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Review on tidal stream energy and blade designs for tropical site conditions and a look at Philippines' future prospects

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Abstract. Tidal stream energy extraction remains a site-specific resource due to the "first generation" criteria requiring high-velocity tidal streams. Most studies on tidal energy and turbine blade design heavily focus on installation sites with higher velocity conditions that are non-existent in tropical countries such as the Philippines. To shorten this gap, this review paper tackles tidal turbine design considerations for low-energetic regions such as the tropics. In-depth discussions of operating principles, methods of analysis, and designs of tidal turbine blades are presented. Notable tidal stream projects around the world are also mentioned in the paper. Also, it provides a perspective on the potential of this renewable energy to produce electricity for various sites in the Philippines. Finally, the paper emphasizes the need for new tidal turbine blade designs to be viable in tropical regions, such as the Philippines.

Keywords: low energetic flows; ocean renewable energy; tidal turbine representations

1. Introduction

Energy generation has become one of the human necessities since the discovery of electricity during the Industrial Revolution. Since the start of this breakthrough, for the past five decades, the average temperature of the globe has been rising at an unprecedented rate. The rising temperature is primarily attributed to the collection of carbon dioxide and other greenhouse gases in the atmosphere. These greenhouse gases absorb the sunlight and solar radiation that have bounced off the surface of the earth; thus, causing global warming (MacMillan and Turrentine 2021). On a global scale, the major contributor to greenhouse gas emissions is electricity and heat production (Liu 2015). The threat brought by climate change and global warming resulted in interest in research investigating renewable energy generation systems. Countries have started to shift to renewable energy sources such as wind and solar for their electricity production to cut global emissions and provide cheaper

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electricity. However, apart from wind and solar, countries have started looking at another viable source, which is ocean renewable energy (ORE) (U.S. Environmental Protection Agency).

Although ORE is not as technologically mature as other renewable energy sources, using ocean energy has been around for more than a century. It can be harnessed in multiple ways: this can be in the form of tidal energy, wave energy, or ocean thermal energy conversion systems. Among the ORE, tidal energy is considered as the most technologically mature and widely used. Tidal energy can be extracted through tidal range or tidal streams (or currents). Tidal streams utilize the horizontal flow of the water during incoming (flood) and outgoing (ebb) flow to drive the hydrokinetic turbines. On the other hand, tidal ranges rely on the more traditional hydropower principles and require the establishment of dams and barriers. An advantage of tidal energy over other renewable energy sources is its predictability, which is attributed to the predictable nature of ocean tides. The relative motion of the moon and the sun is responsible for the periodic raising and lowering of the surface of the sea, which occurs according to several interacting cycles. The cyclic nature of the rise and fall of the tides makes it easier to predict.

The technological maturity of tidal energy would make it more viable compared to wave energy and ocean thermal energy. Construction of large-scale tidal barrages has proven to be effective in harnessing tidal energy. An example of this is the Sihwa tidal power plant in South Korea which is capable of generating 552.7 GWh of electricity annually (Vikas *et al.* 2016, International Hydropower Association) However, its construction requires large capital investments and brings ecological concerns. An alternative to this is using tidal stream turbines (TST), underwater turbines optimized for their location to maximize kinetic energy extraction from free-flowing water. The most common turbine configuration is the Horizontal-axis tidal turbine (HATT), which is already in the pre-commercial and implementation phase with various developers. However, these devices are still more expensive than other forms of renewable energy (Vikas *et al.* 2016, Encarnacion *et al.* 2019).

The performance of a tidal turbine revolves mainly on the rotor blade's design. The rotor blades are responsible for extracting the kinetic energy from the free-flowing water, and are primarily responsible for the performance, loads and dynamics of the whole turbine system. This crucial step in the design process makes the rotor blades a key component of HATT design (Bir *et al.* 2011). In the wind turbine industry, the Blade Element Momentum Theory (BEMT) has been utilized to design and predict the performance of wind turbine blades. Studies performed by Batten *et al.* (Batten *et al.* 2007, Batten *et al.* 2008) have shown that employing the BEMT in HATT design can also compute the HATT blade performance. The primary difference between the wind turbine and tidal turbine design is the working fluid because water is over eight hundred times denser than air under standard atmospheric conditions. The primary implication of this is the greatly increased kinetic energy density of the flowing fluid, which allows for tidal turbines to be much smaller than wind turbines (Winter 2011). However, this can also have negative implications such as cavitation occurrence and blockage effects.

Most studies related to tidal blade design and simulation are heavily focused on installation sites with high velocity conditions that are non-existent in tropical countries such as the Philippines. At present, there are only a few studies concerned with tidal turbine designs for tropical site conditions, and existing tidal power plants are found mostly in Canada, South Korea, Northern Ireland, Scotland, China, the United States, and the United Kingdom (Chauhan *et al*. 2015). The tidal turbine designs in these existing installations might not be suitable and will perform poorly in the tropical site conditions found in Philippine waters due to the difference in site conditions.

Even though studies have been conducted for the estimated total amount of energy available in various tidal energy harvesting sites, the fraction of that total amount that a HATT blade design could harvest in tidal energy harvesting site has not yet been conducted in detail. Different HATT blade designs extract kinetic energy from the flowing fluid at different rates, making it important to design a HATT blade suitable for the site.

In this review paper, the necessary theoretical background for hydrodynamic modeling and turbine representation are discussed. Related studies that have been reviewed are also presented to gain insight as to the methods and findings of those researchers. The said discussions aim to provide a solid understanding on the theories for the subjects in tidal energy and tidal turbine in general

2. Tidal energy as a renewable energy resource

Tidal energy is currently one of the more preferred forms of ORE because of its predictability, which is attributed to its origins being the astronomical tide generated forces. Despite being predictable, tidal energy still possesses similar features with the majority of renewable resources such as tidal energy being intermittent, diurnal and semi-diurnal, to fortnightly timescales (Neill and Hashemi 2018).

