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# A Review on Numerical Development of Tidal Stream Turbine Performance and Wake Prediction

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**ABSTRACT** Recently, the output of Computational Fluid Dynamic (CFD) prediction on tidal stream turbine systems has been receiving great attention owing to the vast and untapped tidal stream potential. For several years, many publications have documented the accuracy of CFD methods for steady flows, but not for unsteady flows. A challenging area persisting in the computational field is its dependence on large computing resources, and the unsteady nature of usual tidal streams. To overcome this problem, researchers have proposed modelling simpler, representative devices or combined CFD with alternative predictive methods. Nevertheless, the turbulent modelling has been a critical issue in the CFD methods and great effort has been devoted to the study of turbulence and wave effect on the wake and functioning of the turbine. The present paper is a review of CFD application on tidal stream turbine performance in both steady and unsteady flows. The performance of the turbine predicted by actuator and blade resolved methods, has been in accordance with laboratory observations. Findings of the wake have been both consistent and inconsistent with measurements, arising from interpretation of the blade force, fluid-solving method and onset flow model, and downstream range distance. With regards to arrays, preliminary work shows turbine arrangement can have profound effects in the onset flow, and in consequence, the performance of adjacent turbine rows. The results reported appear to support the wind similarity assumption, such as wake Gaussian velocity distributions and fluctuating turbine output in unsteady flows. Under the influence of surface waves, the wake recovers faster than steady flow condition due to the flow's convective acceleration, but the mean performance stays almost equal. The findings in this paper give a critical review and insight of important implications for future turbine research, such as experimental validation of the turbine prediction output in small and large arrays.

**INDEX TERMS** Computational fluid dynamic, tidal stream turbine, unsteady flow, turbine performance, wake characteristics.

## I. INTRODUCTION

Reducing the reliance on high-carbon fuels is an important issue for governments. Quite recently, the kinetic energy of tidal streams has been converted into electricity through horizontal-axis tidal stream turbine (TST). Tidal stream and wind turbines are very similar concepts, but differences in the incident fluid result in significant differences on cost, operation and surrounding impact [1]. Two of the big advantages of tidal stream energy, compared with wind's, are the regularity of tidal currents and its large energy density ratio [2], [3]. The water density is about 800 times the air's, and since the

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turbine's theoretical power and fluid density are proportional, thus a tidal stream turbine requires a diameter, smaller than the wind's, in order to produce the same rated power [4].

Because wind generator turbines have existed for at least 100 years [5], they now pertain to a remunerative industry. For the most part, the wind industry flourished with the development of several key elements: cost-effective foundations; fatigue-resistant, composite materials; efficient power systems; competitive grid supply; and low ecological impression. The development of tidal stream technology links to the offshore wind industry [5]. Yet, tidal stream industry is underdeveloped and highly priced, but it is improving and becoming profitable. Headlands and constricted natural sites across the globe are being intensively studied due to its large current speeds and ability to hold tidal stream devices: horizontal and vertical-axis turbines with fixed and floating sub-sea foundations, ducted turbines, oscillating foils, helical screw designs and underwater kites [6], [7]. Despite the paucity of high-quality research describing the advantages and constraints of each energy-converter design, the industrial preference has been placed on horizontal-axis tidal stream turbines, as a result of economics and high-efficiency design [8]. Therefore, for reasons of space, only the fluid dynamics of this concept are considered in the paper.

Sources put the global tidal potential at 3 TW [9]–[11], but only 50 GW may be exploited via streams [12], once subject to a site feasibility study. Conceivable areas comprise, amongst others, the coastlines of UK (∼11.4 GW), Japan (∼2.2 GW), Canada (2GW), France (1GW), and South Korea [1GW] [12]. For instance, only the tidal stream capacity of the coast of Pembrokeshire, in Wales, UK, has been assessed by the Crown Estate to be around 2 to 4 GW [13]; although this investigation was representative of the practical sites (low depths and high speeds) [14], thus findings may increase over time as technology is improved, costs are reduced, and environmental consequences are proved to be negligible in the medium to the long term [15], [16].

Studies of wind electricity-generating devices over the past decades have provided important yet limited information on the tidal device's functioning and economics. The existing research recognizes the critical role played by structural design on the tidal system's reliability, public acceptance and growth. To fulfil the envisioned tidal stream potential, it is crucial to establish steps committed to the financial success of electricity-delivering tidal stream systems. These include the development of cost-effective foundations and understanding of turbine performance in site conditions, requiring the characterization of the marine currents and flow past the turbine.

### A. AMBIENT FLOW

The simple, ideal case for turbine functioning is the non-varying speed flow, named the steady state. Inevitably, both natural and artificial impediments generate turbulence in the ambient flow. In the literature, there is no general agreement on the intrinsic properties of turbulence [17]–[19]. Turbulence is unpredictable, disorganized, damaging to turbine and foundation, undesirable and unproductive.

In practice, the valuable traits to determine in the tidal currents are the turbulence intensity ($TI = u'/U_0$ where $u'$ is the Root-Mean-Square of fluctuating velocity and $U_0$ is the mean velocity) and the length scale (L) by using the Taylor's hypothesis. Tidal streams generally contain a $TI = 5\sim13\%$ [20], [21], and may or not combine with waves [22]. The bed friction, topography of the site and wind are to account for the shear flow profile in tidal streams.

There exist various approaches to characterize the tidal stream turbulent nature. The 1/7th power law, is a well-known, experimentally-backed approach [22], based on the adjustment of the steepness of the flow. Given method has been effective in the implementation of numerical programs [23], [24].

