribution on HF1020 at 10° AOA and Re of 190,000.
Figure 4.25. Turbulence kinetic energy distribution on HF1020 at 6° AOA and Re of 2,000,000.

Figure 4.26. Turbulence kinetic energy distribution on HF1020 at 10° AOA and Re of 2,000,000.
4.4.1.4. Comparison of Hydrodynamic Characteristics of HF10XX Hydrofoils with other Hydrofoils

Most common hydrofoils used for HATCT are NACA44XX series, NACA63-8XX series and RisØ-A1-XX series. The hydrodynamic characteristics of hydrofoils HF10XX series were compared with NACA44XX series and NACA63-8XX series.

The comparison of $C_{p_{\text{min}}}$ for NACA series and HF10XX series are shown in Fig. 4.27, the optimum AOA for both the NACA series are around 11°, it is 3° degrees below the actual optimum AOA, the actual AOA for NACA series is around 14° which was determined from drag polar of $C_L$ and $C_D$. NACA4415 (used at tip) and NACA4416 (used at mid section) has $C_{p_{\text{min}}}$ at the optimum AOA of around -4 and -3.5, at Re of 2M. NACA 63-812 (used at the tip) and NACA63-817 (used at mid section) are used in 20 m rotor blades, the $C_{p_{\text{min}}}$ for these sections are around -6 to -3.3 at Re of 2M. The $C_{p_{\text{min}}}$ of NACA hydrofoils are lower compared HF1016 and HF1020 which are used in the outer half of the blade. Hydrofoils with lower $C_{p_{\text{min}}}$ will encounter earlier cavitation even at lower tidal current velocities and will affect the rotor performance in changing tidal flow and turbine operation. The $C_L$ was also compared at operational AOA and Re of 2M, for NACA 44XX series; $C_L$ is around 1.5 as shown in Fig. 4.28 and for NACA 63-8XX series $C_L$ is between 1.5 and 1.35. The $C_L$ values of NACA hydrofoils are lower whereas for those of HF10XX are between 1.6 and 2. Similarly the L/D ratio for NACA 44XX is around 95 and for NACA 63-8XX, it is between 40 and 50 as shown in Fig. 4.29, it is lower compared to L/D ratio of hydrofoil HF10XX. Turbine blades sections with lower $C_L$ and L/D usually result in poor hydrodynamic performance.
Figure 4.27. Comparison of minimum coefficient of pressure for HF1016 and HF1020 with other hydrofoils.

Figure 4.28. Comparison of coefficient of lift $C_l$ for HF10XX with other hydrofoils.
4.4.2. Turbine Performance Analysis using BEM Theory

The BEM theory is widely used for predicting theoretical power for HATCT blade rotors at the turbine design stage. It is useful to predict the rotor performance and optimize the taper and twist distribution for best performance. The theoretical power prediction calculated using BEM was validated using experimental results which are presented in ref. [19]. There is a very good agreement between experimental and theoretical power prediction and shows that BEM theory can be used to predict the power for HATCT at the design stage. BEM theory predicts the rotor performance analyzing and matching the blade forces generated by the blade element to the momentum changes occurring in the fluid through the rotor disc. The hydrofoil characteristics $C_L$, $C_D$, turbine geometry such as chord length of individual section, local AOA of sections, and the turbine operating parameters such as $U_o$ and tangential velocity together with water property (water density), were feed into the BEM theory equations given above. The calculations were done to calculate $C_{Po}$ at number of iterations until $a$ and $a'$ converged. The detailed calculation procedure is given in BEM theory manual [54].
A 10m HATCT rotor was designed for rated tidal current velocity of 2 m/s and TSR of 4, the rotor power in KW and efficiency ($C_{PO}$) at different TSR and tidal current velocities were calculated using BEM theory and are shown in the Figs. 4.30 and 4.31. The blade was pitched to 20.75° (the pitch angle is between rotating plane and blade root), for tidal current speeds of 1 m/s, 1.5 m/s and 2 m/s the pitch is actually equal to the maximum twist of the blade at the root. But the blade was further pitched to 24.75° for tidal current speed of 2.5 m/s so the blades local AOA moves further away from cavitation inception. Similarly, the blade needs to be pitched to 28.75° for tidal current velocity of 3 m/s so there is no cavitation inception in extreme conditions.