Tidal energy relies on the occurrence of tides on our ocean. Tides primarily occur as a result of the gravitational attraction of the moon and the sun acting on the earth. In the case of Earth-Moon system, both entities revolve around a common center of gravity, which results in the balancing of the gravitational attraction by the outward centrifugal force. However, due to the Earth having a mass that is two times greater than the Moon, the center of gravity of the Earth-Moon system lies 1700 km underneath the surface of the Earth, which has a radius of 6,371 km. This results in slight imbalances between the centrifugal forces and the gravitational forces being experienced by both entities. These slight imbalances, which are responsible for the occurrence of tides, are referred to as tide-generating forces. Another entity responsible for these tide-generating forces is the sun. Despite being considerably farther than the moon, the sun still has a considerable amount of mass that is 27 million times greater than the mass of the moon. This results in the sun having a significant influence on the tides, but its influence is just half of the moon's influence (Neill and Hashemi 2018).

Tidal analysis is often utilized to identify regions of interest for tidal energy extraction. By identifying the type of tides frequent in the region, the feasibility for tidal energy extraction is identified. The extraction of tidal energy can then be done through either tidal range or tidal stream.

2.1 Tidal range

Tidal range is the difference in height between the low and high tides. Tidal range power plants primarily rely on these height difference for electricity production. The difference in height, which is also known as head height, is primarily responsible for the movement of water flowing from a higher water level to a lower water level. This motion is harnessed to produce electricity and the amount of energy produced from motion depends on the height difference of the water levels during the different tidal periods or the velocity of tidal currents (The World Business for Sustainable Development 2008). Thus, it can be said that tidal range power plants use the potential energy created by the difference water levels between low tides and high tides to produce electricity (Kalogirou 2014).

The operating principles for a tidal range power plants are the same to those found in hydropower plants. Wherein, a barrage is installed to act as an obstruction to water flow to obtain a difference in water level between the sides of the power plant and to restrict the flow of water. The head height is used to drive low head turbines. Apart from this, the power plant may also employ the use of sluice gates that are responsible for the filling or emptying of the reservoir (Multon 2011).

Presently, several tidal barrage power plants have been constructed such as the Rance Tidal Power Plant in La Rance, France and the Sihwa Lake Tidal Power Plant in Sihwa Lake, South Korea. The Rance Tidal Powerplant in La Rance (France) and the Lake Sihwa Tidal Power Station in Sihwa Lake (South Korea) tidal barrages generate 254 and 240 MW, respectively. The Rance Tidal Power Plant is known for being the first tidal power plant ever commercialized, and the Lake Sihwa Tidal Power Station is known for currently being the world's largest active power plant.

However, in terms of development, tidal range technology has received less research attention from governments, private entities, and academia. Majority of the research is being focused on tidal stream technology, which is believed to be cheaper and less environmentally invasive (Thomas *et al.* 2016)

2.2 Tidal stream

Tidal stream refers to the horizontal movement of water caused by the continuous rising and falling of the tides. However, unlike the continuous and unidirectional steady horizontal movement of water in streams or rivers, a tidal stream changes its speed, direction and horizontal movement according to the tide generating forces currently acting upon it. Also, unlike tidal range power plants, tidal stream energy generators is a non-barrage tidal scheme that uses the kinetic energy of flowing water to power the turbines (Kalogirou 2014).

The operating principles of tidal stream energy generators has more similarities with wind turbine technology than tidal range technology. Like wind turbines, tidal stream turbines utilize the kinetic energy of moving fluids. The only differences between the two is the form of fluid and its working environment (Winter 2011). Furthermore, due to water being 850 times denser than air, tidal stream turbines do not need to run at high velocities to produce justifiable amounts of energy, and tidal stream turbines are smaller in size because they do not need a large blade to capture as much energy as a wind turbine (Winter 2011).

Another observation is the higher amount of loads experience by tidal turbines. This higher load explains why tidal turbines are often built using advance carbon fiber composite materials compared with the glass fiber used by wind turbines. Furthermore, it can be observed that the power output for tidal turbines is more variable compared to those of wind turbines. This pulsing output is due to the pitch system of tidal turbines being unable to react quickly enough to control the turbine's rotor speeds, unlike the pitch system of the wind turbine which tightly regulates the rotor speeds of wind turbines. However, in the context of operating in a tidal turbine farm, the variations will most likely be averaged out (Winter 2011).

One of the present tidal power generators is the Race Rocks Tidal Power Project, which is the first in-stream tidal power generator, and served as a demonstrator for tidal power using a prototype turbine made by Lester B. Pearson College and EnCana Corporation (Khare and Nema 2018, Zobaa and Bansal 2011). It was installed near Victoria in British Columbia, Canada on September 2006.

The prototype had to be decommissioned so that the water-lubricated bearings could be redesigned and reinstalled. Clean Current Power Systems Incorporated reinstalled the single unit on October 2008 (Fletcher). The joint project ended on September 2011 and turbine generator unit was removed permanently.

The world's first and large scale commercial tidal energy generator is SeaGen (Douglas *et al.* 2008). It was installed in Strangford Narrows between Strangford and Portferry in Northern Island.

Table 1 List of notable Tidal Stream Projects as of 19th February 2020 (European Marine Energy Centre)

Station	Capacity (MW)	Country	Year Commissioned
Bluemill Sound Tidal Stream Array	0.3	United Kingdom	2016
MeyGen	6	United Kingdom	2017
Strangford Lough SeaGen (Decommissioned in 2016)	1.2	United Kingdom	2008
Alderney Tidal Plant	800	United Kingdom	Proposed
Bay of Fundy Tidal Plant	1.2	Canada	Proposed
Gulf of Kutch Project	20	India	Proposed
Mezenskaya Tidal Power Plant	24000	Russia	Proposed
Penzhinskaya Tidal Power Plant	87000	Russia	Proposed
Skerries Tidal Stream Array	10.5	United Kingdom	Proposed

The turbine blades attached to a rigid pillar can be raised and lowered for inspection. At the time of installation, it was reported to be four times more powerful than any tidal power installation in the world (Strain, 2008). SIMEC Atlantis Energy Limited decommissioned SeaGen having provided over 11.6 GWh to UKs national grid since 2008 (Sauser). Table 1 further shows a list of all tidal stream projects, both operational and proposed, as of 19th February 2020 (European Marine Energy Centre).

