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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

2 The development of marine renewable energies represents a major opportunity and an
3 attractive alternative to reduce greenhouse gas emissions [1]. The oceans provide a massive

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

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

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

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



(a)



(b)

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

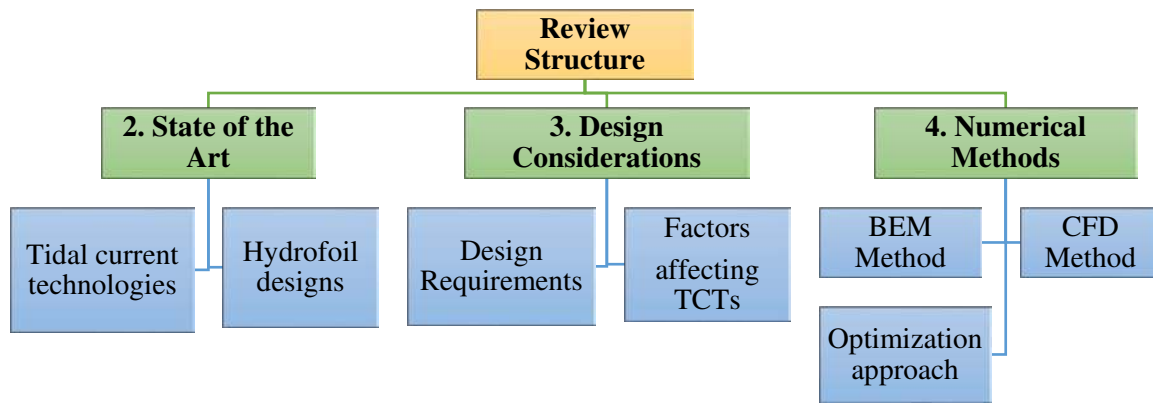
62

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

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

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

81



82

83

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

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

88 **2.1. A review of tidal current technologies**

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

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

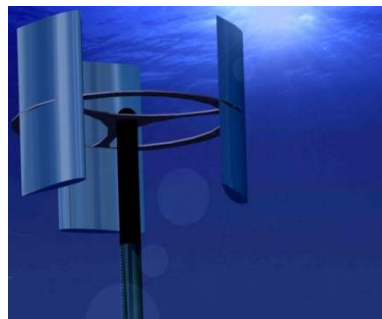
- 109 (a) **Horizontal-axis turbine:** works in the same manner as wind turbines that capture
 110 energy from moving air, horizontal device (HATCT) converts the kinetic energy of
 111 free-flowing water into rotational energy and then this rotational energy into
 112 electricity.
- 113 (b) **Vertical-axis turbine:** the main working principle of this type is similar to the
 114 horizontal systems, except the tidal current rotates the rotors around the vertical axis
 115 and produce power.
- 116 (c) **Oscillating hydrofoil:** a hydrofoil is tied to a swing arm. The marine current moving
 117 either side of hydrofoil, generates a lift. This motion then trains fluid in a hydraulic
 118 circuit by a motor. The resultant rotational movement can be transformed into
 119 electricity.
- 120 (d) **Ducted turbine or enclosed tips:** these devices are primarily horizontal axis
 121 turbines enclosed within a nozzle. This is designed to expedite and focuses the fluid
 122 motion. Turbines enclosed within a nozzle could also decrease turbulence around the
 123 turbines and ease the alignment of water flow for the turbines.
- 124 (e) **Archimedes' screw:** the Archimedes screw is a helical system that presents a
 125 variation of water level through the helix in order to draw power by turning the
 126 turbines.
- 127 (f) **Tidal kite:** tidal kite systems hold a kite tied with a small turbine. The kite steals by
 128 the flow, growing the relative flow speed coming in the turbine.

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

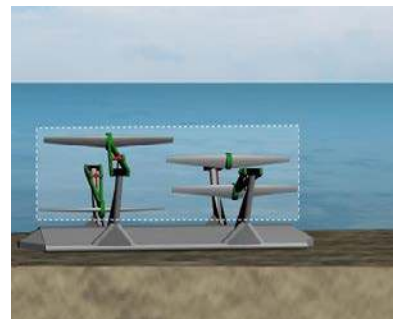
132



(a)



(b)



(c)



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

133

134

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

142 Based on the rotor configurations, the TCT can be grouped as vertical axis turbines
 143 (VATs) and horizontal axis turbines (HATs) [43]. Recently, diverse vertical axis and
 144 horizontal axis tidal current turbines (TCTs) have been improved and described in the
 145 literature [44-48]. Other abbreviations are also used for horizontal axis turbines reported in
 146 the literature like horizontal axis tidal turbine (HATT) and horizontal axis tidal stream turbine
 147 (HATST) concept [49]. For vertical axis turbines, the following abbreviation is found in the
 148 literature, vertical axis tidal turbines (VATT) [50]. Relating to Priegue and his co-workers'
 149 [51], the experiments tests confirmed that blade roughness of a vertical axis tidal turbine
 150 (VATT) affects negatively turbine performance. On the other hand, majority of manufactured
 151 tidal current turbines (TCTs) are known by the term horizontal axis turbines. As reported by
 152 Zhou and co-workers [52], HATT is well-respected and one of the most economical
 153 technology for big-scale TCTs with power capacity of over 500 kW currently, and the more
 154 mature between diverse tidal current energy technologies. The principal disadvantages of
 155 vertical axis turbines include weak current velocity range, relative low self-starting capability,
 156 and problems in dynamic stability which limit it's perform to suitable in lower current
 157 conditions only. The benefits and drawbacks of vertical and horizontal turbine blades have
 158 been described in detail in [50].

