A review on the technologies, design considerations and numerical models of tidal current turbines

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Abstract:

Tidal current turbine is one of the innovative and emerging technologies of marine renewable energies because it offers constant and predictable energy source that can be very beneficial, especially for commercial scale production of electrical power. Hydrofoils (HF) are essential elements of tidal current turbine (TCT) and should be properly designed as they play a vital role in improving the turbine output and providing adequate resistance to the blade structure. In connection with the hydrofoil designs, it is noteworthy that the primary objectives in their designs are to increase the coefficient of lift and to reduce the coefficients of drag and pitching moment, thus delaying the cavitation phenomenon. In this paper, the technology developments of the hydrofoil designs used in the horizontal axis TCT industry are reviewed, including the hydrodynamics design and the mechanical structure design. Besides, an up-to-date review and the newest achievements of marine TCT technologies with their developing histories are further explored. Included are also reviews on the numerical models used to assess the performance of TCT and optimization methods applied to design the hydrofoils. This in turn significantly contributes to a better knowledge on the recent designs of TCT hydrofoils for the researchers working in the marine turbine energy domain. Such information could also have important implications in the design of more sophisticated hydrofoils for the exploitation in diverse tidal current energy technologies for reaching a sustainable future.

Keywords: Up-to-date review, Marine renewable energies, Hydrofoil design, Tidal current turbine (TCT), Performance prediction.

1. Introduction

The development of marine renewable energies represents a major opportunity and an attractive alternative to reduce greenhouse gas emissions [1]. The oceans provide a massive source of potential energy resources in the form of fluid flow, thermal gradient, surface waves, and salinity gradients [2]. Extracting energy from tides is not recently developed. There are two systems for harnessing tidal energy which are the kinetic energy of the flowing fluids and the potential energy of the rising water [3]. Tidal current turbine (TCT) is used to recover this energy to overcome the rising energy demand while decreasing the impact on the hydrological ecology [4]. The success of employing tidal turbines to exploit the tidal currents is reliant on predicting their hydrodynamic performance. Several global investigations have confirmed that marine current energy has great potential as a regular, and predictable and clean energy source for power generation, with fewer harmful influences on the environment opposed to tidal barrages [5,6]. In general, three technologies are utilized to convert tidal currents into mechanical energy to produce electricity: horizontal axis turbines, oscillating hydrofoils, and vertical axis turbines [7]. These technologies can be established on the sea bottom, on the surface, or in between. Among these technologies, the horizontal axis turbines are the more developed one and can be utilized to obtain a large quantity of energy from marine currents [8]. Systems for studying the physical and operational parameters of the turbines are required to be installed to upgrade their execution. These advancements are invaluable when contrasted with wind turbine because of negligible infrastructural investment, diminished natural effects and sound issues [9]. The power generation that can be exploited with tidal current technologies is assessed to be around 75 GW worldwide, 11 GW in Europe especially in UK (6GW) and France (3.4 GW) [10]. Numerous researches have been carried out on TCT in recent years but these studies are still in the experimental phase in diverse sites: European Marine Energy Center (EMEC), Scotland [11], the Marine Energy Research Center in Canada [12], and the experimental site of Paimpol in France [13]; Only prototypes had been tested till now that includes two-bladed SeaGen project turbines manufactured in the UK [14]. Most of the prototypes that exist so far showed that the designers of the tidal turbines had tried to rely on technology that is already devoted to the wind because of the similarity in working principle. For further information about the projects of renewable marine energies, in particular, tidal and wave energy in the world between 2015-2022 including project proponent, technology, location and capacity (MW), the reader is referred to the report [15].

In a recent survey, some researchers [16-20] had listed the companies that have started establishing tidal current turbine farms such as Andritz Hydro Hammerfest (AHH) in Anglesey (Wales, UK), Sabella in France, GE & Alstom Energy (France), MeyGen in

Scotland, GE & Alstom Energy, and DCNS, EDF (France & Canada) which will start working in following years. These pre-commercial TCT projects account for the industrial solution in the future years and can be verified from the websites of these enterprises with up to date commercial news about the advancement in TCT technologies. For example, the EMEC was set up with the goal to test and improve marine renewable energy systems and is functioning from 2005 [21] .

The MeyGen project is presently the largest arranged tidal stream project on the planet, and the principal business multi-turbine cluster to initiate development of this energy system [22]. On the other hand, established in 2016 with European Union funding, the FloTEC project is aimed to demonstrate the potential of floating tidal systems to generate predictable, low-cost, reliable, and low-risk energy for European electricity grid (Fig. 1). In order to achieve this goal, the SR2000 turbine has been launched which is considered to be the most powerful tidal turbine in the world [23]. In its first year of testing in the Orkney Islands, the 2 MW turbines generated more than 3 GWh of renewable energy which was higher than that generated by all Scottish tidal energy and wave fields during combined 12 years before the launch of the SR2000 in 2016. The energy generated by the SR2000 during one year of full-time operation is sufficient to meet the annual electricity need of approximately 830 UK homes. In addition, it has also satisfied more than a quarter of the electricity needs of the Orkney Islands at that time. Moreover, the design of SR2000 turbine features some innovations such as a 50% higher energy recovery rate due to larger rotors running at a lower nominal velocity, high-efficiency blades and mooring load dampers. The SR2000 is also compatible with the local infrastructure, and offers full access to all of its systems through optimized configuration of its platform [24]. Nowadays, this project is collecting environmental data to provide information regarding its application to reach more than 10 MW of installed capacity for the first period.

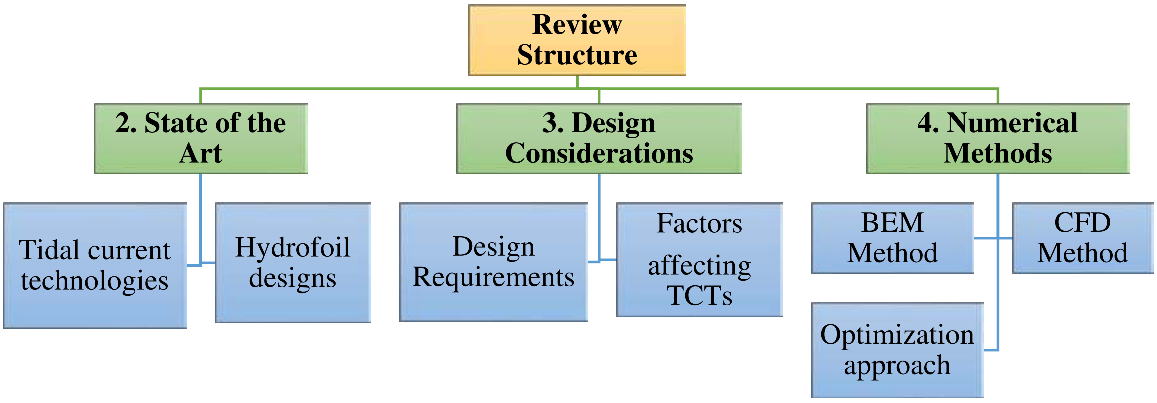
(a) (b)

Fig. 1: MeyGen (a) and FloTEC (b) projects.

In general, TCT converts the kinetic energy of free-flowing water into electric energy which shows that the blades play an essential role to enhance the turbine output and furnish enough strength to the blade structure, it is very important to design the hydrofoils correctly. Accordingly, in this paper, we aim to explore the recent advancements in TCT with an emphasis on the current design considerations essential for the hydrofoils used in the tidal current turbine industry. Included are also reviews on the published numerical work on the designs of hydrofoils for effective blade designs to eventually achieve good turbine performance. What is more, detailed discussions on the two main groups of numerical models used to evaluate the performance of tidal turbines, namely, blade element momentum model and computational fluid dynamics are also provided.