### B. TURBINE OPERATION

There are two modes of operation for a turbine, namely the steady and unsteady state. Performance in steady state is reliable and predictable. Traditionally, the performance of a tidal stream turbine is normalised with the free-stream flow into power ($C_p = P/(0.5\rho A U_0^3)$) and thrust coefficient ($C_t = F/(0.5\rho A U_0^2)$), and rotor's Tip Speed Ratio ($TSR = R\Omega/U_0$), where $\rho$ is the density, $P$ is the power, $F$ is the thrust, $A$ is the turbine sweeping area, $R$ is the turbine radius and $\Omega$ is the rotating speed. Generally, physical models of turbines have been based on the Froude Scale law similarity. Therefore, results of physical model characteristics, particularly of thrust and power are biased, given the self-reported nature of blade dependence with the Reynolds Number.

Compared to an onshore turbine, a tidal stream turbine is frequently subject to harsh and extreme environmental conditions. Furthermore, corrosion, scour effects, biofouling, unsteady rotor operation and cavitation are to be accounted in the design of the support and turbine. Cavitation is a well-known water-related issue to cause wear on the blades, and it may influence the organic life due to incrementation of turbine noise and changes in the sediment transport as a result of turbine proximity to the sea bed [25]. To counteract it, the static pressure along the blade sections must be above the saturated vapor pressure of the current. Two manners to obtain this are to elevate the turbine, and to decrease the range of TSRs. However, since tidal currents are depth dependent and turbine losses increase with lower TSRs [26], the determination of a practical and highly-efficient turbine, free of cavitation, is technically challenging.

Additionally, since tidal stream turbines are practical at shallow sites, designers must account for the fluid constrained by the large vertical proportion of the turbine diameter to channel depth: usually one to two-thirds [27]. This is named blockage. As a result, the flow disturbance and performance obtained from a wind turbine in an unbounded flow is not expected to be the same as a tidal stream turbine [28].

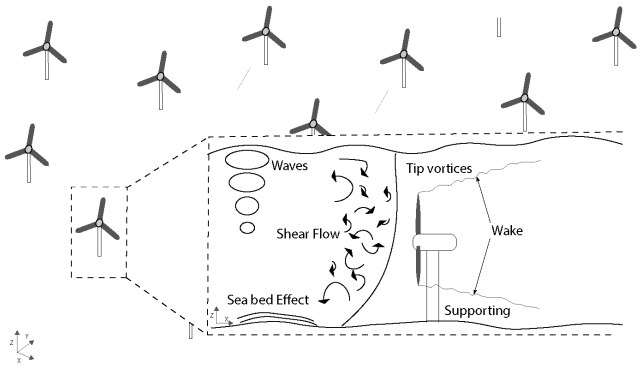



**FIGURE 1.** **Physical processes of wake flow generated by a turbine and within the farm.**

In the last years, many attempts have been made to quantify the association between the disc properties and inflow conditions, and its hydrodynamic coefficients [29], [30]. Although considerable amount of works has been published on the disc, no clear method exists for designing a porous disc, equal to a rotor; much of the research up to now relies in experimental evidence [31].

Difficulties arise, however, when the rotor operates in an unsteady state. The unsteady-flow condition leads to cyclic turbine operation [32], dynamic stall [33], aerodynamic effects [34] and overall reduction of power in wind turbines [35], whereas in tidal stream turbines, its effects are little understood. In recent years, various scaled turbines are being studied in test laboratories comprising different flow conditions: current with low and high turbulence alone, and current combined with waves [36].

### C. WAKE

A widely held view to exploit economically the tidal resources is to deploy numerous, tidal devices, in various geometrical distributions, called simply farms. A primary concern of the tidal farms is to maximize profits in a small-invasive ecological manner [37]. In many cases, it may be associated with the resulting, disturbed rotating flow behind a single turbine, named the wake; since the changes in onset flow are known to have a serious effect in the turbine's production of electricity [38].

A summary of the physical processes affecting the wake of a turbine in isolation and within the farm are given in Fig.1. As observed, the flow impinged to the blade sections will be unsteady and height dependent due to the shear profile and influence of waves, and the tip vortices will be affected by the bed and water surfaces. Assuming the rotor has identical blades, using a constant-rotational strategy, the forces experienced by each blade will inherently be time-varying and unique. To further complicate matters, preliminary work shows the turbine performance will be highly cyclic due to the blockage and operation of the turbines in an array, namely, rotating speed and pitch condition [39], and thus understanding will be more complex. Whereas increasing efficiency with blockage seems to be reasonable, secondary effects appear, such as need of high TSRs, deriving into cavitation [40]. At this case, it is important to first understand the underlying mechanisms of the simplest condition, a single turbine apart from the farms, to then see how it contributes to the total performance. But clearly, the challenge now is to develop engineering tools and techniques for the characterization of the complex nature of the wake and support interference on a case-by-case basis, combined with the influence of bed surface and wave effects and other turbine wakes.

Much can be learned from wind, since the wake of wind turbines in farms has been widely investigated [41], [42] and associated with the rotor's rotation and torque [43]. Until now, two wake parameters are identified as potentially important: the width and downstream distance of the wake.