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

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

171 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.

172 **TRL refers to technology readiness levels**

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

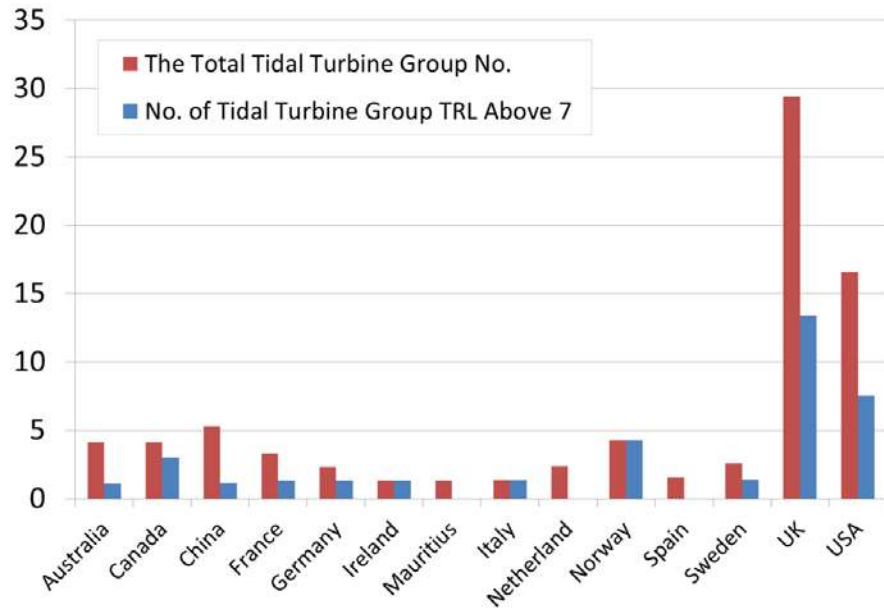


Fig. 3 : Technology readiness levels of the TCTs technology [54].

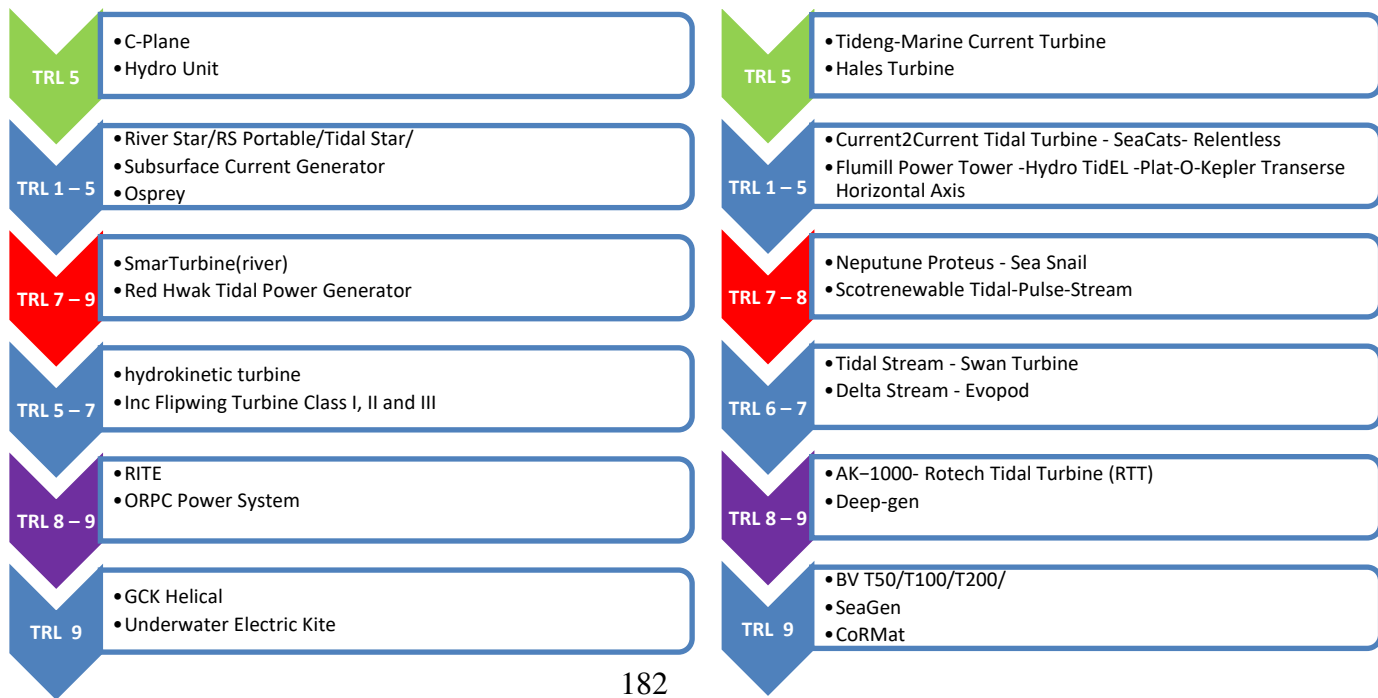


Fig. 4: Some tidal turbine design from (a) USA and from (b) UK.