Despite being less environmentally invasive than tidal range power plants, the site of tidal stream energy generators must still be carefully selected to further minimize its environmental impact. Furthermore, the site for a tidal stream energy generator also dictates the design of the tidal stream turbines to be used. Therefore, it is important to understand the conditions present in the tidal stream sites.

2.3 Tidal stream site conditions

The selection of a tidal stream site is essential to not only maximize the power that can be harnessed but also how that power is distributed to consumers and how the turbine or array of turbine will affect the environment. To address these concerns the following are the factors considered for the selection of tidal stream sites that determine the method of deployment and installation costs (University of Strathclyde Engineering, 2014):

1. Resource potential
2. The local grid structures
3. Environmental impacts.

From these criteria, channels, and constrictions between two land masses seem to be the best locations. Other suitable sites include large headlands that do not interfere with the flow, estuaries, and narrow entrances to lakes (Thake 2005). Grid proximity is also an important aspect to keep in mind. Most areas that fall in the above description are usually remote and have weak transmission infrastructure (Steiner-Dicks 2011). This makes transporting power to a paying customer costlier.

Presently, despite there being significant progress in the research and construction of tidal stream energy generators the technology still faces the challenge of being highly site-specific (Thomas *et al.* 2016). Currently preferred sites are those with peak spring tide velocities exceeding 2.5 m/s and have water depths between 25 and 50 meters (Robins *et al.* 2015). This can be further observed back in Table 1 that illustrates presently operating and proposed tidal stream energy generators are located in temperate waters. The assumption of preferring sites with spring tide velocities with 2.5 m/s and depths of 25 to 50 meters is referred to as “1st generation” criteria. Following this criterion resulted in a calculation of limited available resources with little scope for long-term sustainability for the Irish Sea (Robins *et al.* 2015). The inclusion of sites with 20% lesser velocity and deeper waters resulted in a seven-fold increase of tidal stream resource availability in the Irish Sea (Robins *et al.* 2015).

Furthermore, present studies were particularly focused on far flung areas that are far from areas of peak electricity demand. A review of related literature by Roberts *et al.* (2016) shows that little interest has been given on exploring the potential of tidal projects from more diverse locations closer to the areas of peak electricity demand. A drawback of including low velocity sites is that the tidal resource in such areas is less rich in tidal energy compared to areas with higher velocities.

2.4 Tropical tidal stream

Countries that belong to tropical region have tidal current velocities lower than those existing in the temperate regions. The temperate regions where most operational and proposed tidal stream energy generators are located are known for having a mean spring tidal velocity of 2 m/s or higher (Fraenkel 2006). Meanwhile, the waters in the tropical region are known for having low annual tidal velocities with some areas averaging only 1 – 2 m/s (Looi *et al.* 2013). This can be observed in the São Marcos Bay, Brazil, where the median tidal velocities measure at 1.1 m/s. However, the peak current velocities in São Marcos Bay can reach a range of 2 – 2.5 m/s (González-Gorbeña *et al.* 2015). In the case of the Philippines, the country’s tidal resource is characterized as having flow velocities less than 2 m/s, with some areas even only reaching 1.4 m/s (Encarnacion *et al.* 2019).

Another example of an area with tropical tidal streams is the strait of Malacca, Malaysia. The strait of Malacca is a long international navigation route separating mainland Malaysia and North-West Indonesia. An almost constant current of 1-2 m/s flows through the strait (Ghazvinei *et al.* 2018). Another characteristics of low flow velocities can be seen in the Kuroshio current in Japan. Unlike the periodic tidal currents in the strait of Malacca and São Marcos Bay, the Kuroshio current is a strong marine current in the western North Pacific Ocean. Despite having generally low flow speeds, a marine current has much more continuous and unidirectional flow than those of periodic tidal currents (Shirasawa *et al.* 2016).

The extraction of tidal energy would rely on an appropriate generator whose design would depend on the usable water velocity, tide characteristics and the energy that can be harnessed from the tides in the site (Lam and Chen 2014).

2.5 Tidal stream energy converters (TEC)

Tidal stream energy converters are turbines that rotate in the water flow, providing a mechanical power output that can be converted into electricity. Many utilize similar technologies to those used by the wind industry. The prevalent wind turbine design in use today is a horizontal axis wind turbine mounted on the top of a tall tower. The same type of technology can be used for marine currents; however, the tower would be attached to the sea or riverbed.

Apart from the horizontal axis turbine another viable alternative for marine power is the vertical axis turbine. Various forms of the latter were tested during the early days of wind power development, but as the technology matured the designs were mostly abandoned for the standard horizontal axis turbine design in use today (Breeze 2019).

HATTs are the only tidal energy tech that have been develop on a full-scale and successfully tested in open waters suggesting that HATTs would be the most optimal technology for further development (Sangiuliano 2017).

2.5.1 Horizontal-axis tidal turbines

HATTs often possesses many features similar with horizontal axis wind turbine. A typical device may have a three-bladed rotor mounted on a shaft which drives a generator through a gearbox. Because it operates underwater, all the electrical and mechanical components must be protected in a watertight container.

Although majority of the tidal stream turbines possess three blades, some designs may have two or more blades. These may be of a fixed pitch, which is considered as the simplest design in terms of structure, or these may be of a varying pitch to control rotational speed. However, speed control is generally less critical for tidal stream turbines because the water speeds are much more predictable than wind speeds (Breeze 2019). Fig. 1 below shows a few examples of HATTs.