A commonly held view by many scholars is to classify the wake as belonging to near or far downstream, in terms of the shear velocity layer structure. The blade section performance and support obstruction are more important in the near than far wake, as a consequence of their induced vortices and decrease of axial velocity due to the blade power extraction. Since the blades apply a torque to the flow, the wake rotates, and a shear stems from the tip; this effect is more pronounced with higher TSRs. Due to energy balances, the pressure undergoes a pressure jump across the disc and is restored at the far wake but with a reduced velocity. The factor found to be increasing the wake recovery is the turbulence, induced by the ambient flow, blade tip, and obstruction of the tidal device. Authors argue the wake velocity deficit between a wind and tidal stream turbine is similar; the wake profile follows a Gaussian-type distribution [44], [45] and flow recovers to ambient pressure at 8 (turbine) radii downstream. As a result, individual turbines must be positioned either in non-overlapping sections or farther downstream of other turbines, where the wake flow is recovered to the free-stream conditions. Debate still continues about the best distribution for array of turbines, in terms of overall power extraction, noise and flow reduction impact. Several authors investigate the factors influencing the wake, namely the array configuration, spacing [46] and free-stream characteristics: Turbulence intensity, Reynolds number [47], [48].

A numerical-study approach is often adopted to obtain this, prior to prototype construction and field measurements. The advantages include reduction of costs and manufacturing time, and assessment of project output and economic yields.

As a general rule, increasing the model complexity leads to more computing requirements and accurate results. With the recent trends in climate change action and proliferation of farm project proposals, more knowledge will become available from field trials and prototypes, thus corroborating the above findings.

## II. COMPUTATIONAL TECHNIQUES

Various approaches can compute the turbine performance; namely vortex methods (VM), blade element momentum (BEM) Methods and CFD methods. There are

differences among approaches in terms of model's complexity, of solution accuracy, and of demand for computing resources. VM is distinguished from other methods, by focusing on the vorticity shed by the airfoils, rather than on the velocity and pressure of the stream tube [49]. Areas where VM's relevance for tidal stream turbine can be found include the wake tracking and formation, and performance in time-varying flows. The BEM is a mixed theory, based on the momentum theory (MT) and blade element theory (BET) [31]. The use of pieces of software based on BEM to predict the tidal stream turbine performance is increasingly becoming popular [36], but provide limited wake information. Instead, simulations using CFD with commonly RANS (Reynolds Average Navier Stokes) and LES (Large Eddy Simulation) approaches lead to a wider understanding of turbine's and wake's behavior, but they are time-demanding and memory expensive to run [50].

The above methods, however, suffer from methodological limitations, thus, whilst refinements in the models are being made, a case-by-case examination of the studied turbine situation remains the best solution. Because local blade performance and inflow characteristic (speed and pressure) are highly correlated, the shear flow, either as steady or non-steady, inherently exert radial variations of force and power, leading to net unsteady performance. Including these depth variations in combined models is potentially viable but results difficult [51] when treated as steady, and even more difficult, when regarded as time-varying [52]. There is almost null information on the wake by BEM (only wake velocity at recovered pressure) and uncertainty on the turbine power and lack of swirl in the wake due to the actuator disc method. The BET requires previous knowledge of the airfoil characteristics over a range of Reynolds number, either from experimental or numerical approaches. Due to the high complexity of the turbulence nature, CFD methods only account partial turbulence nature and accuracy must be experimentally validated: RANS method produces statistical results, whilst (LES) only considers the large-scale energy containing eddies.

A comparison of results among the methods is shown in Tab.1. Overall these results indicate the importance of CFD models for their wake capacity; although RANS models would benefit from further refinement for predicting the near wake zone. The LES method works well across different wake distances but reducing its computer requirement remains a challenge.

**TABLE 1. Summary of different computational techniques.**

| Method | Blade model | Turbulence closure model | Capacity of Wake prediction | Reference |
|---|---|---|---|---|
| VM | Lifting surface + BET | / | validation needed | Urbina et al.[53] |
| BEM | MT + BET | / | / | Wu et al.[54] |
| CFD | Actuator disk | RANS ($k-\varepsilon$) | validation needed | Sun et al.[55] |
| | Actuator BEM | RANS ($k-\omega$ SST) | Far wake | Olczak et al.[56] |
| | Actuator Line | RANS ($k-\omega$ SST) | Far wake | Baratchi et al.[57] |
| | | LES | Far and near wake | Creech et al.[58] |
| | Blade resolved | RANS ($k-\omega$ SST) | Far wake | Zhang et al.[44] |
| | | LES | Far and near wake | Afgan et al. [59] |

### A. BLADE ELEMENT MOMENTUM THEORY

BEM is a simple, well-tested approach, regularly used for pilot device design and testing. MT maintains the rate of change of momentum, side to side of a stationary disc in a free-stream flow, is proportional to the disc pressure, multiplied by its normal area. The speed of the flow prior to and past the disc is reduced, but then recovers (initial conditions) at a far downstream distance [29]. Because continuity equation applies in the flow, the normal flow area must increase or reduce to offset the velocity fluctuation. The shape of the flow formed is named the stream tube, and the flow past the disc, the wake. The term force, embodies various concepts and factors, such as the change of axial flow between free stream and disc velocity, named axial induction factor, and change of angular rotor velocity to rotational velocity flow, called tangential induction factor [21]. The theory provides a useful account of how a device can obtain power and thrust in a steady, unbounded flow. In the case of tidal stream sites, a considerable literature has grown up around the theme of bounded flows, such as due to water surface and bed channel [60]. This blockage increases the speed of the bypass, flow between wingtip and surface boundaries, resulting in a greater pressure drop across the turbine. When increasing number of turbines are placed along the channel, given effect pronounces, leading to higher power efficiencies; but it is only valid to a certain limit, as flow stagnation begins to occur [61]. As a result, the power of a tidal device in blockage conditions may exceed the Betz limit set in wind turbines [49]. Despite its simplicity, MT suffers from predicting the disc behavior with axial inductions greater than half, named as the turbulent-wake state; its determination relies on experimental validation.