The rest of the article is structured as follows. Section 2 provides an overview over the current state-of-research of tidal current turbine technologies and the recent design of hydrofoils. The factor affecting TCTs and design requirement of hydrofoil for TCTs are explored in Section 3. Section 4 exposes a comprehensive review on the numerical models employed in TCTs including the hydrodynamic and structural models that are essential for evaluating the TCTs performance. In section 5, one discusses and summarizes what was presented in the previous sections. We conclude by summary and final remarks in Section 6.

A schematic diagram synthesizing the different aspects of the article is given below.



2. State of the art in TCT technologies and Hydrofoil designs

In this section, one exposes the latest achievements of the tidal current turbine technologies with their developing histories. Subsequently, the recent developments in the design of hydrofoils for tidal Current turbine are presented.

2.1. A review of tidal current technologies

Actually, tides are the rise and fall of sea levels caused by the predictable interactions between the gravitational fields of the sun, earth, and moon [25-27]. Harnessing tidal energy is not a new idea. Since 1981, Underwater Electric Kite has developed a new technology to harness marine currents with tidal current turbines [28]. Generally, there are three systems of catching force from marine tidal sources: the primary is by building up a tide over a bay, an estuary or stream, the second is by exploiting the kinetic energy from tidal marine flows using different sorts of turbines and the third is by using a hybrid application of tidal systems. The latter one has excellent potential if its concept and foundation can be combined with the arrangement and design of new framework for seaside towns [29]. Moreover, one prevalence thought about the TCT technologies is the utilisation of tidal floods by using adaptable gadget versatility and because of their exceptional predictability, could result in a significant source of electricity production [30]. Tidal floods are more expensive and are constantly prepared for GW control limits that could exceed the supply for remote islands [31].

Tidal current systems are similar in working principle to wind turbines except the kinetic energy of tidal streams instead of wind are used to generate electricity [32-34]. Tidal current technologies have had more than 40 novel systems exhibited from 2006 to 2013 [35]. The significant difference between these systems is the type of turbine used which can be vertical axis, horizontal axis or in some instances can be ducted [36]. These technologies are categorized into six classes based on the characteristics of turbines as follows (they are illustrated in Fig. 2):

(a) **Horizontal-axis turbine:** works in the same manner as wind turbines that capture energy from moving air, horizontal device (HATCT) converts the kinetic energy of free-flowing water into rotational energy and then this rotational energy into electricity.

(b) **Vertical-axis turbine:** the main working principle of this type is similar to the horizontal systems, except the tidal current rotates the rotors around the vertical axis and produce power.

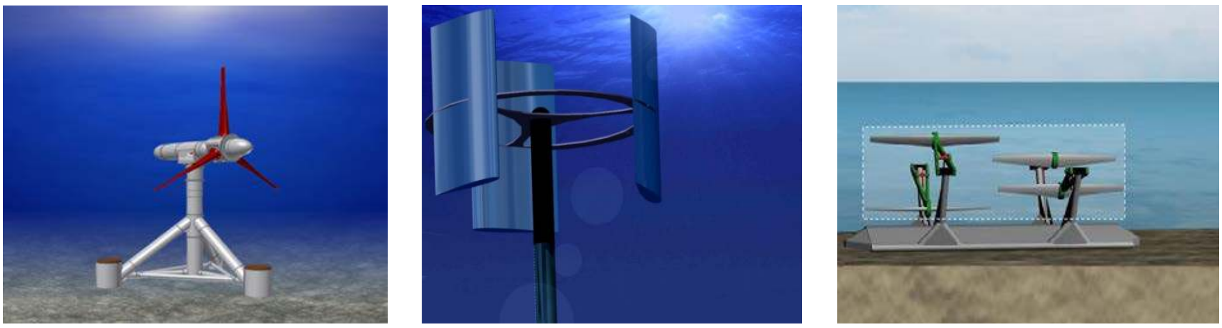
(c) **Oscillating hydrofoil**: a hydrofoil is tied to a swing arm. The marine current moving either side of hydrofoil, generates a lift. This motion then trains fluid in a hydraulic circuit by a motor. The resultant rotational movement can be transformed into electricity.

(d) **Ducted turbine or enclosed tips:** these devices are primarily horizontal axis turbines enclosed within a nozzle. This is designed to expedite and focuses the fluid motion. Turbines enclosed within a nozzle could also decrease turbulence around the turbines and ease the alignment of water flow for the turbines.

(e) **Archimedes' screw:** the Archimedes screw is a helical system that presents a variation of water level through the helix in order to draw power by turning the turbines.

(f) **Tidal kite:** tidal kite systems hold a kite tied with a small turbine. The kite steals by the flow, growing the relative flow speed coming in the turbine.

Note that there may be other types of turbines, other than those mentioned above, which encompass those technologies that have a unique and very different design of systems that the information on the device's feature could not be determined.



(a) (b) (c)

(d) (e) (f)

Fig. 2: The main types of tidal energy converters [28].

In this regard, we draw the reader's attention to that in the literature; there are many abbreviations and terminologies used to represent the tidal current technologies, such as tidal stream turbines (TSTs) [37], tidal stream generators (TSGs) [38], tidal energy converters (TECs) [39], tidal current turbines (TCTs) [40], marine current turbines (MCTs) [41], and hydro-kinetic turbines (HKTs) [42]. All these technologies can be found synonymously in the literature since the objective is to produce electricity from kinetic energy utilizing energy converting devices.

Based on the rotor configurations, the TCT can be grouped as vertical axis turbines (VATs) and horizontal axis turbines (HATs) [43]. Recently, diverse vertical axis and horizontal axis tidal current turbines (TCTs) have been improved and described in the literature [44-48]. Other abbreviations are also used for horizontal axis turbines reported in the literature like horizontal axis tidal turbine (HATT) and horizontal axis tidal stream turbine (HATST) concept [49]. For vertical axis turbines, the following abbreviation is found in the literature, vertical axis tidal turbines (VATT) [50]. Relating to Priegue and his co-workers' [51], the experiments tests confirmed that blade roughness of a vertical axis tidal turbine (VATT) affects negatively turbine performance. On the other hand, majority of manufactured tidal current turbines (TCTs) are known by the term horizontal axis turbines. As reported by Zhou and co-workers [52], HATT is well-respected and one of the most economical technology for big-scale TCTs with power capacity of over 500 kW currently, and the more mature between diverse tidal current energy technologies. The principal disadvantages of vertical axis turbines include weak current velocity range, relative low self-starting capability, and problems in dynamic stability which limit it's perform to suitable in lower current conditions only. The benefits and drawbacks of vertical and horizontal turbine blades have been described in detail in [50].

Although, several turbine developments had been published in some research articles and review papers but most of these developments were only at the prototype phase at the time when these articles were issued. Recently published in 2017 reviews technological characteristics of various kinds of the tidal current turbine; these technologies comprise both industrialized and design-stage prototypes [53]. Some large tidal current turbine such as Sabella, OpenHydro, and GE-Alstom turbines are also reported in it. Limited published studies are found on the improvement of TCTs due to the fact that they are fabricated originally by private societies. Therefore, efforts have been made in this article to present updated information on recent TCTs and to offer a more understanding review of the manufacturer of the TCTs and the academic researchers as well.

In general, the development of this technology from the conceptual idea to the industrial stage is envisaged to rise through five defined stages in Table 1.

Table 1: Tidal current development protocol.

Stage	Tidal current development protocol
TRL 1-3	Tidal-current energy conversion concept formulated (Scope of Protocol begins here)
TRL 4	Technical analysis (CFD, FEA, Dynamic analysis…) at intermediate scale
TRL 5-6	Technical analysis at large scale
TRL 7-8	Performing prototype-scale tests at sea
TRL 9	The experimentation of an industrial demonstrator at sea for a prolonged period.