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

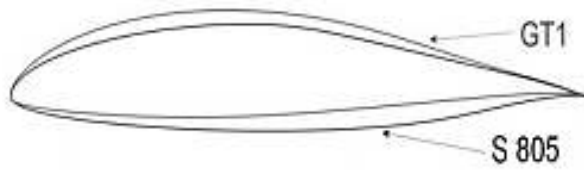
Hydrofoils are essential elements of horizontal axis hydrokinetic turbine that help to transform kinetic energy into mechanical energy and their excellent design results in increase of overall performance of the blade. Generally, there is no existing hydrofoil, which satisfies

192 all conditions, or manufacturer expectations so far, each manufacturer has his proper
193 approach and approved tools to proceed. Several methodologies can be adopted, some likes
194 to use an inverse design technique (like the Eppler code) suggested by Lighthill [55] and
195 widely promoted by Eppler to ordain flow parameters and obtain the resulting shape
196 (hydrofoil) from the code by iteratively changing the pressure repartition on the hydrofoil
197 surface. Others prefer to use a hydrofoil initially and then apply analysis codes (or a wind
198 tunnel) to proceed in a trial and error style to achieve an excellent hydrofoil shape. In general,
199 this second approach is often used in combination with a numerical optimization code [56].

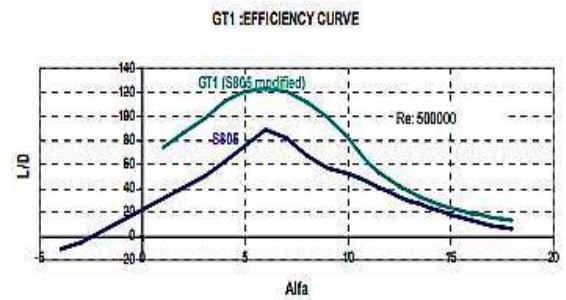
200 Several studies have been conducted to furnish an appropriate blade section for
201 HATCT [57,58]. The principal objective of blade design as discussed before is to improve the
202 coefficient of lift and reduce the coefficient of drag and the coefficient of pitching moment
203 [59]. Several research groups are doing exceptional work in executing experimental and
204 numerical investigations to design hydrofoil. NASA, RISØ, and NREL are amongst the well-
205 known hydrofoil developers. The most productive research team is the Sustainable Energy
206 Research Group (SERG) at the Faculty of Engineering and the Environment (FEE),
207 University of Southampton, which is guided by Professor Bahaj [60]. Since 2003, this group
208 issued hundreds of key articles on hydrofoil design, and on experimental tests regarding tidal
209 current turbine. Their numerical and experimental studies helped many researchers [61–75].
210 Ahmed [76] performed a general study on the evaluation of blade to be utilized in TCTs and
211 the wind turbine. Coiro et al. [77] employed NREL series of blade sections to design a new
212 hydrofoil (GT1) which has low cavitation number and high lift coefficient (Fig. 5(a)).
213 Lawson and Sale [78] used NACA 63-series blade to model a HAHT rotor of 20 m diameter
214 because the coefficient of minimum pressure is large enough in this airfoil, to provide
215 resistant to cavitation. Grasso [79] designed two novel hydrofoils called G-hydra-A, G-hydra-
216 B using an algorithm of sequential quadratic programming (SQP) which presented excellent
217 performance compared to DU96-W-180 and NACA 4418 blade sections (Fig. 5(b)). Goundar
218 et al. [80] used HF10XX family of blade sections to design a 3-bladed horizontal axis tidal
219 current turbine rotor of 10 m diameter. Hydrofoils with various thicknesses were employed at
220 the different parts of the blade, and then the maximum power of 150 kW at the current of 2
221 m/s speed was applied which resulted in the maximum efficiency of 47.5% (Fig. 5(c)). Batten
222 et al. [81] employed NACA 63-8xx profiles to predict a horizontal axis TCTs rotor
223 performance and described the cavitation experiments for NACA series (63-815 and 63-215).
224 Jing et al. [82] designed a complete tidal current energy conversion device and established it
225 under the real operating requirements. Molland et al. [83] assessed lift and drag feature using