By contrast, in the BET, the rotor force and torque stems from the blade properties (2D lift and drag coefficients), in accordance with the flow characteristics: Reynolds number [48]. Using the geometric configuration of the airfoil (pitch angle and chord), velocity balances can be made between rotor rotation and inflow speed to obtain the forces parallel and perpendicular to the airfoil. Developments in the aeronautic sector have led to a proliferation of foil shapes (high lift or speed), and several airfoil nomenclature and classifications exist. Current methods to obtain lift and drag characteristics include computer models and wind tunnel tests.

In BEM, the forces from BET and MT are assumed to be equal. Thus, in order to obtain the performance, the blade is divided into small independent sections, where equations of

momentum balance must satisfy the analogous components induced in the airfoil by the lift and drag components. The solution is found using standard, iterative procedures, written in a numerical code routine [60]. The sections outcome is finally aggregated to acquire the total performance of the device. The traditional BEM is comprehensive but limited. Since BET fails to resolve the hub and wingtip vortex losses, the available BEM methods take these variables into accounts with experimental formulae. Specific details can be found in wind assessment references [48]. However, these results may not be applicable to tidal stream turbines due to at least two reasons. First, as the tidal stream turbine constricts the channel current, the bypass flow is accelerated, thus modifying the axial induction factor, an important parameter in the tip-loss formulae [28]. Second, the lower rotating speed condition of tidal turbines increases the wake effects, thus requiring further implementations to obtain precise calculations [26].

BEM can be used to predict cavitation, as shown in works of [62], although turbulence, waves and surface effects can impose pressure differences along the blades, leading to inaccuracies in the model [63]–[65].

### B. CFD TURBULENCE CLOSURE MODELS

CFD methods are popular due to their high reputation in assessing dynamic coupled energy-converter systems, such as propellers [66], shaft tubular turbines [67] and wind turbines supported by floating platforms. During the last two-hundred years, mathematical findings regarding flow phenomena led to the development of the five-coupled dynamic fluid equations, or Navier-Stokes equations. CFD pieces of software solve partially these differential equations via numerical methods, to describe the flow behavior in complex conditions, including the turbulence's [68]. Since its first formulation, various attempts have been made to solve the full equations describing the turbulence, but all methods result too complicated and have failed. Instead, techniques to simplify the governing conditions, such as using turbulent flow-approximating models, reduce the number of coupled equations from 5 into 4 or less. This approach proves sufficient.

In the tidal stream field, two well-known, practical fluid-solving methods include the RANS and LES [17]. The conceptual RANS model is based on treating the fluid properties (eg. velocity in turbulent field) in a statistically-averaged manner by using two parameters: a mean and a zero-fluctuating component. As a consequence of this decomposition, a Reynold stress, caused by the fluctuating part, appears in the original Navier-Stokes formulation; and to fully solve this fluid behavior, modelling of the turbulence is initially required [44].

For incompressible flows, the Reynolds-averaged momentum equation is indicated by Equation (1) as follows:

$$\frac{\partial \overline{u}_i}{\partial t} + \frac{\partial (\overline{u}_i \overline{u}_j)}{\partial x_j} + \frac{\partial (\overline{u_i' u_j'} - 2\mu \overline{S}_{ij})}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \overline{p}}{\partial x_i} + \overline{f}_i \quad (1)$$

where $i$ and $j$ (range from 1 to 3) represent the directions, $x$ is the spatial co-ordinate, $u$ and $p$ are the Reynolds-averaged velocity and the pressure respectively, $\rho$ and $\mu$ are fluid density and dynamic viscosity respectively, $\overline{f}_i$ refers to the time-averaged volume tensor term and $S_{ij} = 0.5 * (\partial \overline{u}_i / \partial x_i + \partial \overline{u}_j / \partial x_i)$ is the rate-of-strain tensor. By definition, the Dirac function is $\delta_{ij} = 1$ for $i = j$ and $\delta_{ij} = 0$ otherwise. The $k - \varepsilon$ [69] and $k - \omega$ [70] model, known generally as the Reynolds-averaged turbulence model which are used to solve the Reynolds stresses $\overline{u_i' u_j'}$. The $k - \omega$ SST (Shear Stress Transport) model, a refined turbulent technique put forward by Menter [71] combines the best of standard $k - \omega$ and $k - \varepsilon$ turbulence models.

In the $k - \omega$ SST model, the transport equations for turbulent kinetic energy $k$ is:

$$\frac{\partial (k \overline{u}_j)}{\partial x_j} = \frac{\partial}{\partial x_j}\left((\nu + \sigma_k \nu_t)\frac{\partial k}{\partial x_j}\right) + P_k - \beta^* k\omega \quad (2)$$

This equation differs from the standard $k - \omega$ model as the production of turbulent kinetic energy $P_k$ is limited by:

$$P_k = \min(\nu_t \frac{\partial \overline{u}_i}{\partial x_j}\left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i}\right), 10\beta^* k\omega) \quad (3)$$

Whilst the transport equation for the specific turbulent kinetic energy dissipation rate $\omega$ is:

$$\frac{\partial \left(\omega \overline{u}_j\right)}{\partial x_j} = \frac{\partial}{\partial x_j}\left((\nu + \sigma_\omega \nu_t)\frac{\partial \omega}{\partial x_j}\right) + \alpha \frac{1}{\nu_t} P_k - \beta \omega^2 + 2(1 - F_1)\sigma_{\omega 2}\frac{1}{\omega}\frac{\partial k}{\partial x_i}\frac{\partial \omega}{\partial x_i} \quad (4)$$