TRL refers to technology readiness levels

Presently, USA and UK are leading in the design of the TCTs technology. Fig. 3 presents the global classification of tidal turbine designers. There are 75 designers with 15 designers in USA and 29 in UK (Figs. 4 (a) and (b)). Within 75 designers, 34 designers have carried out the lab experiment stage leading to technology readiness levels (TRL 7) amongst which, 7 are conducted in USA and 13 in UK. In addition, 8 designers have arrived to technology readiness levels (TRL 9) [54].

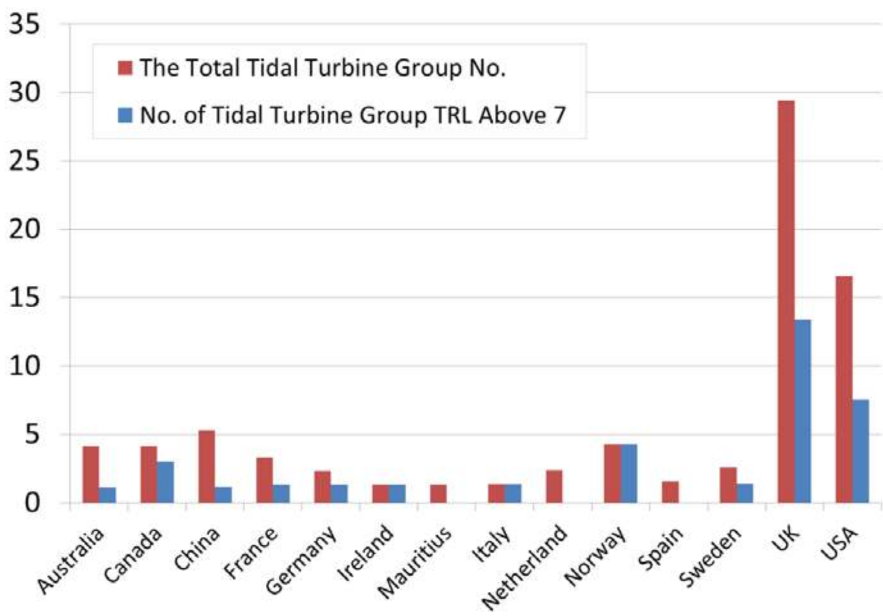
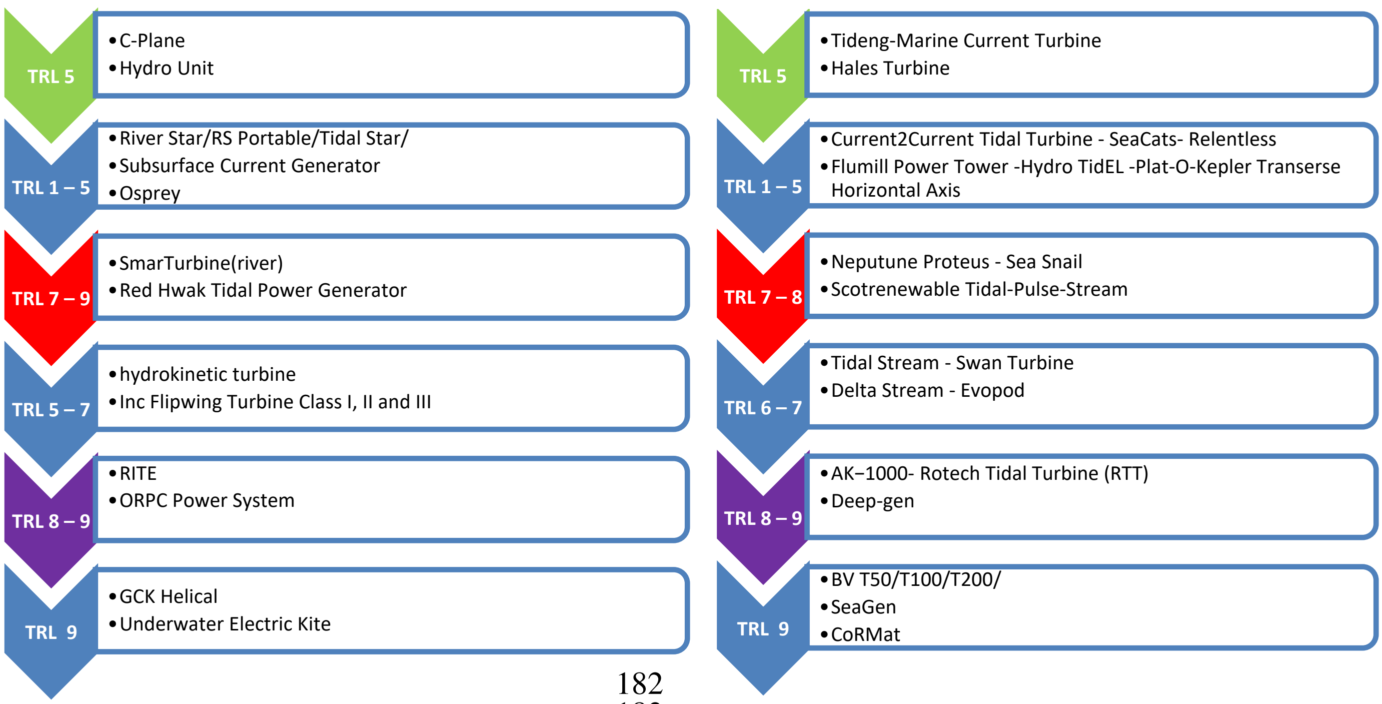


Fig. 3 : Technology readiness levels of the TCTs technology [54].



(a) (b)

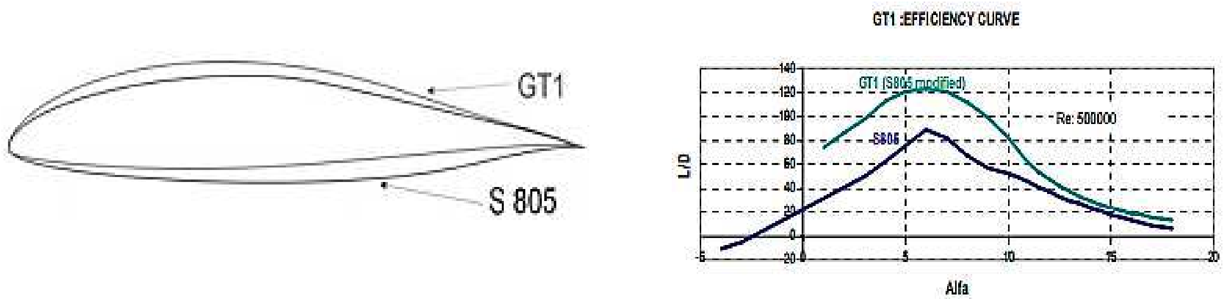
Fig. 4: Some tidal turbine design from (a) USA and from (b) UK.