226 numerical codes cavitation tunnel and experimental tests on NACA 6615, 63-815 and 63-215
 227 foils. Hydrofoil which has high lift coefficient and high camber was endangered to limited
 228 cavitation. Luo et al. [84] analyzed a new hydrofoil by optimizing airfoil NACA 63815 (Fig.
 229 5(d)). Goundar et al. [85] compared the hydrodynamic characteristics of new hydrofoil
 230 HFXX with different pre-existing of hydrofoils. On the other hand, Grogan et al. [86] used
 231 RISØ-A series of blade sections to design a hydrokinetic turbine blade. In an investigation
 232 conducted by Jonkman and Musial [87], RISØ-A1-XX and NACA44XX profiles of hydrofoil
 233 series were compared and it was observed that RISØ foils were better than NACA foils when
 234 used in stall controlled turbines. Ahmad [76] had studied S805, S814, RISØ-A1-24 and GT1
 235 hydrofoils and concluded that they are feasible to be used in tidal current turbine blades.
 236 Singh et al. [88] combined two hydrofoils (DU91-W2-250, S814) for designing a new
 237 hydrofoil MNU26 which has a good structural strength with 26% thickness that can be
 238 practised throughout the blade length (Fig. 5(e)).
 239

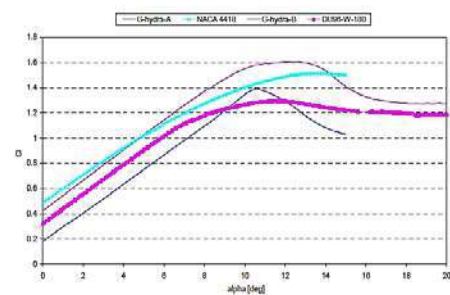
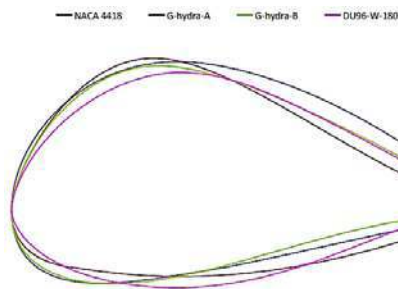
Hydrofoil design



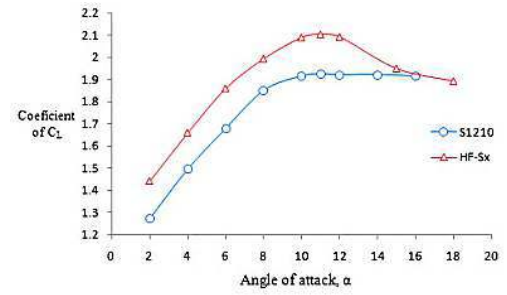
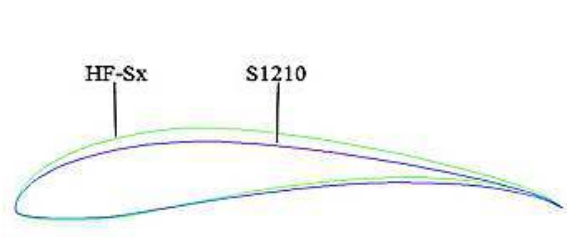
Hydrodynamic performance



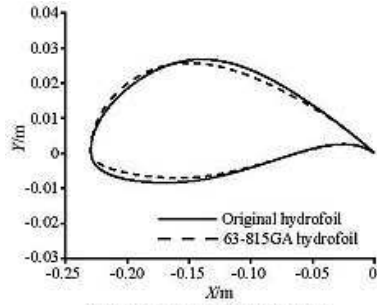
(a) New hydrofoil (GT1) [77]



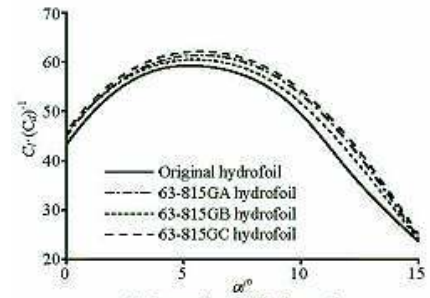
(b) New hydrofoil (G-hydra-A, G-hydra-B) [79]



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

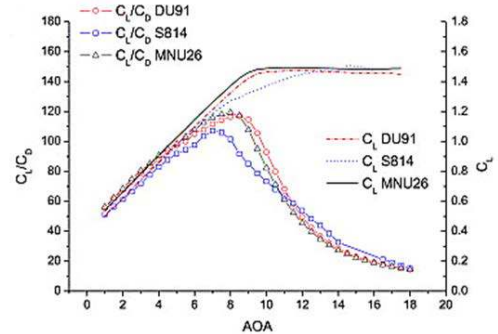
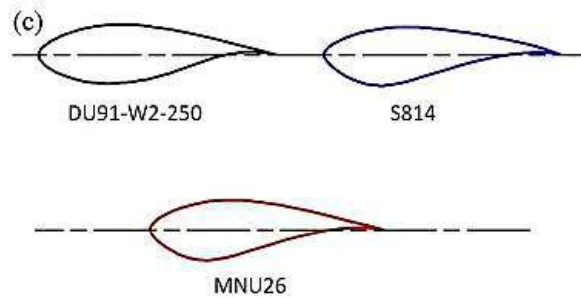


(a) 63-815GA and original hydrofoil



(a) Comparison of lift-drag ratio

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



(e) New hydrofoil (MNU26) [88]

240

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

241

242

From the above literature, it is apparent that the performance of tidal current turbine primarily

243

depends on optimal hydrofoil design in the following manner:

244

- 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.