The maximum theoretical power at the rated tidal current velocity of 2 m/s and TSR of 4 is 150 kW as shown in Fig. 4.31. About 75% of the total power was produced from the outer half of the blade (from r/R of 0.5 to 0.95). The inner half of the blade is thick to provide strength to the blade. The maximum efficiency of the rotor at 2 m/s and at TSR of 4 is 47.56%. The rotor has higher $C_{PO}$ over a wide range of TSR - $C_{PO}$ is around 0.47 for TSR of 3.3 to 4.7, the TSR always fluctuates in actual conditions due to changes in tidal flow patterns and interference of tidal velocity by wave action. Therefore, the turbine must maintain its efficiency for other TSR. This turbine has higher efficiency over a wide range of TSR, therefore, it will perform well in changing conditions. The local AOA at TSR of 4 and Tidal current velocity of 2 m/s is between 7.7 to 9.2, that is between the optimum operational AOA, giving the maximum $C_L$ of around 1.9. For these AOA, $C_{P_{min}}$ is around -2.6 from Fig. 4.20 which is way above $C_{P_{crit}}$ which was - 4.7 from Fig. 4.4. Therefore, there will not be any cavitation at the rated tidal current speed of 2 m/s and TSR of 4.

At the cut-in tidal current speed of 1 m/s, the maximum power output is around 19 KW, and maximum $C_{PO}$ of 0.47 at TSR of 4. The maximum power and $C_{PO}$ increased to 64.6 KW and 0.475 for tidal current speed of 1.5 at TSR of 4 for both the velocities 1 m/s and 1.5 m/s, the local AOA of blade was between 7.7° to 9° that is in the range of optimum AOA for all the blade sections. There is no cavitation inception at tidal current velocities of 1 m/s and 1.5 m/s. At 2.5 m/s the maximum power was around 290 KW and maximum $C_{PO}$ of 0.471 at TSR of 4. The local angle of attack of hydrofoils were slightly lower between 4.5° at the tip and 8.5° at the root, this is because blade was extra pitched to increase the local $C_{P_{min}}$, hence reducing chance of
cavitation. Especially towards the tip of the blade, the local AOA is 4.5 for which $C_{p_{\text{min}}}$ is around -2; it is above the $C_{p_{\text{crit}}}$ which is around -3 from Fig. 4.4. The turbine was designed to operate at extreme sea conditions at maximum or cutoff tidal current speed of 3 m/s. At 3 m/s and TSR of 4 the maximum power achieved was around 475 KW at the efficiency of 44%, the efficiency decreases because of extra pitching of blade. The extra pitching of the blade reduces the local AOA at the tip to be 1.3° for it the minimum $C_p$ is -1.7 it is above the $C_{p_{\text{crit}}}$ which is -2.1. The tidal current speed is not generally predicted to exceed 3 m/s for Fiji. However the turbine is designed to operate at cut off tidal current speed of 3 m/s in unpredictable extreme sea conditions.

The designed rotor has good theoretical efficiency than some of the HATCT rotors presented, A three bladed 20 m diameter rotor designed and presented in reference [52] has the maximum efficiency of 45% at rated tidal current speed of 2 m/s, another 3 bladed 20 m rotor designed and presented in reference [19] has the maximum theoretical efficiency of 45% operating at rated tidal current speed of 2 m/s and TSR of 4. This rotor has similar efficiency to the 3 bladed; 5 m rotor designed and optimized using genetic algorithm which is presented in reference [40], it has maximum efficiency around 47% – 48% operating at rated tidal current velocity of 2.1 m/s.
Figure 4.30. Graphs of coefficient power for HATCT at different tidal current velocities and Tip speed ratios.

Figure 4.31. Graphs of power output for HATCT at different tidal current velocities and Tip speed ratios.
4.5. Summary