2.2. Current state-of-research on recent design of hydrofoils

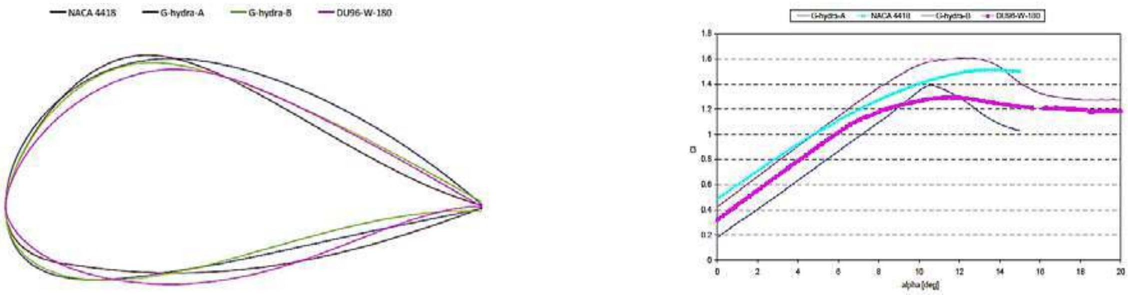
Hydrofoils are essential elements of horizontal axis hydrokinetic turbine that help to transform kinetic energy into mechanical energy and their excellent design results in increase of overall performance of the blade. Generally, there is no existing hydrofoil, which satisfies all conditions, or manufacturer expectations so far, each manufacturer has his proper approach and approved tools to proceed. Several methodologies can be adopted, some likes to use an inverse design technique (like the Eppler code) suggested by Lighthill [55] and widely promoted by Eppler to ordain flow parameters and obtain the resulting shape (hydrofoil) from the code by iteratively changing the pressure repartition on the hydrofoil surface. Others prefer to use a hydrofoil initially and then apply analysis codes (or a wind tunnel) to proceed in a trial and error style to achieve an excellent hydrofoil shape. In general, this second approach is often used in combination with a numerical optimization code [56].

Several studies have been conducted to furnish an appropriate blade section for HATCT [57,58]. The principal objective of blade design as discussed before is to improve the coefficient of lift and reduce the coefficient of drag and the coefficient of pitching moment [59]. Several research groups are doing exceptional work in executing experimental and numerical investigations to design hydrofoil. NASA, RISØ, and NREL are amongst the well-known hydrofoil developers. The most productive research team is the Sustainable Energy Research Group (SERG) at the Faculty of Engineering and the Environment (FEE), University of Southampton, which is guided by Professor Bahaj [60]. Since 2003, this group issued hundreds of key articles on hydrofoil design, and on experimental tests regarding tidal current turbine. Their numerical and experimental studies helped many researchers [61–75]. Ahmed [76] performed a general study on the evaluation of blade to be utilized in TCTs and the wind turbine. Coiro et al. [77] employed NREL series of blade sections to design a new hydrofoil (GT1) which has low cavitation number and high lift coefficient (Fig. 5(a)). Lawson and Sale [78] used NACA 63-series blade to model a HAHT rotor of 20 m diameter because the coefficient of minimum pressure is large enough in this airfoil, to provide resistant to cavitation. Grasso [79] designed two novel hydrofoils called G-hydra-A, G-hydra-B using an algorithm of sequential quadratic programming (SQP) which presented excellent performance compared to DU96-W-180 and NACA 4418 blade sections (Fig. 5(b). Goundar et al. [80] used HF10XX family of blade sections to design a 3-bladed horizontal axis tidal current turbine rotor of 10 m diameter. Hydrofoils with various thicknesses were employed at the different parts of the blade, and then the maximum power of 150 kW at the current of 2 m/s speed was applied which resulted in the maximum efficiency of 47.5% (Fig. 5(c)). Batten et al. [81] employed NACA 63-8xx profiles to predict a horizontal axis TCTs rotor performance and described the cavitation experiments for NACA series (63-815 and 63-215). Jing et al. [82] designed a complete tidal current energy conversion device and established it under the real operating requirements. Molland et al. [83] assessed lift and drag feature using numerical codes cavitation tunnel and experimental tests on NACA 6615, 63-815 and 63-215 foils. Hydrofoil which has high lift coefficient and high camber was endangered to limited cavitation. Luo et al. [84] analyzed a new hydrofoil by optimizing airfoil NACA 63815 (Fig. 5(d)). Goundar et al. [85] compared the hydrodynamic characteristics of new hydrofoil HFXX with different pre-existing of hydrofoils. On the other hand, Grogan et al. [86] used RISØ-A series of blade sections to design a hydrokinetic turbine blade. In an investigation conducted by Jonkman and Musial [87], RISØ-A1-XX and NACA44XX profiles of hydrofoil series were compared and it was observed that RISØ foils were better than NACA foils when used in stall controlled turbines. Ahmad [76] had studied S805, S814, RISØ-A1-24 and GT1 hydrofoils and concluded that they are feasible to be used in tidal current turbine blades. Singh et al. [88] combined two hydrofoils (DU91-W2-250, S814) for designing a new hydrofoil MNU26 which has a good structural strength with 26% thickness that can be practised throughout the blade length (Fig. 5(e)).

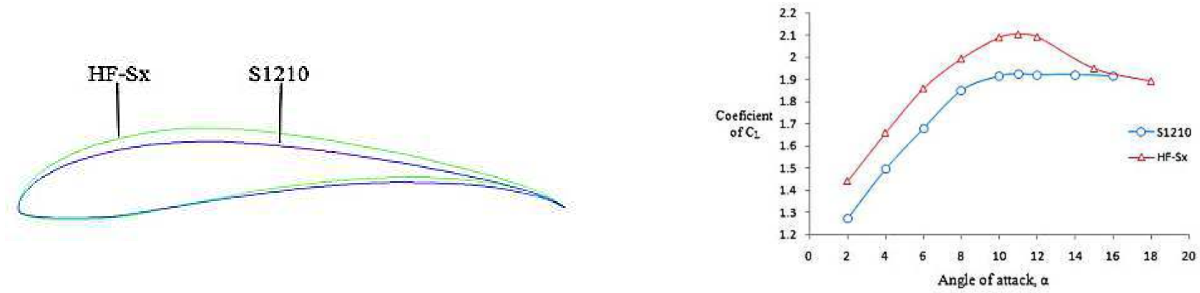
Hydrofoil design **Hydrodynamic performance**



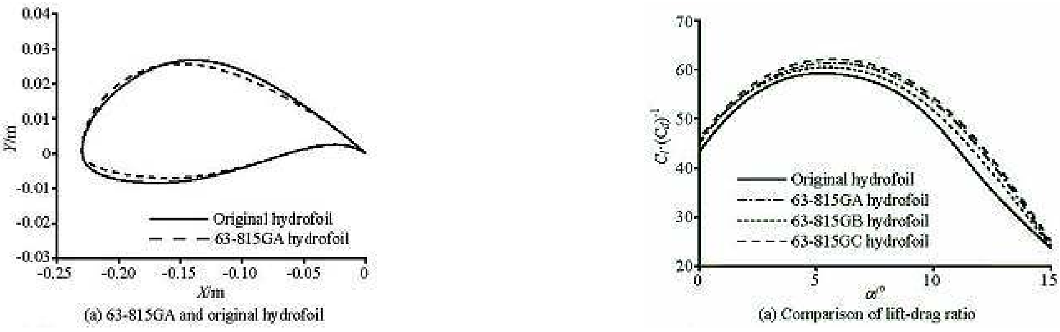
(a) New hydrofoil (GT1) [77]



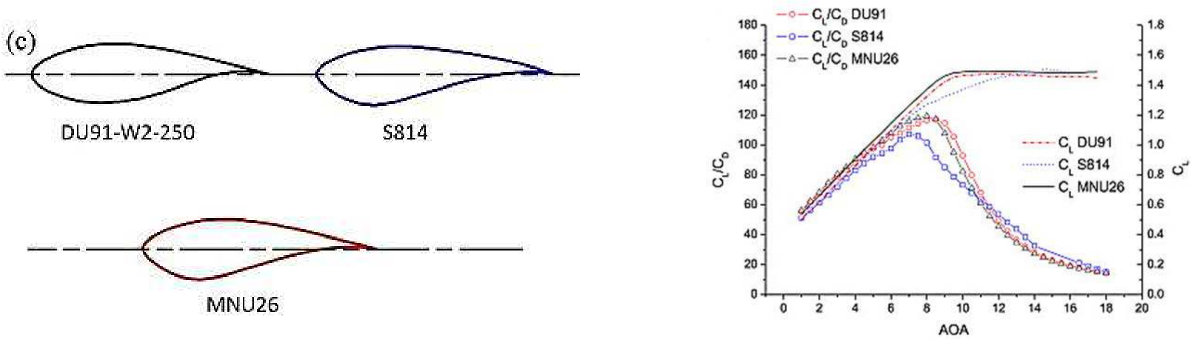
(b) New hydrofoil (G-hydra-A, G-hydra-B) [79]



(c) New hydrofoil (HF-Sx) [80]



(d) New hydrofoils (63-815GA, 63-815GB, 63-815GC) [84]



(e) New hydrofoil (MNU26) [88]

Fig. 5: Recent designs of new hydrofoils for tidal current turbine.