245

246

247

- 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° .

248

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

258

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

265

266 **3. Design requirements and factor affecting the TCTs**

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

272

273 **3.1. Design requirements and features**

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

279 In this context, tidal current turbine hydrofoil design can be divided into two very
280 distinct interdependent domains. The first is its hydrodynamic design, whilst the other is its
281 structural design. The purpose of the hydrodynamics design is to achieve a preferred external

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

308 The hydrodynamic parameters for hydrofoil include studying the pressure distribution
309 of the hydrofoil, minimum coefficient of pressure (CP), coefficient of lift (CL), coefficient of
310 drag (CD), and lift to drag ratio (L/D). Further design parameters include pitch, twist, and
311 taper distribution of the blade and its performance characteristics on a rotating blade. The
312 hydrodynamic design is further complicated due to non-uniform speed and direction of the
313 current, the shear profile in the tidal flow, and the influence of water depth and the free
314 surface [95]. In addition, it's very important avoiding the cavitation, since it will have a
315 detrimental effect on the hydrodynamic performance of the blade. Attukur [96] performed the

316 numerical simulation to maximize the lift-to-drag ratio and lift coefficient of the hydrofoil at
317 design flow conditions and to avoid cavitation at off-design flow conditions. The method of
318 multi-objective optimization problem uses a python module named OpenMDAO framework
319 in order to solved the Non-Sorting Genetic Algorithm (NSGAI). The cavitation performance
320 at the tip of the blade could be improved by decreasing the pitch angle, thereby increasing the
321 AOA [97]. For this issue, Material-induced bend-twist coupling can be introduced by
322 tailoring the composite layups. Well-designed composite marine lifting surfaces can increase
323 the efficiency, and delay cavitation, separation, and stall [98]. Liu [99] proposed a new design
324 method of C groove for vortex suppression and energy performance improvement for a
325 NACA0009 hydrofoil. The results showed that the C groove method improves energy
326 performance by 2.79% and suppresses tip leakage vortex by 67.94%.

327

328 **3.2.Factors affecting TCTs**

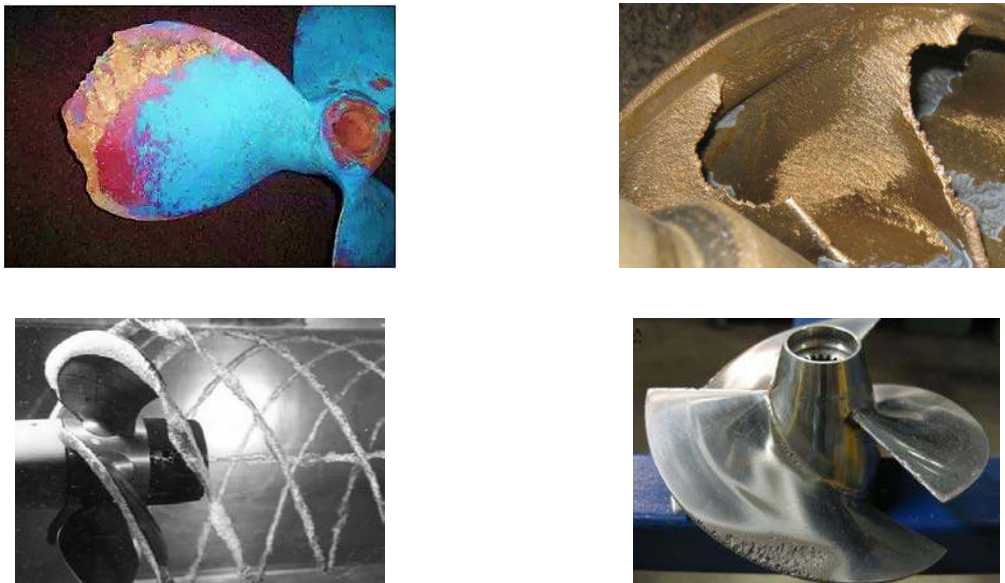
329 Although device reliability and engineering design is the most essential part when it
330 comes to devices such as tidal turbines, improving the turbine performance based on the
331 environment where it is installed is also a crucial step in developing this technology. This is
332 why the authors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