The turbulence viscosity can be calculated using the following relation [72]:

$$\nu_t = \frac{\alpha_1 k}{\max(\alpha_1 \omega, SF_2)}; \quad S = \sqrt{2 S_{ij} S_{ij}} \quad (5)$$

The remaining undefined terms are calculated from the following relations:

$$F_1 = \tanh\left\{\{\min[\max\left(\frac{\sqrt{k}}{\beta^* \omega y}, \frac{500\nu}{y^2 \omega}\right), \frac{4\sigma_{\omega 2} k}{C_{Dk\omega} y^2}]\}^4\right\} \quad (6)$$

$$C_{Dk\omega} = \max(2\rho\sigma_{\omega 2}\frac{1}{\omega}\frac{\partial k}{\partial x_i}\frac{\partial \omega}{\partial x_i}, 10^{-10}) \quad (7)$$

$$F_2 = \tanh[[\max(\frac{2\sqrt{k}}{\beta^* \omega y}, \frac{500\nu}{y^2 \omega})]^2] \quad (8)$$

where, $y$ is the distance to the nearest wall, $S$ is the invariant measure of the strain rate, $F_1$ and $F_2$ are blending functions.

The SST model applies $k - \omega$ formulation in the boundary layer of the flow, and in the freestream it switches to $k - \varepsilon$ behaviour to alleviate sensitivity in the $k - \omega$ model [71], [73]. The relevance of the SST applies for flows under adverse pressure gradients, eg. development of boundary layers around the flume walls [73]–[75].

Model constants are obtained by a blend from the corresponding constants of the standard $k - \omega$ model $(\alpha_1, \beta_1, \alpha_{k1}, \alpha_{\omega 1})$ and the transformed version of $k - \varepsilon$ model

$(\alpha_2, \beta_2, \alpha_{k2}, \alpha_{\omega 2})$ via the general form $\emptyset = \emptyset_1 F_1 + \emptyset_2 (1 - F_1)$. Typical values are as follow [71]:

$$\alpha_1 = \frac{5}{9}, \alpha_2 = 0.44, \beta_1 = \frac{3}{40}, \beta_2 = 0.0828, \beta^* = \frac{9}{100}, \quad \alpha_{k1} = 0.85, \alpha_{k2} = 1, \alpha_{\omega 1} = 0.5, \alpha_{\omega 2} = 0.856 \tag{9}$$

To develop a fuller picture of the turbulence, the modelling requires the resolution of turbulence scales of different lengths, a resulting memory-expensive procedure, known as direct numerical simulation (DNS). Alternatively, the computing time may be decreased, albeit with less accuracy, via treating only the large-scale energy containing eddies directly. The aforementioned approach is called LES [76], [77]. The effects of small-scale eddies are accounted for modeling using a subgrid-scale (SGS) mode.

To eliminate the effects of small eddies, the LES method writes the equation (10) in terms of a filtered residual velocity:

$$\frac{\partial \overline{u}_i}{\partial x_i} = 0, \quad u_i = \overline{u}_i + u_i' \tag{10}$$

In cases where incompressibility is significant, the momentum equation (11) is:

$$\frac{\partial \overline{u}_i}{\partial t} + \frac{\partial (\overline{u}_i \overline{u}_j)}{\partial x_j} + \frac{\partial \tau_{ij}}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \overline{p}}{\partial x_i} + \overline{f}_i + \frac{\partial \sigma_{ij}}{\partial x_j} \tag{11}$$

where $\sigma_{ij}$ is the stress tensor provided by equation (12), $\tau_{ij}$ is the subgrid-scale stress defined by equation (13):

$$\sigma_{ij} \equiv \upsilon \left( \frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i} - \frac{2}{3}\frac{\partial \overline{u}_i}{\partial x_i}\delta_{ij} \right) \tag{12}$$

$$\tau_{ij} \equiv \overline{u_i u_j} - \overline{u}_i \overline{u}_j \tag{13}$$

where $\upsilon$ is the kinematic viscosity. The subgrid-scale stress is required for modelling the equation closure. It can be computed using the Boussinesq hypothesis as equation (14):

$$\tau_{ij} - \frac{1}{3}\tau_{kk}\delta_{ij} = -2\upsilon_{SGS}\overline{S}_{ij} \tag{14}$$

The term $\tau_{kk}$ defines the isotropic part of the subgrid-scale stresses, not added to the filtered static pressure, and $\upsilon_{SGS}$ is the subgrid-scale turbulent viscosity.

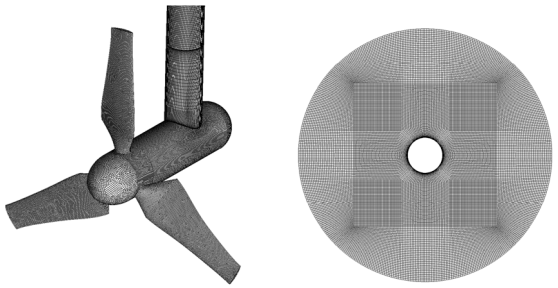
A descriptive comparison of the two methods is described in McNaughton *et al.* [78]. The rotor operated under a TI of 1%. Tab.2 highlights the number of meshes employed, and the computational resources of both methods. Results were close to measurements at maximum power generation, but lower, at other TSRs. Overall, LES was significantly better than RANS, albeit at a higher computing cost. The SST $k-\omega$ model proved better than the $k-\varepsilon$.