The rotor blade is the essential element that captures energy from the tide. It primarily dictates the performance, loads, and dynamics of the entire turbine system, regardless of the configuration that is used. Therefore, the HATT's success depends on having an effective blade design.

2.5.2 Vertical-axis tidal turbines

Vertical-axis tidal turbines (VATTs) also harness tidal stream kinetic energy from a rotating mass, but the design of the blades is different due the orientation of their axis of rotation. The blades of a VATT mostly rely on drag to move and do not require as large a footprint as a HATT. As a result, VATTs can produce power from currents coming from any direction. Fig. 2 below shows some examples of VATTs.

2.5.3 Other TECs

A less common TEC uses and oscillating airfoil instead of a rotating turbine (Fig. 3). The airfoil

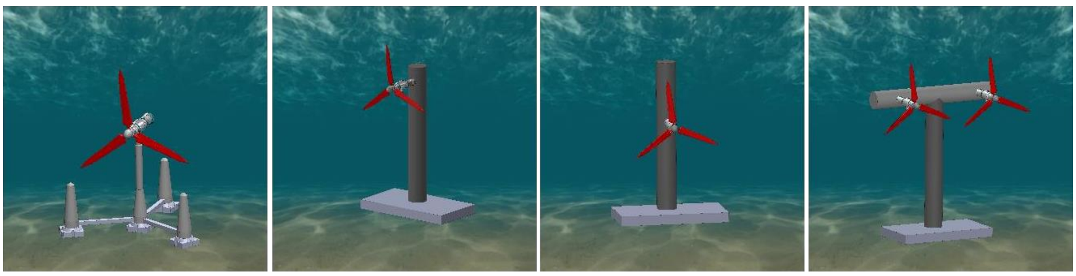

Fig. 1 Examples of Horizontal-Axis Tidal Turbine (a) Piled-Jacket (b) Gravity base (Upper Turbin e) (c) Gravity base (Mid Turbine) (d) Monopole-Supported (Artist impression)

Fig. 2 Vertical Axis Tidal Turbine (a) 4-bladed (b) 3-bladed (Artist impression)

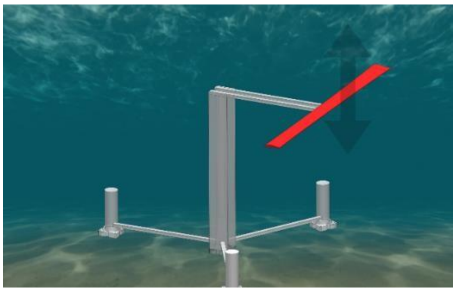

Fig. 3 Oscillating TEC 3D model (Artist impression)

possesses a symmetrical shape and the oscillation is induced by eddies forming behind the airfoil (Farthing). These eddies cause periodic pressure drops on the sides of the airfoil causing it to oscillate.

2.6 Turbine blade design for tropical tidal streams

The design parameters for a turbine are dependent on the conditions identified in the site. The primary research interests in tidal turbine design are performance and reliability of the design, since for tidal turbines to compete with existing traditional energy sources, tidal turbines must show that they are economical, and the costs are justified (Laws and Epps 2016). One of the key issues regarding the design of tidal turbines is the hydrofoil and blade design.

The primary objective of blade design is to maximize its hydrodynamic efficiency by improving the coefficient of lift, while reducing the coefficient of drag and pitching moment (Nachtane *et al*. 2020). The purpose of a hydrodynamic design is to achieve an external blade profile that provides the optimal performance, the likes of having delayed stall, and being cavitation-free. Apart from the hydrodynamic design considerations, another aspect to consider when designing turbine blades is improving the design based on the turbine's working environment. The following are the environmental factors affecting tidal turbines:

1. Cavitation: This is considered to be one of the most limiting factors in hydrofoil selection. The occurrence of cavitation decreases the efficiency of the hydrofoil by the

decreasing lift coefficient and increasing the drag coefficient, resulting in a lower lift-to-drag ratio. Numerous studies are still being conducted to address the issue of cavitation.

2. Biofouling: Another factor is the reaction between the working environment and the blade material. Biofouling causes a degradation of tidal turbine performance because of the surface roughness it causes. The usual solution to this is by applying fouling control coatings.
3. Interaction with stanchion: The performance of the turbine could be affected by the stanchion's geometry and distance from the rotor. A hydrofoil shaped stanchion was found to have an increase of 20% in its power output and a decrease in the total thrust by 35% than with a square shaped stanchion (Harries *et al*. 2014).
4. Wake length: The interaction between tidal turbines installed within close proximities could affect the total amount of electricity generation, thus the resulting wake must be studied (Nuernberg and Tao 2018).

Blade design is primarily facilitated by numerical codes which are usually based on blade element momentum theory (Laws and Epps, 2016). One of these codes is HARP_Opt. HARP_Opt utilizes BEMT and a multi-objective genetic algorithm to maximize annual energy production that could be subjected against constraints such as cavitation (Laws and Epps 2016).

In a review of present developments in the field, Nachtane, et al (Nachtane and 2020), were able to identified that the performance of a tidal turbine is heavily dependent on the selection of an optimal hydrofoil design in the following manner:

- To avoid cavitation, the coefficient of pressure should be lower than the cavitation coefficient. And to achieve higher lift-to-drag ratio, the maximum value for the coefficient of pressure must be lower than 1.77, especially at the leading edge of the TCT blade.
- To avoid the occurrence of stall and separation, the angle of attack must be kept lower than 9^{o}.
- It was observed that the implementation of a double blade hydrofoil may contribute to a higher value of the coefficient of lift than that of a single blade hydrofoil. The implementation of the double blade hydrofoil also increased the maximum coefficient of performance closer to the Betz limit at tip speed ratio of 3.5.