334

335 **3.2.1. Cavitation**

336 Cavitation phenomenon is the greatest limitation in selecting a hydrofoil for tidal
337 current turbine blades. These phenomena affect negatively the efficiency of the hydrofoil. By
338 decreasing lift coefficient and increasing drag coefficient [100,101]. In general cavitation is
339 another difference between wind and tidal turbine layout, besides bio-fouling. If bio-fouling
340 remarkably appears on blade surfaces with low speed, cavitation generally appears close high
341 speed areas of the blades. Static pressure instantly reduces due to the increased dynamic head
342 at high speed location and can create vapour bubbles. These bubbles will finally be
343 disintegrated and create high frequency and high-pressure pulses which initiate the process of
344 corrosion on the surface and turning the blade surface rougher. Once more, a tough blade will
345 reduce the performance of the blade since it changes the design of the aerofoil particularly
346 when the roughness is close to the tip of the blade where the maximum of energy production
347 is generated. Wang et al. [102] have examined the using of cavitation tunnels and marine
348 propellers examination solution to be valid in the study of small-size tidal turbine
349 performance once cavitation is present. In addition there are numerous types of cavitation that

350 will impact the turbine's performance as presented in Fig. 6. Also, it was presented that
 351 cavitation increases noise pollution particularly in critical situations and could disturb marine
 352 creatures. It was additionally proposed that tidal turbines might be placed above the sea
 353 bottom at least by one diameter size distance to prevent erosion and sediment movement.
 354 Bahaj et al. [103] supported the thought of negative issues of cavitation to the energy
 355 extraction of tidal turbine and it always depends on the shape. It was eventually proposed that
 356 the blade tip speed must be lower than 7 m/s to avoid cavitation. Barber et al. [104]
 357 performed various numerical analysis employing a BEM-FEM solver to check out the blade
 358 reaction to the cavitation. It was mentioned also that the blade response is separated of the
 359 material direction. It was also discovered that cavitation was observed for tested tidal turbine
 360 at normal operating condition; therefore it must be associated with the design process.
 361 Relating to modern design, it was identified by Nicholls et al. [105] that adaptable blade be
 362 changed or adapted according to the stream conditions, and also can reduce the probability of
 363 cavitation in their BEM analysis of a model tidal turbine.



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

365

366

3.2.2. Bio-fouling

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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

372 blade due to erosion. Marine fouling as a result of deposited microorganisms on the surface
373 will finally colonize areas of the blade. This will depend on water deepness, temperature,
374 salinity, and position of the site. Although, its dependence on position, tidal systems (blade
375 root and rotor hub) at 5 m under water will be coated with fouling especially at low speed of
376 water as mentioned in [107]. Fouling may be stopped by applying fouling control coatings
377 that are commonly used for ship structures and are categorized into two main types, the
378 biocide-based paints and the fouling-release coatings. The first was depending on controlled-
379 release of active substances to control fouling as the other was predicated on the physical
380 properties of the covering itself. Yebra et al. [108] presented the functions of the two coatings
381 in relation with turbine performance across time-immersion with the covering. Biocide paint
382 will not have a significant drop before 2-3 years of experienced installation. Foul-release
383 coatings have an unexpected decline in performance for the first couple of years but will have
384 self-clean and recuperate performance. The same author also offered a study around the
385 effects of three different fouling mechanisms (three circumstances from three different
386 coatings) in the efficiency of tidal turbines. The results demonstrated a loss of about 7.5%,
387 22.5% and 40% in the daily energy generated after 5 years of direct exposure for the three
388 coatings respectively. Chen [109] also stated that at higher level of fouling on the blade of a
389 tidal turbine may reduce 70% of efficiency. Fig. 7 exemplifies the growth of plants and other
390 marine life on the supporting structure of tidal current turbine.

391



392

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

394

395

3.2.3. Interaction with Stanchion

396 The interaction with the stanchion can affect the performance and loading on a tidal stream
397 turbine. In addition to the number of blades, the magnitude of the effect is also influenced by
398 the geometry of the stanchion [110] and the distance between the rotor and the stanchion
399 [111]. The former study found that the power output of a turbine with an elliptical or
400 hydrofoil shaped stanchion is around 20% higher than with a square stanchion and the total
401 thrust around 35% lower. The latter work also showed that the power output increased by
402 around 10% when the rotor to stanchion distance was increased from 1 to 2 hub diameters
403 with the turbine upstream of the stanchion. Furthermore, although the average power output
404 was found to reduce by only around 7% when the rotor was downstream of the stanchion, the
405 fluctuations in power over the rotational cycle increased from around 2.5% to around 30%
406 and the fluctuations in thrust from 1% to 15%.

407

408 **3.2.4. Wake Length**

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

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

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

434

435 **4. Numerical models of tidal turbines**

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

446

447 **4.1. Blade element momentum (BEM) method**

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

460 BEM modeling method was thereafter incorporated into the design of wind and tidal
461 turbines, the first time by Sorensen and Kock [120]. They used tabulated aerofoil

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

474 Based on BEM method, performance analysis of horizontal axis tidal current turbine
475 (HATCT) has been carried out by several researchers. Chen et al. [124] used a combination
476 of BEM and CFD for blade design and analysis the performance of HATCT. Bir Gunjit et al.
477 [125] outlined the procedure of the HATCT composite blade design using a developed code
478 based on BEM theory. Nicholls-Lee and Turnock [126] performed BEM analysis of a
479 horizontal axis tidal turbine model, and it was found that the concept of passively adaptive
480 blade reduces blade loading and delays cavitation inception. Batten and Bahaj [127,128]
481 predicted the power output performance of a 0.4 m diameter HATCT using the BEM method,
482 it was shown that power production and the blade tip speed reduced with yaw angle except
483 for situations with high blade inflow angles.