Hydrofoils were designed for a 3 bladed, 10 m HATCT blade; they have increasing thickness as from tip to root and are named as HF10XX series. These hydrofoils will meet the turbine operation requirement of superior turbine performance, no cavitation inception at operating velocities of 1 m/s to 3 m/s and provide strength to the blade structure. The initial numerical studies were performed using Xfoil. After Xfoil results for HF1020 were validated with Experimental and Ansys-CFX results. Hydrofoils HF10XX series have good hydrodynamic characteristics, it has higher $C_L$ and L/D ratio for optimum operational AOA between 9° and also at lower AOA, which will give higher performance to the rotor. Also, the hydrofoils have higher $C_{p\min}$ at optimum AOA and also at lower AOA to prevent cavitation at operating velocities between 1 m/s – 3 m/s and TSR of 4. However the blade needs to pitch when turbine is operating at velocities above 2 m/s. The hydrofoils HF10XX hydrodynamic characteristics were compared, and they have better hydrodynamic characteristics compared with other common hydrofoils used for HATCT. The blade chord and twist distributions were optimized for rated tidal current speed of 2 m/s and TSR of 4 using BEM theory. After cavitation criteria was predicted in 2-D section, taking into account $C_{p\min}$ at optimum AOA. The theoretical power for the rotor was calculated using BEM theory. Which is frequently used to predict the theoretical power of HATCT rotors and is already validated with experimental results. The maximum power for rotor at rated tidal current velocity of 2 m/s and TSR of 4 is 150 KW and maximum efficiency is 47.5%. This rotor has better or similar efficiency compared to some of the HATCT already designed for HATCT used for capturing tidal current energy. A theoretically successful rotor has been designed to operate at a wide range of tidal current velocities and operating conditions. Special studies must be done on materials for HATCT; this can solve the problems of performance loss by cavitation erosion, structural blade loading and blade fouling.
5. Conclusion and Future work

Lot of fossil fuel is consumed while meeting the electricity demand for Fiji; tidal current energy is an alternative renewable energy source. If a potential site has tidal current velocity exceeding 2 m/s then HATCT can be installed to extract tidal current energy. HATCT is frequently is the preferred turbine to tap tidal current, current development have made it possible to operate turbines in bi-directional tidal current with good efficiency.

The sites at which tidal current potential surveys were carried out are Wilkes passage, and Gun-barrel passage. Initial measurements were done in many passages in Fiji waters, to see if the location is appropriate for detailed assessment or not. It was difficult to get correct reading from boat, because it moves while taking readings. The average velocity for 3 months at Wilkes passage was around 0.452 m/s. The maximum peaks were between 1-1.5 m/s, the tidal current was strong during ebb tide time for Wilkes passage. The tidal current followed similar trend for all three lunar months. The tidal current is not so strong to place HATCT at this location. Other tidal current energy converter can be placed to extract tidal current energy for these locations. Gun-barrel passage has very good potential for tidal current energy, the maximum peaks exceed 2 m/s for most the days, and average current for 3 months is 0.85 m/s. This passage has both tidal and non-tidal currents, the current is very strong when tidal and non-tidal current are in the same direction. The nature of current at this location is quite different from other tidal streams. Current is very low during low tide, increases as the water level increases and it is maximum at high tide. The current is strong and HATCT can be placed at this location to extract marine current.

A 10 m, 3 bladed HATCT was designed to operate at rated speed of 2 m/s and TSR of 4. Hydrofoils were designed for different parts of blade and hydrofoils are named as HF10XX. The cavitation criteria were predicted for different sections under its operating condition. These blade sections have good hydrodynamic characteristics compared to other common hydrofoils used and section will not encounter cavitation while operating at tidal current velocities of 1 m/s – 3 m/s. The BEM theory is valid, once a cavitation criterion is predicted at 2-D design stage. The twist and taper distribution of the turbine was optimized using BEM theory the rotor performance and efficiency was also predicted using BEM theory. The maximum power at rated
tidal current speed of 2 m/s is 150 KW, and maximum efficiency of 47.5%. This rotor has better theoretical efficiency compared to other rotors designed for HATCT.

Future work that can be done extending this work includes measurement and simulation of tidal current across and along the channel, to estimate the energy flux. Testing the turbine model in actual flow conditions to analyze the actual performance at various speeds can be performed. Simulating water flow in the channel including multiple turbines, to see the effect of blockage and effect of turbine wake can also be carried out in future.

The technology of HATCT is still developing, further research and development needs to be done, before this technology comes for commercial use. Development is required particularly in the area of materials; it can help in problem of cavitation, and the blade strength. Material which prevents erosion of blade from cavitation can prevent the rotor from reducing its performance. Bio-fouling of the blade is also a major problem of the HATCT blade, blade fouling significantly reduces rotor performance, especially when it is operating at higher TSR. Special application of coating on blades to prevent and regular maintenance is needed to prevent this.
Acknowledgement

Funds for carrying out this work were provided by Taiwan/ROC under their Regional Development Assistance for 2009-2010 and the Faculty Research Committee (FSTE FRC) of the University of the South Pacific. Funds for buying the Nortek ADCPs were provided by KOICA under their East-Asia Climate Partnership 2009-2010.
References:


[12] Chapter 9 tides and tidal currents.