For tropical site conditions, a study conducted by Attukur et *et al*. states that to be viable in lower the tidal streams in tropical regions, HATT blade designs that are already in use need to be modified to improve their efficiency (Attukur Nandagopal and Narasimalu 2020). Meanwhile, Encarnacion *et al.* have presented a methodology for tackling HATT design for low energy (Encarnacion *et al.* 2019). They have found that low-solidity high tip- speed ratio blades had an 8.5% power drop compared to conventional blade designs but reduced the torque requirement by 30% which would reduce the costs from downsizing the needed generator and simplifying power take-off mechanism. From the findings that these researchers above have, the tidal turbine blade geometry would need to be designed with a high tip-speed ratio in mind in order to be viable in tropical regions with lower stream velocities compared to temperate regions.

2.7 Tidal turbine representation

For computers to calculate the different forces acting on and the effects of a free stream energy harvesting turbine it has to be modeled mathematically first. This section presents how tidal turbines

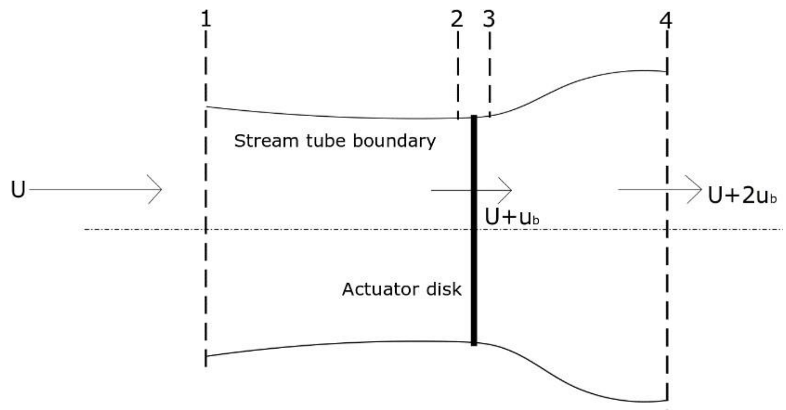

Fig. 4 A visual representation of the Actuator Disk Model

are mathematically modeled and eventually coupled to CFD. Here are well-known methods to represent a turbine: the actuator disc method, blade element momentum theory, and the fully-resolved turbine.

2.7.1 Actuator disc method

The Actuator Disc Method is the least accurate but the most cost-efficient way, in terms of computing requirements, of representing a turbine for CFD simulations. Fig. 4 below illustrates how an actuator disc is represented. The assumptions for the actuator disk method are:

1. An infinitely thin disk making it permeable to fluids.
2. Inviscid, incompressible, and isotropic.
3. Thrust and velocity are uniformly distributed on the disk.
4. Far up and downstream pressure are ambient pressure.
5. Thrust loading is uniform over the disk.

The actuator disk can be thought of as extracting momentum from the incoming fluid, which lowers the kinetic energy of the passing fluid. The extracted momentum is converted into power by taking the difference in kinetic energy fluxes at planes 1 and 4 as shown in Fig. 4 above. The velocity of the passing fluid slows and the pressure directly behind the disc increases due to Bernoulli's principle, which states that the square of the velocity of a flowing fluid is inversely proportional to the pressure it exerts.

The model is implemented by applying the conservation laws of mass, momentum and energy on control volume such as a cylinder with a larger radius compared to the turbine. The thrust T and power P can be calculated using the incoming flow velocity U, the disk radius R and the average inductance u_b.

$$T = -2\pi\rho R^2(U + u_b)u_b \tag{1}$$

$$P = 2\pi\rho R^2(U + u_b)^2 u_b \tag{2}$$

Note that u_b will be positive for a propeller and negative for a turbine. Finally, the thrust and power coefficients are

$$C_t = \frac{2T}{\pi\rho U^2 R^2} = -4\left(1 + \frac{u_b}{U}\right)\frac{u_b}{U} \tag{3}$$

$$C_p = \frac{2P}{\pi\rho U^3 R^2} = -4\left(1 + \frac{u_b}{U}\right)^2 \frac{u_b}{U} \tag{4}$$

The power coefficient represents the efficiency of the turbine, $P_{turbine}/P_{fluid}$. The highest possible value for the coefficient of power Cp_{max} = 16 / 27 = 0.593. This is known as the Lanchester-Betz-Joukowsky limit or simply the Betz limit, which is the theoretical limit on the amount of kinetic energy that can be harvested.

2.7.2 Blade element momentum theory

Blade Element Momentum Theory combines both blade element theory and momentum theory and calculates the local forces on a turbine blade. First developed by Froude then refined by Glauert, this theory considers the angular momentum generated by the fluid-blade interactions. Forces are calculated in segments or elements on the blade. These are represented as annular rings with radius r and radial width -r in the disc as the blades rotate. The forces are calculated with the assumption that they can be calculated with a two-dimensional hydrofoil model based on blade element theory (Burton *et al.* 2011). Fig. 5 below illustrates how BEMT can be used to calculate the blade geometry of a tidal turbine.

a and a' are the axial and tangential flow induction factors. $V_0(1-a)$ can be replaced by the velocity component V_v in the CFD code using the coordinate system shown in Fig. 5(a), then the induction factor a' can be related to V_u and V_W as

$$a' = \sqrt{\frac{{V_u}^2 + {V_W}^2}{\omega r}} \tag{5}$$

The lift and drag forces normal and parallel to the direction of W on a blade element with width δr are