484 From the review of the above literatures, it can be seen that BEM theory was extensively
485 used, as it shows promising capabilities in designing and analyzing the performance of tidal
486 turbines with the merit of being more robust, faster and less computationally intensive as
487 compared to other numerical methods. However, it can have some limitations that probably
488 critical to certain analyses. One of the major limitations of the BEM technique is that it
489 cannot be employed to examine the influence of a rotor on the surrounding flow, and where
490 an analysis of wake dynamics is needed, alternative modeling methods should be employed.
491 A number of such alternatives were developed to assess the turbine wakes. Lawson Michael
492 et al. [129] developed a computational fluid dynamics methodology to simulate the
493 hydrodynamics of HATCT, wherein the design procedure based on the coupled methods of
494 BEM theory and CFD was employed. Malki et al. [130] also developed a modeling approach
495 based on BEM theory to predict the performance of tidal stream turbine in the ocean

496 environment; through the coupling of the BEM method with CFD flow domain, the effect of
497 upstream hydrodynamics on rotor performance was accounted for. The CFD modeling
498 method, which is more relevant when the rotor undergoes complex flow conditions such as
499 high levels of turbulence and variable flow directions will be covered in the sequel.

500

501 **4.2. Computational fluid dynamics (CFD)**

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

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

529 computational time to resolve, via filtering out the small turbulent flow scales from the large
530 unsteady flow motions.

531 We aim here at elaborating the current literature that has employed CFD to explore issues and
532 topics related to tidal turbines. Harrison et al. [131] and Batten et al. [132] exploited full CFD
533 model to simulate the hydrodynamic performance of a HATCT, and the numerical data
534 resulting from simulations were validated with a full turbine model experiment carried out in
535 a cavitation tank. Morris [133] used CFD to study the effect of solidity on the performance,
536 swirl characteristics, and wake length and blade deflection of a HATCT. Batten et al. [134]
537 conducted CFD simulations to study the influence of wake induced turbulence and oceanic
538 flows on the performance of tidal turbines. MacLeod et al. [135] described the application of
539 CFD techniques in the modeling of tidal turbine wakes, where an in-house code called “3D-
540 NS” which is a RANS solver with κ - ϵ closure has developed to simulate clusters of turbine in
541 any configuration. Gant and Stallard [136] used CFD model to simulate time-dependent
542 turbulent flow around a tidal turbine, where porous disc modelling was used for tidal turbines
543 with a RANS k - ϵ to provide some insight into the influence of large-scale flow oscillations on
544 the wake of the turbine. Churchfield et al. [137] applied LES approach to arrays of tidal
545 turbines to provide useful unsteady information about wakes and power production, wherein
546 the subfilter scale (SFS) turbulence model was used for the RANS simulation for smaller
547 scales. Mason-Jones et al. [138] conducted a series of CFD models of the tidal turbine when
548 it was subjected to either a plug flow or a profiled high shear flow in order to evaluate the
549 effect of the rate of shear across the turbine diameter; in these models the RANS equations
550 was used to relate the Reynolds stresses to the mean velocity gradients. O’Doherty et al. [139]
551 used CFD models to assess the performance of a 10 m diameter, three-bladed HATCT in
552 terms of torque, power and axial load against a plug flow and two profiled flows. Kang et al.
553 [140] simulated 3D turbulent flow past marine hydrokinetic turbine by developing a
554 computational framework for performing high-resolution LES in arbitrarily complex domains
555 involving moving or stationary boundaries. Afgan et al. [141] investigated the blade loading
556 and turbulent flow in tidal turbine using RANS and LES and compared the two CFD models.
557 Furthermore, there were a few models that have developed by a number of researchers to
558 couple CFD and BEM methods to overcome the limitation of BEM method. In these models,
559 BEM was used as tool for initial design purposes in order to reduce the design iterations
560 before using CFD method. For example, Malki et al. [142] developed a coupled BEM-CFD
561 model to study the effect the upstream hydrodynamics on rotor performance. It was found
562 that such coupling between CFD and BEM results in addressing the limitation of BEM in