### C. ROTOR THRUST REPRESENTATION

An implication of the Navier-Stokes equation is the possibility of external source loads, such as the turbine's by the blade effect. The most comprehensive study is to account the whole tidal system and identify how both the turbine and the support interact with the tidal current [44]. This approach is called blade resolved as shown in Fig.2 (a) [79], [80].

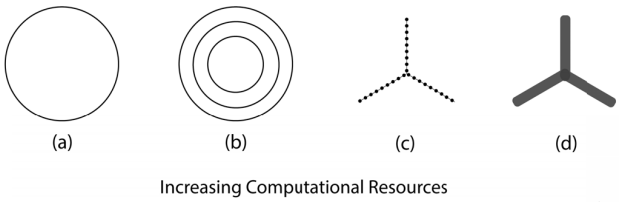
**TABLE 2. Comparison between RANS and LES calculation by McNaughton *et al* [60].**

| Turbulence model | | Meshes (million) | Resources | Time for calculation |
|---|---|---|---|---|
| RANS | $k-\varepsilon$ | 3.7 | 32-128 cores on the University of Manchester's CSF | several days |
| | $k-\omega$ SST | 3.7 | 32-128 cores on the University of Manchester's CSF | several days |
| LES | | 7.4 | 2048 processors on the EDF Blue Gene P supercomputer | 2~3 months |



(a) Blade resolved mesh (b) Actuator mesh

**FIGURE 2. Generated meshes on a tidal stream turbine and a disc for the CFD simulations, modified from Olczak [79].**




(a) Actuator disk (b) Actuator BEM (c) Actuator line (d) Blade resolved

**FIGURE 3. Techniques to characterize the turbine in the CFD simulations, modified from Olczak [79].**

However, there are limits to how far these concepts can be adopted, especially for the amount of difficulty and resource demand regarding the turbine geometry and nearby flow simulation.

Various turbine load-representing methods have been put forward to solve this issue as indicated in Fig.2 (b) [79]; namely actuator disk, actuator BEM, actuator line in Fig.3 [79]. Each approach has its unique benefits and disadvantages. The constant actuator disk method is based on MT [38] and has attractive features: the first is the simplicity of the modelling, stationary rather than non-stationary mesh solution; and the second is the methods confidence [81]. However, the main disadvantage is the lack of swirl in the flow, an important characteristic of the wake formation and recovery. The blade force by BET is one of the more practical ways, by virtue of the airfoil properties widely available from

experimental studies. Two methodologies can be derived by the treatment of the blade force in respect to: a distributed annulus, named Actuator BEM, or a revolving line, named Actuator Line. This force may be applied in different forms: steady and unsteady, uniform and non-uniform along the radius; thus, method has been found valid for analyzing both steady and unsteady operation of arrays [82]. Therefore, a possible flow discrepancy near the blades cannot be ruled out, when compared to a blade resolved model.

Since the actuator line's conceptual framework leads to unsteady loads, its computational resources are typically higher than for actuator BEM methods. Although accuracy is to a degree, within reach of each method, significant differences can be found in the tidal turbine's mesh-independent solution: ∼3∗10^6 cells [83] using blade resolved method, as opposed to actuator BEM's 4∗10^3 cells [79].

## III. NUMERICAL SIMULATION OF TURBINE PERFORMANCE AND WAKE

### A. CURRENT CONDITION

The unsteady-state operation of a single wind turbine [84]–[86] and a tidal rotor share a number of key features. The turbulent current has been found to cause variation of thrust and power [87], [88], resulting in several issues: fatigue [89]; reduction of system reliability by the appearance of extreme forces [36]; and loss of power by variable turbine output [36], [90]. A descriptive case study of shear flow is difficult, and thus findings differ by method and evaluated parameter: thrust, power, wake profile. Tab.3 compares findings and intercorrelations among single and multiple turbines in current, as computational requirement is increased for a given method. Clearly, all the methods anticipate appropriately the thrust but main differences found include the wake capacity: near and far zone. As pointed out in Tab.1, the LES is far more computationally costly, and therefore better adapted to assess the mechanisms underlying in the wake development, than the other methods.

When it comes to economization of computational resources, the research shows the prediction of the average wake velocity and TI from actuator disc of various porosity ratios is similar to, but below, the experimental data [31]. Particularly, the extension of the wake and recovery of the far region is greater than the observed. The reason for discrepancies could be partly attributed to the lack of swirl in the method, tending to over-estimate the prevalence of mixture in the wake region [95]. Being limited to a disc, the approach lacks information on the blade performance.

By contrast, the actuator BEM is well suited for the determination of thrust and average properties of single turbine's wake, but discrepancies of thrust up to 12% may be found in turbines arrays [56]. The main drawbacks associated with the use of actuator BEM model are the failure in capturing the shed vortices [91] and the inconclusiveness of the most suitable turbulence model. The method is as well sensitive to the foil properties (lift and drag curves) as described in Guo *et al.* [91]; performance simulations were found more consistent to Bahaj *et al.*'s experiments [96], by using numerical rather than experimental values.