From the above literature, it is apparent that the performance of tidal current turbine primarily depends on optimal hydrofoil design in the following manner:

- In order to avoid cavitation, coefficient of pressure should be less than cavitation coefficient. For obtaining high lift to drag ratio, maximum coefficient of pressure should be less than 1.77, especially at leading edge of TCT blade.
- The stall and separation occur when angle of attack has high value. To avoid stall and separation, angle of attack should be kept less than 9°.

- By implementing hydrofoil blade profile, performance of the tidal current turbine can be improved. Different types of hydrofoil have been tested so far for this purpose. It is found that Modified S1210 i.e. HF-Sx hydrofoil is having best performance among all.
- It is also observed that, implementation of double blade hydrofoil may increase the coefficient of lift more than that of the single blade hydrofoil. Coefficient of lift increases with implementation of double blade hydrofoil. Moreover, maximum coefficient of performance also increases closer to Betz limit at tip speed ratio of 3.5.

After listing the latest technologies for tidal turbines and the recent development of hydrofoil designs, it is very important to present the factors that could affect the operation of tidal turbines. For instance, tidal turbine blades can be subjected for example to cavitation, biofouling whilst in operation. Such factors can affect the durability and the performance of tidal turbine blades and must be considered in the development of tidal current energy conversion systems as will be shown in the next section.

3. Design requirements and factor affecting the TCTs

The design of the hydrofoils of TCT is an encompassing work, which consists of the hydrodynamic design and mechanical structural design. This section aims at highlighting on these issues in conjunction with the existing literature and current trends. Besides, this section will mainly focus on the horizontal axis TCT blade conception because it has gained widespread use in marine current energy.

3.1. Design requirements and features

The efficiency of the rotor is often depended on the shape of hydrofoil employed [89]. The principal objective of hydrofoil conception is to increase the coefficient of lift and to reduce the coefficient of drag and the coefficient of pitching moment [90]. In order to find the most appropriate condition for the hydrofoil operation for a given profile section, the lift-to-drag ratio is one of the key performance feature.

In this context, tidal current turbine hydrofoil design can be divided into two very distinct interdependent domains. The first is its hydrodynamic design, whilst the other is its structural design. The purpose of the hydrodynamics design is to achieve a preferred external profile of the blade that provides the optimal performances, such as delayed stall, and cavitation-free. But, the major requirements of hydrofoil design are high coefficient of lift (C_L) and high lift-to-drag ratio over a wide range of angles of attack (AoA) in order to get excellent turbine performance. Some of the existing airfoils for wind turbines have also a high value of the maximum lift coefficient (C_{lmax}) and a relative high value for the design lift coefficient (C_l); this means that, for a certain load, a smaller chord is necessary. A lower chord in the outboard sections also reduces weight [91]. For marine applications, the stall behavior is more important than the C_{lmax}. So, the transition and the separation should move gradually when the angle of attack increases. A high C_l value (and lower associated chord) reduces the amplitude of load fluctuations resulting from wind gusts and so fatigue loads. In water, the turbulence is lower; this means that problems connected with fatigue have lower priority. In wind turbines, because of gusts, the local angle of attack for the single airfoil can suddenly change and be in pre-stall or stall zone. So, it is important to have an angle of attack range between the design angle of attack and the one for which, noticeable separation occurs on the airfoil [92]. For tidal turbines, especially if the turbine is a stall regulated turbine, it is convenient to reduce this margin to few degrees in order to use stall mechanism to stop the turbine as soon the turbine overcomes the design condition. Another important consideration is related with the sensitivity of the airfoil to the roughness [93]. An airfoil with a large laminar flow extension will be very efficient in “clean” conditions, but very bad in case of “dirty” conditions. A large value for the leading edge can improve this aspect and, at the same time, it can help to avoid cavitation by preventing from rapid expansions. On the other hand, the moment coefficient ($C_{mc/4}$) should be taken into account because large values of moment coefficient will give higher torsion moment on the blade. For tidal turbines however, the aspect ratio is lower than for wind turbines; this means that the blade is more rigid regarding torsion deformation, so the blade torsion does not play a crucial role in the design process [94].

The hydrodynamic parameters for hydrofoil include studying the pressure distribution of the hydrofoil, minimum coefficient of pressure (CP), coefficient of lift (CL), coefficient of drag (CD), and lift to drag ratio (L/D). Further design parameters include pitch, twist, and taper distribution of the blade and its 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 [95]. In addition, it’s very important avoiding the cavitation, since it will have a detrimental effect on the hydrodynamic performance of the blade. Attukur [96] performed the numerical simulation to maximize the lift-to-drag ratio and lift coefficient of the hydrofoil at design flow conditions and to avoid cavitation at off-design flow conditions. The method of multi-objective optimization problem uses a python module named OpenMDAO framework in order to solved the Non-Sorting Genetic Algorithm (NSGAII). The cavitation performance at the tip of the blade could be improved by decreasing the pitch angle, thereby increasing the AOA [97]. For this issue, Material-induced bend-twist coupling can be introduced by tailoring the composite layups. Well-designed composite marine lifting surfaces can increase the efficiency, and delay cavitation, separation, and stall [98]. Liu [99] proposed a new design method of C groove for vortex suppression and energy performance improvement for a NACA0009 hydrofoil. The results showed that the C groove method improves energy performance by 2.79% and suppresses tip leakage vortex by 67.94%.

3.2. Factors affecting TCTs

Although device reliability and engineering design is the most essential part when it comes to devices such as tidal turbines, improving the turbine performance based on the environment where it is installed is also a crucial step in developing this technology. This is why the authors of this study have chosen to consider the effect of the various parameters that may limit the performance of the HTCT.

3.2.1. Cavitation

Cavitation phenomenon is the greatest limitation in selecting a hydrofoil for tidal current turbine blades. These phenomena affect negatively the efficiency of the hydrofoil. By decreasing lift coefficient and increasing drag coefficient [100,101]. In general cavitation is another difference between wind and tidal turbine layout, besides bio-fouling. If bio-fouling remarkably appears on blade surfaces with low speed, cavitation generally appears close high speed areas of the blades. Static pressure instantly reduces due to the increased dynamic head at high speed location and can create vapour bubbles. These bubbles will finally be disintegrated and create high frequency and high-pressure pulses which initiate the process of corrosion on the surface and turning the blade surface rougher. Once more, a tough blade will reduce the performance of the blade since it changes the design of the aerofoil particularly when the roughness is close to the tip of the blade where the maximum of energy production is generated. Wang et al. [102] have examined the using of cavitation tunnels and marine propellers examination solution to be valid in the study of small-size tidal turbine performance once cavitation is present. In addition there are numerous types of cavitation that will impact the turbine's performance as presented in Fig. 6. Also, it was presented that cavitation increases noise pollution particularly in critical situations and could disturb marine creatures. It was additionally proposed that tidal turbines might be placed above the sea bottom at least by one diameter size distance to prevent erosion and sediment movement. Bahaj et al. [103] supported the thought of negative issues of cavitation to the energy extraction of tidal turbine and it always depends on the shape. It was eventually proposed that the blade tip speed must be lower than 7 m/s to avoid cavitation. Barber et al. [104] performed various numerical analysis employing a BEM-FEM solver to check out the blade reaction to the cavitation. It was mentioned also that the blade response is separated of the material direction. It was also discovered that cavitation was observed for tested tidal turbine at normal operating condition; therefore it must be associated with the design process. Relating to modern design, it was identified by Nicholls et al. [105] that adaptable blade be changed or adapted according to the stream conditions, and also can reduce the probability of cavitation in their BEM analysis of a model tidal turbine.