[18] Technology Considerations. 2011

Available: http://www.esru.strath.ac.uk/EandE/Web_sites/0304/marine/tech_consider.htm


[41] Burton T, Sharpe D, Jenkins N, Bossanyi E. Wind energy handbook. Wiley; 2000


Available: [http://www.umaine.edu/mecheng/peterson/classes/design/2007_8/project_webs/tidal_test/pdf/Fraenkel%202002%20PIMEa%20%20power%20from%20marine%20turbines.pdf](http://www.umaine.edu/mecheng/peterson/classes/design/2007_8/project_webs/tidal_test/pdf/Fraenkel%202002%20PIMEa%20%20power%20from%20marine%20turbines.pdf)


Available: [http://www.tidalenergyltd.com/technology.htm](http://www.tidalenergyltd.com/technology.htm)


Appendix A: Equations for velocity profile and Pictures of tidal current turbines

For any reference velocity and depth-average velocity is given by [55]:

\[
\bar{u} = \frac{h_2}{h_1} \left[ \int_{h_1}^{h_2} u \, dz \right]^{1/10} = \frac{h_2}{h_1} \left[ \int_{h_1}^{h_2} u_o \left( \frac{z}{z_o} \right)^{1/10} \, dz \right]^{1/10} = u_o \left( \frac{1}{z_o} \right)^{1/10} \frac{10}{11} \left( h_2^{11/10} - h_1^{11/10} \right)
\]

A.1

When the reference velocity is the surface velocity, then:

\[ h_2 = \text{channel depth (D)}, \quad h_1 = 0, \quad z_0 = \text{reference elevation} = h_2 \text{ at the surface and the depth average velocity is:} \]

\[
\bar{u} = \frac{u_o}{D} \left( \frac{1}{D} \right)^{1/10} \left( \frac{10}{11} \right) \left( D^{11/10} - 0^{11/10} \right) = u_o \left( \frac{10}{11} \right) \approx 0.909 u_o
\]

A.2

Since flow power density is proportional to the cube of flow velocity, and then an expression for the depth-averaged power density can be derived in a similar way:

\[
\bar{u^3} = \frac{h_2}{h_1} \left[ \int_{h_1}^{h_2} u^3 \, dz \right]^{1/10} = \frac{h_2}{h_1} \left[ \int_{h_1}^{h_2} u_o^3 \left( \frac{z}{z_o} \right)^{3/10} \, dz \right]^{1/10} = u_o^3 \left( \frac{1}{z_o} \right)^{3/10} \frac{10}{13} \left( h_2^{13/10} - h_1^{13/10} \right) = u_o^3 \left( \frac{10}{13} \right) \approx 0.769 u_o^3
\]

A.3
**Delta Stream turbine**

Figure A1. Delta stream turbine [56].

**Evopod Tidal Turbine**

Figure A2. Evolop tidal turbine [57].
Free Flow Turbines

Figure A4. Free flow turbine [58].

Gorlov Helical Turbine

Figure A4. Gorlov Helical Turbine [59].
**Lunar Energy Tidal Turbine**

![Lunar Energy Tidal Turbine Diagram](image)

*Figure A6. Lunar energy tidal current turbine [60].*

**Neptune Tidal stream Device**

![Neptune Tidal Stream Device Diagram](image)

*Figure A7. Neptune Tidal Stream Device [61].*
Nereus, solon, dual rotor kong turbine and AK-1000 tidal current turbine

Figure A8. Nereus tidal current turbine [62].

Figure A9. Solon tidal current turbine [63].

Figure A10. Ak1000 tidal current turbine [64].
Figure A11. Open center Turbine [65].

SeaFlow and Seagen Marine current turbines

Figure A12. Seaflow tidal current turbine [66].
Figure A13. Seagen Tidal current turbine [67].

TidEl stream Generator

Figure A14. TidEl tidal current turbine [68].
Figure A15. Tidal stream turbine [69].
Appendix B Locations for initial assessments

Figure B.2. Google image of votua passage.

Figure B.3. Google image of Navula passage.
**Figure B.4.** Google image of assessment site near Ngau Island

**Figure B.5.** Google image of assessment location near Dravuni.
Figure B.6. Google image of tidal current measurement sites near Beqa Island

Figure B.7. Google image of cast way passage.