**TABLE 3. Comparison of findings and intercorrelations among single and multiple turbines in current.**

| Turbine configuration | Method | Average accuracy | | Numerical requirement | Ref. |
|---|---|---|---|---|---|
| | | Blade performance | Wake characteristics | | |
| Single turbine | Actuator disk | / | Similar trends but recover more slowly | Low | [31] |
| | Actuator BEM | Accurate prediction of the thrust but over-estimation of power | Reasonably reflection of the averaged velocity instead of the detailed flow features | Low | [91] |
| | Actuator Line | Accurate prediction of means load by RANS, while mean and unsteady loads by LES | LES performs well in predicting the mean flow and turbulence characteristics | Medium (RANS) High (LES) | [92] |
| | | | Good prediction in far wake while discrepancies in near wake by RANS | | [80] |
| | Blade resolved | Within 3% difference by LES but up to 10% by RANS | Match well with experiment in far wake, LES provides blade tip vortices in details | High (RANS) Very high (LES) | [44, 59] |
| Multiple turbines | Actuator BEM | 3% to 12% over-prediction of the thrust | The wake flow accuracy has been assessed up to twelve turbines | Medium | [56] |
| | Actuator Line | Within 2.9% difference of predicted power with experiments | Validates well with the experiments in terms of flow characteristics | High (RANS) Very high (LES) | [82, 93, 94] |

In both actuator line and blade resolved techniques, the LES surpasses the RANS, as it gives a more accurate representation of the flow near the blade tips, and past the turbine and support structure (see Tab.3). Furthermore, LES is able to predict well the unsteady performance [92] and yields slightly better averaged results [59], over a large range of TSRs. As noted by [97], improvements in the RANS method can be made by normalizing results with the turbine rotation and average velocity of the swept area. As Tab.3 shows, most RANS studies in the wake field have only been validated on the far wake with the k-$\omega$ SST model. This inconsistency may partly be explained by the statistical nature and inexactitude of the RANS for predicting the flow separation phenomena (eg. tip-shed and tower vortices), an important correlation in the near wake region. A reasonable approach to tackle this issue could be by establishing new effective turbulence closure models.

There are, however, at least three important observations made in studies. Firstly, the capacity of the wake prediction is likely to be related with the intensity of the turbulence [31], [59] and closure model used, as these two have been shown to affect the wake recovery. For instance, Harrison [98] and Shives and Crawford [99] indicated the k-$\omega$ model is more accurate than the k-$\varepsilon$ with experiments, in respect to the expansion of the far field wake. Zhang *et al.* [44] believes the limitation of the k-$\omega$ SST model, relying on uniform flow treatment, may lead to a smoother flow profile near the turbine placement. Secondly, predictions based on BEM-CFD suggest the wake recovery becomes faster with increased convective acceleration [100] and positioning of the turbine farther off from the bed channel [44]. For the latter point, the faster recovery rate was likely caused by the increase of flow between the turbine and the bed, leading to a better mix of the wake and surrounding free-stream flow. This behaviour as well substantiates previous findings of discs in bounded surfaces [88]. Thirdly, the turbine-supporting structure exerts a shadow effect upon the rotor's downstream flow and thereby produces unsteady axial-force support. Authors [58], [100], [101] have identified the tower wake as a minor contributing factor for the rotor wake; although more recent arguments by Chen *et al.* [102] demonstrate the contrary in the near wake region, and this may explain the relatively good correlation between RANS predictions and far wake observations. A further few works have isolated the tower frequency from the load measurements [36], confirming the little association between performance and tower effect. Commenting on the turbine presence, authors [36], [103] argue the height of the free surface suffers a drop at one diameter (1D) downstream, but then recovers further downstream.

Given the performance and wake of turbines within groups and isolation is a major area of interest within the field of tidal stream. Generally accepted targets for farms assessment include: proper prediction of the wake with and without wake interaction, effect of array configuration, and blockage values. However, most of the studies have suffered from a lack of clarity in defining a turbine arrangement and use of experimental disc data, instead of rotor's. Not surprisingly, the array impact is understudied, particularly using actuator BEM methods. For example, Harrison [98] reports inconsistencies between the actuator BEM and actuator disk's predictions of power of in-line turbines, using an array of 10 turbines with infinite transverse rows: 7D and 2D, downstream and lateral offset, respectively. In comparison, results using the actuator line have been promising, although at a high cost, for predicting power and flow properties in a turbine array [82], [93], [94].

Findings suggest several courses of action for increasing array power efficiency but more research is need to better understand the possible link between turbine operation, position and arrangement. Bai *et al.* [104] found a tendency for extractable power to increase by using a staggered array, regardless of the turbine's rotary direction. Conversely, simulations based on the actuator disc RANS [105] demonstrate a non-staggered configuration produces higher power output than a staggered array. If the debate of optimal spacing is to move forward, a better understanding of the complex interaction between the upward and subsequent turbine's wake formation must be developed. Malki *et al.* [106], for instance, considers the performance of downstream turbines to augment ($\sim$10%), if these are placed behind the lateral, unblocked and accelerated flow between two upfront turbines; although Myers and Bahaj [107] states the contrary for a disc array of two rows, by increasing the total efficiency of the farm. Apsley *et al.* [82] examined the relationship of performance of two in-line turbines with centre-line and downstream spacing, using RANS simulations and experiments. The downstream turbine dropped its power and thrust output, if immersed in the wake of the upstream turbine (less than 1D centre-line distance). However, the contrary behaviour occured if the centre line distance between the upstream and downstream turbines are equal to one, one and a half [108], and two or more diameters [106]. Simulations using RANS method shows both low lateral (2D instead of 4D and 6D) [95] and longitudinal row spacing [46] produce optimal energy capture in the tidal array. This rather contradictory result may be partly explained by the higher wake mixture at far downstream distances, resulting in less capture of downstream turbines.