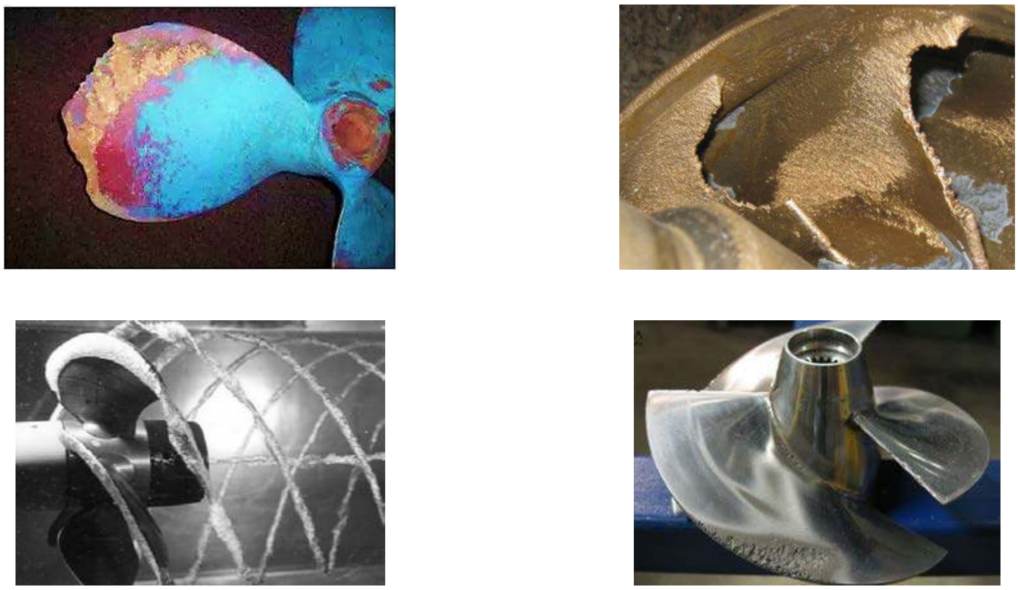


Fig. 6: Structural damage due to cavitation [85–87]

3.2.2. Bio-fouling

One of the primary factors influencing tidal turbine design is the material choice for the blade itself. The main issues that submerged devices confront are the severe corrosion of sea water, fouling growth and abrasive suspended particles. Among the three, bio-fouling is the most recognised factor of degradation of overall performance of marine devices because of the surface roughness as stated by Wood [106]. At worst cases, it could really damage the blade due to erosion. Marine fouling as a result of deposited microorganisms on the surface will finally colonize areas of the blade. This will depend on water deepness, temperature, salinity, and position of the site. Although, its dependence on position, tidal systems (blade root and rotor hub) at 5 m under water will be coated with fouling especially at low speed of water as mentioned in [107]. Fouling may be stopped by applying fouling control coatings that are commonly used for ship structures and are categorized into two main types, the biocide-based paints and the fouling-release coatings. The first was depending on controlled-release of active substances to control fouling as the other was predicated on the physical properties of the covering itself. Yebra et al. [108] presented the functions of the two coatings in relation with turbine performance across time-immersion with the covering. Biocide paint will not have a significant drop before 2-3 years of experienced installation. Foul-release coatings have an unexpected decline in performance for the first couple of years but will have self-clean and recuperate performance. The same author also offered a study around the effects of three different fouling mechanisms (three circumstances from three different coatings) in the efficiency of tidal turbines. The results demonstrated a loss of about 7.5%, 22.5% and 40% in the daily energy generated after 5 years of direct exposure for the three coatings respectively. Chen [109] also stated that at higher level of fouling on the blade of a tidal turbine may reduce 70% of efficiency. Fig. 7 exemplifies the growth of plants and other marine life on the supporting structure of tidal current turbine.

Fig. 7: Biofouling on TidGen turbine deployed in Eastport, Maine in North America [92]

3.2.3. Interaction with Stanchion

The interaction with the stanchion can affect the performance and loading on a tidal stream turbine. In addition to the number of blades, the magnitude of the effect is also influenced by the geometry of the stanchion [110] and the distance between the rotor and the stanchion [111]. The former study found that the power output of a turbine with an elliptical or hydrofoil shaped stanchion is around 20% higher than with a square stanchion and the total thrust around 35% lower. The latter work also showed that the power output increased by around 10% when the rotor to stanchion distance was increased from 1 to 2 hub diameters with the turbine upstream of the stanchion. Furthermore, although the average power output was found to reduce by only around 7% when the rotor was downstream of the stanchion, the fluctuations in power over the rotational cycle increased from around 2.5% to around 30% and the fluctuations in thrust from 1% to 15%.

3.2.4. Wake Length

There is little published data on the wake of a full-scale tidal turbine and none could be found in the public domain. Myers et al. [112,113] conducted small scale experiments, using mesh disks to simulate rotors. These studies showed a recovery of 90% of the upstream flow velocity along the centre line of the disk at a downstream distance of up to 20 diameters. The representation of rotors as mesh disks ignores the swirl transmitted on the flow but the authors state that these effects dissipate speedily and only affect the near-wake region. The results of this study indicate that the thrust on a turbine affects only the near wake with the far wake depending principally on ambient turbulence, proximity to the surface and sea bed, and local bathymetry, McCombes et al. [114] predicted that the vortices shed from the blade will have a major influence on the wake recovery and stated that traditional CFD may underestimate wake length due to the diffusion of vorticity.

Furthermore, research in the wind industry has found that in wind tunnel experiments the velocity at x/D=16 is less than 90% of the upstream value [115]. Masters [116] studied the influence of flow acceleration on wake recovery by including a sloping surface in their models and found that a surface gradient of -0.01 reduced the distance to 80% velocity recovery by almost 50%. Additionally, Olczak et al. [117] found that surface waves can improve velocity recovery and reduce wake length, with larger waves having a greater effect. These findings demonstrate the requisite of extensive field data for a site before installation and the inclusion of as many physical features as practical in a physical or numerical model of a proposed site.

In order to limit these factors that affect the operation of tidal turbines and to reach the optimal design requirements, the carrying out experimental tests on prototypes will be difficult due to the large size of tidal turbines, and the complexity of the system and the expensive price. Therefore, the use of numerical methods is an interesting solution to predict the hydrodynamic and structural performances.

4. Numerical models of tidal turbines

In fact, a much money and time can be saved through using the numerical modeling approaches of tidal turbine rather than experimentation of the prototypes in the waters. Although numerical models cannot truly mimic complex offshore conditions, they are very convenient not only because of lower costs, but also for the possibility of collecting accurate and repeatable data. Furthermore, the key advantage that can be provided by the numerical simulation is the lower risk; despite there is distinctly a need to verify the validity of the measured data. In terms of numerical modeling, the blade element momentum (BEM) model and computational fluid dynamics (CFD) are the two most commonly used numerical models for tidal current turbines. Of particular interest is to a review of the both methods with regard to their merits and limitations.