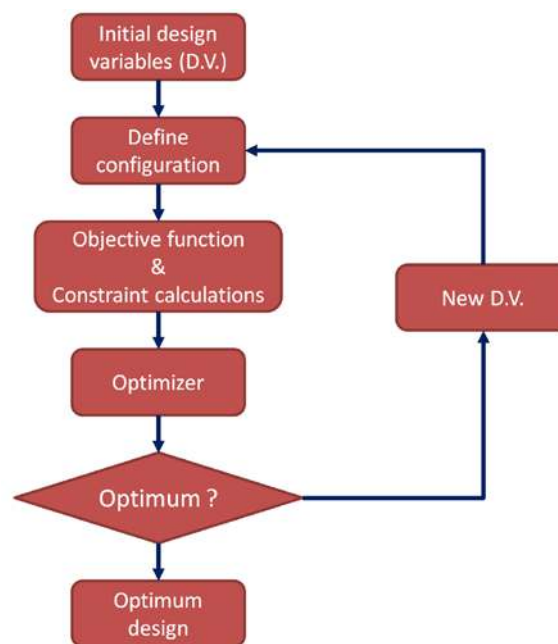
563 analyzing the effect of a rotor to the surrounding flow. Turnock et al. [143] used a coupled
 564 model combining BEM theory to represent blade forces on the flow and CFD to simulate
 565 flow through the domain to predict the hydrodynamics and performance of a tidal current
 566 turbine. Edmunds et al. [144] used a coupled BEM–CFD model to address various aspects of
 567 tidal stream turbine modeling in the natural environment. Williams et al. [145] presented a
 568 combined computational CFD-BEM model that enables the prediction of the performance of
 569 tidal stream turbines at a chosen location using site specific data.

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

572

573 4.3. Design optimization of hydrofoil

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



584

585

Fig. 8: Flowchart of optimization process.

586

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

593 According to the researches cited above, it can be observed that which hydrofoils are
594 used for TCTs in which published articles from experiments test or hydrodynamic design.
595 Moreover, most of these excellent design methods are concentrated on the hydrofoils lift and
596 drag coefficient but not so much on the cavitation phenomenon. So, it is important to
597 investigate a design optimization technique that takes into account the cavitation performance
598 and the lift-drag ratio concurrently for hydrofoils to enhance the hydrodynamic performance
599 of TCTs more efficiently. Two types of optimization technique exist that are widely utilized
600 in tidal current turbine blade design field, namely Genetic Algorithm (GA) [153] and
601 gradient-based optimization methods (GOM) [154,155]. Luo et al. [155] studied and
602 optimized airfoil NACA63815 to get novel hydrofoils by using NSGA-II algorithm.
603 Cavitation and lift-to-drag coefficient ratio characteristics were employed as a goal in this
604 genetic algorithm. Grasso [156] used a design optimization technique and founded two new
605 hydrofoils by using advanced algorithm of sequential quadratic programming (SQP) and the
606 RFOIL solver. Yang and Shu [157] enhanced the lift-drag coefficient ratio of the NACA0012
607 by using the hierarchical fair competition genetic algorithms and CFD simulation. Cocke et al.
608 [158] optimized the hydrodynamic characteristic of hydrofoils (lift-drag ratio, coefficient of
609 lift and coefficient of drag) by using computational fluid dynamic (CFD) simulations and
610 genetic algorithms.

611

612 **5. Summary and discussion**

613 From the above discussions it is clear that technology, hydrofoil, design consideration
614 and numerical optimization approaches play a very important role in optimal design and
615 successful implementation of the TCTs system. Tidal current turbine hydrofoil design can be
616 divided into two very distinct interdependent domains. The first is its hydrodynamic design,
617 whilst the other is its structural design. The objective of the hydrodynamics design is to
618 achieve a preferred external profile of the blade that provides the optimal performances. But,

619 the major requirements of hydrofoil design are high C_L and high Lift/Drag coefficients ratio
620 over a wide range of AOA in order to get great turbine performance. On the other hand, the
621 most important parameters, from the structural point of view, are the maximum hydrofoil
622 thickness and the chord-wise location of the maximum thickness. The thickness of the profile
623 must be able to accommodate the structure necessary for blade strength and stiffness.
624 Depending of the class of the tidal current turbine, certain values for the thickness along the
625 blade can be expected and this fact introduces a first indication for the design problem. The
626 location of the maximum thickness along the chord is also important; when a hydrofoil is
627 designed, also the other hydrofoil along the blade should be considered to guarantee
628 constructive compatibility. This means that, in order to allow the spar passing through the
629 blade, the chord-wise position of the thickness should be similar for the complete blade.
630 Since a hydrofoil for a tidal turbine blade is installed in water, when the water is polluted, the
631 blade is not easy to maintain or repair. Therefore, a hydrofoil with a shape which is less
632 sensitive to surface roughness is needed. In addition, because various loads are structurally
633 imposed on the hub part, the wing tip must have a gradually thick hydrofoil shape. When
634 increasing the thickness of the blades, their strength and camber increased, thereby improving
635 the hydrodynamic characteristics of hydrofoils.

636 Designers face challenges in designing blade sections for TCT as these sections must
637 prevent the occurrence of cavitation and also provide high hydrodynamic efficiency. Tidal
638 turbine technology is still developing and a lot of research and development is needed for
639 large commercial uses. Attention is also given to research on the material used for
640 manufacturing of TCT blade; manufacturing even a very high efficiency rotor is of no use if
641 it experiences cavitation and bio-fouling. Material used for blade must be strong enough to
642 prevent cavitation erosion, and also prevent or minimize the blade fouling, hence minimizing
643 the maintenance cost. Tidal turbine blades also encounter large thrust forces; again stiff
644 material is required for structural strength [159,160].

645

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

651

652 **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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