$$\delta L = \frac{1}{2}\rho c W^2 C_l \delta r \tag{6}$$

$$\delta D = \frac{1}{2}\rho c W^2 C_d \delta r \tag{7}$$

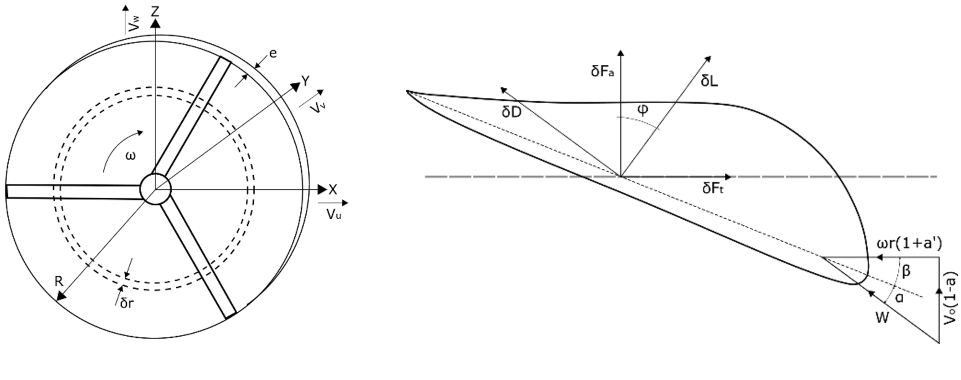

Fig. 5 (a) Disc Model with Blade Element and Regions and (b) Blade Element Velocities and Forces where ρ is the density of water, c is the blade chord at r, C_l and C_d are the lift and drag coefficients as function of the angle of attack a. The axial and tangential forces on a blade element can be calculated for the flow angle 4 in the plane of rotation determined by W from the lift and drag forces as

$$\delta F_a = \delta L \cos\varphi + \delta D \sin\varphi \tag{8}$$

$$\delta F_t = \delta L \sin\varphi - \delta D \cos\varphi \tag{9}$$

Thus, the forces per volume on the disc can be added to the CFD method as axial and tangential momentum source terms S_a and S_t

$$S_a = \frac{Bf_bF_a}{2\pi re\delta r} = \frac{Bf_w\rho cW^2(C_l\cos\varphi + C_d\sin\varphi)}{4\pi re} \tag{10}$$

$$S_t = \frac{Bf_bF_t}{2\pi re\delta r} = \frac{Bf_w\rho cW^2(C_l\sin\varphi - C_d\cos\varphi)}{4\pi re} \tag{11}$$

where B is number of blades, fp is the Prandtl blade tip loss factor.

$$f_p = \frac{2}{\pi}\arccos[\exp\frac{-b(R-r)}{2r\sin\varphi}] \tag{12}$$

Vogel *et al*. have extended BEMT to analytically calculate the blockage effects and static pressure differences using a confined flow BEMT model for both fixed-pitch and pitch-to-feather HATT. Their analytical results were within ±3% of resolved simulations using Reynolds Averaged Navier-Stokes (RANS) model in OpenFoam. They have also found that a pitch-to-feather rotor attained a lower bending moment on the blade's root which leads to a lower fatigue damage rate. (Vogel *et al.* 2018).

Meanwhile, a study by Guo *et al*. (2015) compared the flow field characteristics of a coupled BEM-RANS model to RANS simulations and experimental data on a Horizontal-Axis Tidal Turbine. The study has found that the BEM-CFD results based on the numerical hydrofoil data can accurately predict the thrust but overestimates the power. They have suggested that a more reasonable 2D prediction for the performance of the hydrofoils be considered and that the inclusion of the 3D effects on the hydrofoil would improve the accuracy of the BEM-CFD model.

2.7.3 Fully-resolve turbine

A 3D model is simulated in a fully resolved turbine model and its hydrodynamic forces and flow characteristics using CFD. The parameters applied in the computational domain are the key factors in computing the hydrodynamic performance of the turbine. In the study conducted by Amiri *et al.* (2019), the computational costs were reduced by only solving a subdomain of 1/3 of the computational domain. However, this leads to some errors since the actual flow of ocean waves can be asymmetric. Several turbulence models solve the Navier-Stokes equations depending on the fluid flow characteristics. Some of the standard turbulence models include DNS, LES, and RANS. The DNS computes the exact solution for momentum equations but requires high computational cost and resources. On the other hand, the LES reduces the costs while the RANS model is very low at a cost yet computes accurate, acceptable results.

Another study conducted by Ahmed *et al.* (2017) compares a geometry-resolved full-scale tidal-stream turbine to experimental data from the EMEC test site. The turbulence models used were RANS and LES. It shows that LES with more realistic inflow turbulence simulation produced a spectral distribution of blade bending moments in low- wave conditions. The study also shows that cycle-average power coefficients from RANS and LES are very similar and slightly lower than the experimental power coefficient in low-turbulence situations.

2.8 Tidal stream environmental conditions

Understanding tidal stream environmental conditions is important in the analysis of tidal turbines. Several failures have been reported from the increasing deployment of tidal stream turbines due to flow fluctuations experienced by the turbine (Li and Calisal 2017). Typically, steady flow conditions are used to analyze tidal turbines' performance characteristics and designs (Atcheson *et al.* 2015, Luznik *et al.* 2012). However, at a tidal stream site, the flow developed is characterized by a combination of shear flow, turbulence, and waves, which results in loading variation. Such loading variation is depicted in Fig. 6. With this, it considerably affects turbine operation such as fluctuation in power production and fatigue damage. Also, the blockage significantly affects tidal turbine operation compared to unconfined flow, as it changes the flow conditions (Schluntz and Willden 2015).

2.8.1 Shear flow in open channels

Tidal turbines are subjected to the unsteady and nonuniform environment such as shear flow. In shear flow, momentum is transferred from a high velocity to lower velocity. Eq. (13) shows the apparent shear flow in turbulent flows, where τ is the shear stress, $\partial u/\partial y$ is the velocity gradient, ρ is the fluid density and ν is the eddy viscosity. From the equation, it implies that maximum shearing happens at maximum velocity gradient

$$\tau = \rho\nu\frac{\delta u}{\delta y} \tag{13}$$

An example of the effects of shear flow is the Miyake Island in Japan which is exposed to Kuroshio current; thus a feasible and desirable location for ocean current energy. Acoustic Doppler Current Profile (ADCP) shows that the island experiences shear flow such that in the experiment, the turbine experiences extreme loading for an out-of-plane bending moment - leading to greater fatigue load (Shirasawa *et al*. 2016).