4.1. Blade element momentum (BEM) method

The BEM method is a technique that couples the momentum theory with the blade element approach for the purpose of alleviating some of the difficulties in calculating the induced velocities at the rotor. This method was initially presented by Froude in 1878 [118] and was further refined by Glauert for the study of airplane propellers [119]. This technique generally uses the similar blade element theory where a rotor blade was discretized into smaller parts where forces were calculated individually, and then gathered in a single force operating on the blade. The momentum theory was employed to derive the axial and circumferential inflow factors, with the inclusions of tip loss factors to account for the finite number of rotor blades. While, the blade element approach was involved to model the blade section drag and torque by splitting the rotor blade into a number of elemental sections. The coupling of the momentum theory led to solving the problem of the blade element approach with respect to the induced velocity in the rotor.

BEM modeling method was thereafter incorporated into the design of wind and tidal turbines, the first time by Sorensen and Kock [120]. They used tabulated aerofoil aerodynamic data as input for the numerical analysis, and their model is still widely used as design approach in the wind turbine industry until present time. The BEM method has also successfully been applied to tidal current turbines. Masters et al. [121] integrated BEM method with tidal rotor designs, and it has been proven that this method can be used to calculate tidal turbine performance. Bahaj et al. [122] also validated BEM by using experimental modeling in cavitation tunnel and towing tank of a marine current turbine. Actually, BEM has been integrated into several wind/tidal turbine design software to evaluate the performance of turbines. For instance, Qblade [123], a turbine design software which integrates a turbine blade geometry building function along with a rotor (BEM) solver, to establish a complete rotor performance solver. QBlade further includes the potentials of both XFOIL and BEM that allow simulating the hydrodynamic properties of the hydrofoils at a defined flow condition.

Based on BEM method, performance analysis of horizontal axis tidal current turbine (HATCT) has been carried out by several researchers. Chen et al. [124] used a combination of BEM and CFD for blade design and analysis the performance of HATCT. Bir Gunjit et al. [125] outlined the procedure of the HATCT composite blade design using a developed code based on BEM theory. Nicholls-Lee and Turnock [126] performed BEM analysis of a horizontal axis tidal turbine model, and it was found that the concept of passively adaptive blade reduces blade loading and delays cavitation inception.Batten and Bahaj [127,128] predicted the power output performance of a 0.4 m diameter HATCT using the BEM method, it was shown that power production and the blade tip speed reduced with yaw angle except for situations with high blade inflow angles.

From the review of the above literatures, it can be seen that BEM theory was extensively used, as it shows promising capabilities in designing and analyzing the performance of tidal turbines with the merit of being more robust, faster and less computationally intensive as compared to other numerical methods. However, it can have some limitations that probably critical to certain analyses. One of the major limitations of the BEM technique is that it cannot be employed to examine the influence of a rotor on the surrounding flow, and where an analysis of wake dynamics is needed, alternative modeling methods should be employed. A number of such alternatives were developed to assess the turbine wakes. Lawson Michael et al. [129] developed a computational fluid dynamics methodology to simulate the hydrodynamics of HATCT, wherein the design procedure based on the coupled methods of BEM theory and CFD was employed. Malki et al. [130] also developed a modeling approach based on BEM theory to predict the performance of tidal stream turbine in the ocean environment; through the coupling of the BEM method with CFD flow domain, the effect of upstream hydrodynamics on rotor performance was accounted for. The CFD modeling method, which is more relevant when the rotor undergoes complex flow conditions such as high levels of turbulence and variable flow directions will be covered in the sequel.

4.2. Computational fluid dynamics (CFD)

Although BEM method has shown a good potential for use in tidal turbine performance analysis, it was limited only to the performance of the entire rotor and not the loading acting on individual blades like flow over the blade and the flow physics in the blade sections. To overcome this limitation, CFD simulations and analysis have been used and developed. CFD has been utilized to serve as an additional and/or alternative tool for further analysis of particular issues in tidal turbine performance. It uses numerical techniques and algorithms to analyze and tackle various problems that involve fluid flows. CFD involves the discretization of the fluid body, i.e., spatial domain, into small fluid elements called cells then algebraic variables are attributed to each flow characteristic of each cell. The interfaces of the fluid body that could be walls or openings with fixed pressure drop are used as boundary conditions, where some of those flow characteristics are known. A series of conservation laws of mass, momentum, and energy that govern fluid motion and equation of state, along with the appropriate boundary conditions are then solved numerically. The solutions are therefore the flow characteristics of each cell, knowing the discrete fluid behavior of each cell enables to determine the entire fluid body behavior.

In fact, there are diverse strategies of CFD that's being employed in the analysis of turbine performance, each differs based on how the fluid flow was modeled and solves. The direct numerical simulation (DNS) is the most computationally intensive method. In this method, the Navier-Stokes equations are numerically solved by resolving the whole range of spatial and temporal scales of turbulence; this means the equations are solved without the use of any turbulence model. On the other hand, Reynolds-averaged numerical simulation (RANS) is the most widely used method because it does not necessitate huge computing resources. This method aims for statistical description of flow, where the time-averaged Navier-Stokes equation is used to diminish the number of equations that must be solved at each time step to allow for faster simulation. Another revised model of RANS to address potentially nonstationary and unsteady flows is the large eddy simulation (LES). This model aims at reducing the computational cost by ignoring the smallest length scales, which require high computational time to resolve, via filtering out the small turbulent flow scales from the large unsteady flow motions.

We aim here at elaborating the current literature that has employed CFD to explore issues and topics related to tidal turbines. Harrison et al. [131] and Batten et al. [132] exploited full CFD model to simulate the hydrodynamic performance of a HATCT, and the numerical data resulting from simulations were validated with a full turbine model experiment carried out in a cavitation tank. Morris [133] used CFD to study the effect of solidity on the performance, swirl characteristics, and wake length and blade deflection of a HATCT. Batten et al. [134] conducted CFD simulations to study the influence of wake induced turbulence and oceanic flows on the performance of tidal turbines. MacLeod et al. [135] described the application of CFD techniques in the modeling of tidal turbine wakes, where an in-house code called “3D-NS” which is a RANS solver with κ-ε closure has developed to simulate clusters of turbine in any configuration. Gant and Stallard [136] used CFD model to simulate time-dependent turbulent flow around a tidal turbine, where porous disc modelling was used for tidal turbines with a RANS k-ε to provide some insight into the influence of large-scale flow oscillations on the wake of the turbine. Churchfield et al. [137] applied LES approach to arrays of tidal turbines to provide useful unsteady information about wakes and power production, wherein the subfilter scale (SFS) turbulence model was used for the RANS simulation for smaller scales. Mason-Jones et al. [138] conducted a series of CFD models of the tidal turbine when it was subjected to either a plug flow or a profiled high shear flow in order to evaluate the effect of the rate of shear across the turbine diameter; in these models the RANS equations was used to relate the Reynolds stresses to the mean velocity gradients. O'Dohetry et al. [139] used CFD models to assess the performance of a 10 m diameter, three-bladed HATCT in terms of torque, power and axial load against a plug flow and two profiled flows. Kang et al. [140] simulated 3D turbulent flow past marine hydrokinetic turbine by developing a computational framework for performing high-resolution LES in arbitrarily complex domains involving moving or stationary boundaries. Afgan et al. [141] investigated the blade loading and turbulent flow in tidal turbine using RANS and LES and compared the two CFD models.

Furthermore, there were a few models that have developed by a number of researchers to couple CFD and BEM methods to overcome the limitation of BEM method. In these models, BEM was used as tool for initial design purposes in order to reduce the design iterations before using CFD method. For example, Malki et al. [142] developed a coupled BEM-CFD model to study the effect the upstream hydrodynamics on rotor performance. It was found that such coupling between CFD and BEM results in addressing the limitation of BEM in analyzing the effect of a rotor to the surrounding flow. Turnock et al. [143] used a coupled model combining BEM theory to represent blade forces on the flow and CFD to simulate flow through the domain to predict the hydrodynamics and performance of a tidal current turbine. Edmunds et al. [144] used a coupled BEM–CFD model to address various aspects of tidal stream turbine modeling in the natural environment. Williams et al. [145] presented a combined computational CFD-BEM model that enables the prediction of the performance of tidal stream turbines at a chosen location using site specific data.

So far, the most used numerical models for tidal turbines including BEM, CFD or coupled BEM-CFD have been reviewed with addressing their potentials and limitations.

4.3. **Design optimization of hydrofoil**

The ongoing advancements in computer technology, both hardware and software, allow researchers to deal with the optimization problems using computational resources, as evidenced in the large number of optimization strategies that have been applied to the field of renewable and sustainable energy. Banos and his colleagues [146] performed an excellent review paper of the current state of the art in computational optimization approaches applied to renewable and sustainable energy. In order to design a hydrofoil, many techniques can be employed such as the inverse design approach, suggested by Lighthill [147] and broadly progressed by Eppler and Drela [148]. Despite its great employ, there are many inconveniences related with this approach. The objective of the design optimization is to find an optimal solution. A general optimization process is illustrated in Fig. 8.

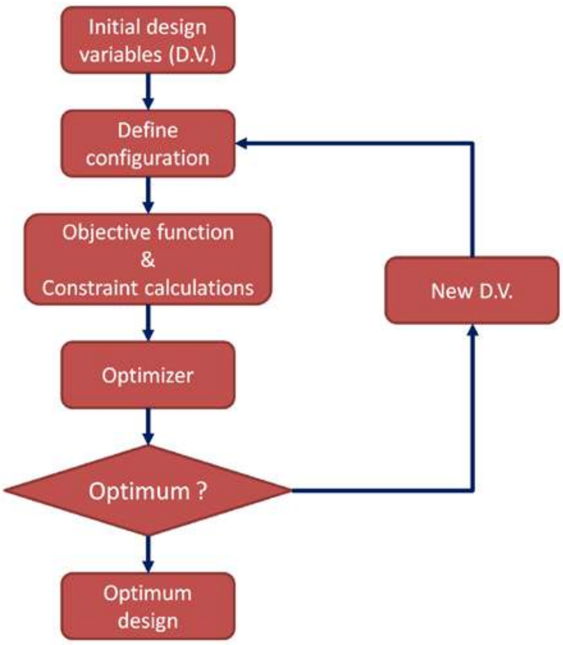


Fig. 8: Flowchart of optimization process.

The experimental analyses of hydrofoil via wind tunnel tests are rather hard to conduct due to the expensive cost of the wind tunnel. In this context, various numerical investigations codes were created, providing a technical support for the foil study such as XFLR5 [149], RFOIL [150] and JavaFOIL [151]. Theses codes frequently employed for a 2D model which can give coefficient of lift (C_L), coefficient of drag (C_D), and coefficient of pressure (C_P) of the hydrofoil.

According to the researches cited above, it can be observed that which hydrofoils are used for TCTs in which published articles from experiments test or hydrodynamic design. Moreover, most of these excellent design methods are concentrated on the hydrofoils lift and drag coefficient but not so much on the cavitation phenomenon. So, it is important to investigate a design optimization technique that takes into account the cavitation performance and the lift-drag ratio concurrently for hydrofoils to enhance the hydrodynamic performance of TCTs more efficiently. Two types of optimization technique exist that are widely utilized in tidal current turbine blade design field, namely Genetic Algorithm (GA) [153] and gradient-based optimization methods (GOM) [154,155]. Luo et al. [155] studied and optimized airfoil NACA63815 to get novel hydrofoils by using NSGA-II algorithm. Cavitation and lift-to-drag coefficient ratio characteristics were employed as a goal in this genetic algorithm. Grasso [156] used a design optimization technique and founded two new hydrofoils by using advanced algorithm of sequential quadratic programming (SQP) and the RFOIL solver. Yang and Shu [157] enhanced the lift-drag coefficient ratio of the NACA0012 by using the hierarchical fair competition genetic algorithms and CFD simulation. Cocke et al. [158] optimized the hydrodynamic characteristic of hydrofoils (lift-drag ratio, coefficient of lift and coefficient of drag) by using computational fluid dynamic (CFD) simulations and genetic algorithms.

5. Summary and discussion

From the above discussions it is clear that technology, hydrofoil, design consideration and numerical optimization approaches play a very important role in optimal design and successful implementation of the TCTs system. Tidal current turbine hydrofoil design can be divided into two very distinct interdependent domains. The first is its hydrodynamic design, whilst the other is its structural design. The objective of the hydrodynamics design is to achieve a preferred external profile of the blade that provides the optimal performances. But, the major requirements of hydrofoil design are high C_L and high Lift/Drag coefficients ratio over a wide range of AOA in order to get great turbine performance. On the other hand, the most important parameters, from the structural point of view, are the maximum hydrofoil thickness and the chord-wise location of the maximum thickness. The thickness of the profile must be able to accommodate the structure necessary for blade strength and stiffness. Depending of the class of the tidal current turbine, certain values for the thickness along the blade can be expected and this fact introduces a first indication for the design problem. The location of the maximum thickness along the chord is also important; when a hydrofoil is designed, also the other hydrofoil along the blade should be considered to guarantee constructive compatibility. This means that, in order to allow the spar passing through the blade, the chord-wise position of the thickness should be similar for the complete blade. Since a hydrofoil for a tidal turbine blade is installed in water, when the water is polluted, the blade is not easy to maintain or repair. Therefore, a hydrofoil with a shape which is less sensitive to surface roughness is needed. In addition, because various loads are structurally imposed on the hub part, the wing tip must have a gradually thick hydrofoil shape. When increasing the thickness of the blades, their strength and camber increased, thereby improving the hydrodynamic characteristics of hydrofoils.

Designers face challenges in designing blade sections for TCT 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 TCT 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 [159,160].

Ultimately, the present paper could be useful for tidal current turbine designer, project developer to provide knowledge about TCTs system for executing the project and compete with the existing market. It is suggested that further in depth optimization study and research may be taken up regarding some of the parameter of TCT for reducing undesirable effect like cavitation and biofouling in combination with augmentation techniques.

6. Conclusion

This paper is focused on the recent advancements in the design of a hydrofoil for the horizontal axis tidal current turbine (HATCTs). An up-to-date review and the newest achievements of marine TCTs technologies with their developing histories are presented. Thereafter, the requirements and specifications essential for the design HATCTs hydrofoil including the hydrodynamics design and the structural design are illustrated. Followed successively by a comprehensive review of the numerical models used for tidal turbines and current state-of-the-art of optimization methods applied to design and assess the performance of HATCTs. This in turn significantly participates to a better knowledge on the recent designs of TCT hydrofoils for the researchers working in the marine turbine energy domain. Such information could also have important implications in the design of more sophisticated hydrofoils that satisfy a wide range of objectives:

- Maximize the coefficient of power.
- Limit the cavitation.
- Resist extreme and fatigue loads and restrict tip deflections (structural safety consideration).
- Minimize weight and cost.

Besides, further works should be done before the commercial deployment of the TCT associated with structural problems, such as mass gain, fouling resistance, corrosion resistance, manufacturing methods and coating technology, the future work will involve the use of composite materials in tidal current turbine because of their excellent mass/durability relations.

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