Moreover, it has been shown from an experiment that a tidal turbine in a water channel with shear flow results in greater hydrodynamic performance compared to a uniform flow (Tian *et al*. 2018). However, in the same study, the difference in the coefficient of performance, thrust and power, using CFD for shear and uniform flow is minimal only. Consequently, the study of Yahagi and Takagi (Yahagi and Takagi 2019) shows that the fluctuations in the coefficient of power using a large shear gradient (40%) are apparent compared to a small shear gradient (10%) which shows small fluctuations. Such results also coincide with the study of Ke *et al.* (2020) where a higher shear rate causes severe loading fluctuations. When waves and shear current are present on a turbine's flow conditions, it causes large variations in thrust and power performance (Draycott *et al.* 2019).

2.8.2 Wave-current interaction

In a tidal site, waves propagate due to the energy passing through the water. It is a disturbance which varies depending on the energy source that leads to its formation. Commonly, waves formed due to the wind blowing along the water surfaces called surface waves. The interaction of waves with current causes fluctuations in the extractable power and blade loading, hence, an important consideration for tidal devices' operation. It causes cyclic loading that can impact turbine design, power control, and accelerate fatigue (de Jesus Henriques *et al.* 2014),

A study by Tatum *et al.* (2016) shows that the turbine performance, specifically the average thrust and power, is only affected by a small amount when waves are introduced. In their study, they investigated the effect of surface waves on a tidal turbine's performance, such that there is an approximately 5% increase in the average thrust and approximately 5% decrease in the average power. Such results also agree with another study (Barltrop *et al.* 2007) wherein there is only a minimal difference in the average performance characteristics of tidal turbines experiencing with or without waves. In an idealized setup, it is expected that there are no changes in the mean performance characteristics since the wave motion, back and forth, would just cancel out the forces (Galloway *et al.* 2010). However, significant fluctuations can be observed in the thrust and power performance of turbines as waves are introduced. It induces a large variation in the turbine's thrust and power performance. The presence of waves shows a strong influence on the loading experienced by turbine blades. As the wave height increases, the variation in the performance characteristics also increases (Wolf and Prandle 1999). From the study of Galloway *et al.* (2014), where they investigate the performance characteristics of surface waves and yaw misalignment, fluctuations on the average thrust and torque characteristics between 37% and 35%.

2.8.3 Blockage effects on tidal turbines

Tidal turbines operate in a partially blocked condition such that they are constrained between the seabed and free-surface, unlike wind turbines (Atcheson *et al*. 2015)

Such condition is called blockage, or flow confinement, defined as the ratio of the rotor swept area and the cross-sectional area of the channel (Adcock *et al*. 2021). It is an essential characteristic of a tidal turbine, especially when dealing with array configurations. It significantly affects the power performance of tidal turbines as shown experimentally and numerically, such that as the blockage exceeds 5%, significant changes can be seen in the turbine performance (Schluntz and Willden 2015, Ross and Polagye 2020).

From the Lanchester-Betz-Joukowsky limit, simply Betz limit, the theoretical limit on the amount of kinetic energy that can be harvested by a turbine is 16/27 or 0.593, as proven using the actuator disc method. However, due to blockage, as the flow is bounded by the seabed and free surface, Garrett and Cummins (2007) showed that the said limit needs to be corrected for tidal turbines. The analysis was done using the actuator disc method in a confined flow. In this case, the maximum coefficient of power considering the blockage is shown in Eq. (14), where B is the blockage ratio defined as the ratio of the rotor swept area and the cross- sectional area of the channel.

$$C_{p_{max}} = \frac{16}{27}\left(\frac{1}{1-\beta}\right)^2 \tag{14}$$

It can be seen that the maximum power coefficient decreases by $(1-\beta)^2$ above the Betz limit when blockage effects are considered. It shows that maximum power can be extracted when a great amount of energy is confined. With this, as the blockage ratio increases, the turbine's resistance to bypass flow also increases (Vogel *et al*. 2018). As the flow conditions change due to blockage, it affects turbine performance. Blockage effects increases the spanwise flow along rotor blades and wake turbulence, resulting in an uplift turbine performance. However, in a confined flow, tidal turbines experience higher loadings which need to be considered for structural analysis, since it produces deformations (Ordonez-Sanchez *et al.* 2019).

2.8.4 Cavitation on tidal turbines

HATTs share design features of wind turbines, but the operational condition of HATTs is harsher than that of wind turbines. The factors that significantly affect the performance of a HATT are cavitation, corrosion, and high structural loading. The study on design of HATTs that includes these factors is quite rare than that of wind turbines (Kumar *et al.* 2019).

A critical problem faced by tidal turbines that must be included in the design process is the possibility of cavitation (Attukur Nandagopal and Narasimalu 2020). Fast underwater rotation causes cavitation, which increases vibration and corrosion in long-term operation, thereby degrading the performance of blades and leading to an increase in fatigue loads (Im *et al.* 2020). These loads ultimately affect blade life. In designing HATT blades, it should consider limiting and delaying the inception of cavitation (Thandayutham and Samad 2019). Hydrodynamic pressure decreases when the fluid velocity increases over the HATT hydrofoil and cavitation occurs when the hydrodynamic pressure is less than or equal to the vapor pressure ($Pvap$). This pressure drop forms bubbles that implode on the surface of the blade causing continuous surface fatigue that can affect the blade performance. The critical cavitation number ($Ccrit$) can be expressed as a non-dimensional number

$$C_{crit} = \frac{P_{stat} - P_{vap}}{\frac{1}{2}\rho V_{rel}^2} \tag{15}$$

Cavitation mostly occur near the blade tip, as the relative flow velocity is high near the tip (Attukur Nandagopal and Narasimalu 2020). Since the pressure around the blade surface is proportional to the minimum pressure coefficient (Cp,min) of the 2D blade section of the hydrofoil, the following constraint is to be satisfied to avoid cavitation

$$Ccrit \geq |Cp,min| \tag{16}$$

The above condition ensures that the ambient pressure surrounding the blade does not fall below the vapor pressure of the sea water. Cavitation inception in a tidal turbine can be delayed by carefully choosing the TSR and depth during the initial design phase. At the initial design phase, the design tip speed ratio of the blade is fixed, hence for a given maximum free stream flow speed, the maximum relative flow velocity at the blade tip is fixed. Therefore, for a given TSR and maximum free stream flow speed, cavitation can be delayed only by choosing a proper deployment depth.

A study was performed by Im *et al*. (2020) to minimize such impacts of cavitation. In their study, minimum pressure coefficient was considered at higher flow speeds and locations of cavitation as a part of blade design to minimize cavitation impacts. Another study was done by Nandagopal and Narasimalu (2020) by optimizing a hydrofoil using a gradient-based algorithm to obtain a high lift-to-drag ratio with a reduced likelihood of cavitation. In this study, hydrofoils with maximum CL and CL/CD at low Reynolds number were optimized and used to design a tidal turbine blade with high Annual Energy Production (AEP) with reduced possibility of cavitation.

3. Tidal energy assessments in the Philippines and its prospects for tidal energy

In line with the global trend wherein countries are moving to renewable energy sources, the Philippines has also made strides towards clean and green energy. To further solidify its commitment, the country launched an Energy Reform Agenda in 2011. The Energy Reform Agenda sought to accelerate the country’s exploration and development of renewable energy sources. Presently, a cause of concern for the country is the looming depletion of the Malampaya gas field, which is the only source of natural gas in the country (Bunye 2020). Due to the situation of the Malampaya gas field, finding alternative energy sources is needed. Shown in Table 2, the currently installed renewable energy facilities in the Philippines are solar, wind, hydro, biomass, and geothermal energy facilities (Department of Energy Philippines 2019). Considering that the Philippines is an archipelago consisting of 7,641 islands surrounded by abundant in ORE resources with an estimate of 170,000 MW available from ORE alone (Global Environment Facility and United Nations Development and Department of Energy 2018), studying the potential of these resources must be considered.

Being located in the tropical region, the Philippines is found to have mean spring tidal velocities to reach in the range of 1 to 1.5 m/s, a quarter of the mean spring tidal velocities in the highly energetic regions in the northern and southern hemispheres. Although there are sites such as the San Bernardino Strait with velocities reaching up to 4.5 m/s, the dominant flow in the country is still a low flow speed (Encarnacion *et al.* 2019).

Early estimations of the potential for the available ocean renewable sources in the Philippines combined range from 150 to 170 GW (Abundo *et al.* 2012). However, a more specific study regarding the country's tidal stream potential has been conducted in the Philippines by Abundo *et al.* (2011). The study utilized predictions from National Mapping and Resource Information Authority (NAMRIA) and simulation results from DELFT3D to calculate the energy potential (EP) metric for areas in the Philippines marked as potential sites by the Department of Energy (DOE). These sites are found on areas where the flow of water is constricted by landmasses.

The Philippines, being an archipelagic country, has a good number of sites where the potential of setting up tidal energy conversion systems can be explored. These low tidal velocities would require downscaling of the size of the turbine to accommodate lower cut-in speeds. Various transect and static surveys have been done in the Philippines to measure through acoustic doppler current profiler (ADCP) the tidal velocities on various sites of interests in the country. In its Mindanao group of islands, the Mindanao Renewable Energy R&D Center (MREC) team has conducted ADCP measurements in the Pakiputan Strait between Davao City and Samal Island, Talicud Channel in Davao del Norte, Hinatuan Passage in Surigao del Norte, and Sitangkai-Sibutu Channel in Tawi-Tawi. However, despite its identification as a potential tidal energy harvesting site, hydrodynamic studies of the site and the design of a HATT suitable for the tidal energy harvesting site have yet to be conducted. If present commercial turbines are used, huge proportion of the tidal velocities available in the Philippines would not reach the required cut in speed by the commercial tidal turbines. Turbine blades need to be redesigned to capture the low energetic tidal velocities in the tropical region.

As stated earlier, the Philippines has great potential for ORE due to its large number of islands surrounded by ocean water which makes it ideal for marine energy extraction. With tidal energy being the most mature among other ORE technologies, this would be the most viable renewable energy if ever implemented in the Philippines from an accessibility standpoint compared to other renewable energy sources. Although it is relatively mature compared to other ORE, implementing tidal technology in the Philippines would be very difficult since little progress has been made to design HATTs and to determine their viability in tropical conditions, specifically in the Philippines. Furthermore, a 1.5 MW tidal power plant has already been proposed by H&WB Asia Pacific and Sabella SAS in 2015. Although, no details have been disclosed so far (Cruz 2017).

4. Conclusions

This review paper presents a comprehensive discussion of the operating principles and methods of analysis of tidal energy and turbine blade designs. New insights are introduced on the need for new turbine blade designs to increase the practicality of tidal stream energy technologies, specifically to low energetic waters commonly found in tropical site conditions. Countries in the tropical region, such as the Philippines, are characterized as having low-velocity tidal currents. A tailored-fit tidal turbine must be designed to efficiently exploit the energy from the ocean tides for relatively low-velocity flows. A means to further solidify the commitment to advancing the tidal stream turbine technology needs to be achieved. Extending the applicability of tidal stream energy resource technologies to tropical site conditions, specifically in the Philippines, is one of the steps to aid in meeting the energy demands of a fast-growing economy and contribute to social inclusion by providing affordable and sustainable energy to communities that are either off-grid or have curtailed electricity supplies.

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