To determine the overall flow array impact, Shives and Crawford [99] have objectively measured and assessed numerically the array performance, consisting of 3 and 2 turbines with a single transverse row. The k-$\omega$ SST model emerged as the most reliable predictor of the wake structure but the velocities near the wake were poor, probably due to turbulent effects not accounted in the simulation [82]. The methodology of using wind Jensen wake models to predict the farm wake of five turbines with three rows, was investigated by Palm *et al.* [109]. The results had a discrepancy of only 10%, when compared to a CFD model, suggesting wind and tidal farm performance share a number of features; although modifications in the Jensen model are still needed, such as inclusion of blockage.

Other authors report the notable weakness of the models for arrays with small downstream offsets [104]. The need to improve the model is still necessary to evaluate the impact of the downstream flow and turbine performance.

### B. WAVES CONDITION

Turbine output in waves is complex since waves cause unsteadiness in the current [27], [110]–[113] and can propagate in-line, opposing, or at a particular angle with the current [114], and the downstream flow may be as well subjected to the sea bed effects [115], [116]. Another important implication is the significance of the ratio of the wave-induced site depth to wavelength of many tidal stream sites, meaning the functioning of deployed turbines will likely be unsteady. Moreover, a 10-20% reduction of tidal extractable

**TABLE 4. Comparison of findings among single and multiple turbines in waves.**

| Method | Average accuracy | | Numerical requirement | Ref. |
|---|---|---|---|---|
| | Blade performance | Wake characteristics | | |
| Actuator BEM | Large fluctuations in power production | Good agreement in both surface elevation and fluid hydrodynamics. | High | [112] |
| Actuator Line | Good agreement with time-varying force | In agreement with the experiments for the far wake. | Very High | [79] |
| Blade resolved | Good prediction in both the torque and thrust force | Physically closer to reality and give reliable results on complex geometry | Very High | [111] |

power is expected due to the bed friction and wave-current combination [117], [118].

Observations indicate the mixing of waves with turbulent current has an increasing effect on the overall turbulent intensity in the vertical and downstream profiles [118] and tip vortices [119]. But in spite of this, the unsteadiness response, on average, is similar to the turbine performance [36], [120] and wake (velocity deficit, kinetic) of steady flows [27]. This interesting outcome was explored in [60] to predict the thrust in wave-current flow as a mixture of steady and unsteady induced forces.

To date, only a few researchers have addressed the issue of waves acting in currents, since most CFD models are largely based on closed flow models with non-free surface effects; since having a surface constraint, greatly affects the wake expansion [121]–[123]. Tab. 4 presents the results obtained from CFD simulations. As observed, the actuator BEM is the far most cost-effective approach and compares well with observations, in terms of wake and surface properties [111]. Increasing in computational complexity, the actuator line provides a closer examination of the wake velocity due to waves presence. The simulated fluctuating forces and trials match well [79]. On the other hand, the blade resolved method addresses properly the wake and performance of the turbine, although it fails to describe extreme torque operating conditions [111].

Other techniques have been developed to solve this problem, such as the volume fluid model used by Tatum *et al.* [124]. In this study, the k-$\omega$ SST model was used with 2.8 million cells to obtain time-varying thrust and moment blade in two wave conditions: one matching, and the other, not matching the frequency of the turbine rotation. Drawing upon extensive analysis, a larger power variation was obtained if the wave had (rather than not) the frequency of the turbine rotation, thus leading to a decline in the blade's durability. According to the CFD RANS simulations of Tatum *et al.* [125], the variations of load may peak if the wave and turbine's rotation frequency are equal, thus requiring proper assessment of site flow conditions prior to turbine deployment.

Turning now to simpler methods, a BEM method attempt was made by Faudot and Dahlhaug [120] to predict the loads on the turbine. The method considered the forces due to flow acceleration, by first assessing the wave-current kinematics using linear wave theory. Predictions were contrasted to a turbine towed in waves, showing the mean thrust and torque were slightly reduced by the waves. Despite these preliminary good results, there is abundant room for further progress. To develop a comprehensive overview of this issue, the BEM method may increase in complexity, by incorporating the dynamic wake, stall, and the added mass effects and wave loads on turbine and support structure [126], [127]. Another fruitful area for further work concerns the effect of oblique waves and turbulence on the turbine and blade reliability.

The experimental research comparing steady and wave-induced flow has found good agreement of mean turbine performance with a torque-control system, and of wave-current kinematics with linear wave theory [128].

Although studies have recognized the good average prediction of the above methods, research has yet to investigate the influence of kinematics on time-varying performance. For instance, Luznik *et al.* [129] provides a quantitative evidence of torque influence due to vertical kinematic oscillation, whilst Galloway *et al.* [127] reports a fluctuation of turbine force, compared with mean force, of 1.37. In addition, even a small periodicity of the current may produce an output variability, as much as 1.5 times the average thrust [126], demonstrating the sensitivity of the turbine with wave characteristic: frequency and amplitude. The extreme thrust of the turbine is exponentially associated with the wave speed amplitude [36]. A key policy priority should therefore be to plan the long-term viability of the tidal systems, by minimising the forces and increasing the overall power efficiency.

## IV. CONCLUSION

CFD methods simulate the functioning of various complex, fluid-related systems. In this review, we have highlighted the current state of CFD methods with regards to tidal flows and device performance. We as well have introduced the basic concepts of fluid modelling and existing solution methods for inclusion of turbulence.

CFD methods can predict the turbine's output, wake, and interactions between multiple turbines, but they employ more computational sources, as accuracy of blade modelling increases. For instance, the main argument against actuator disc methods is the swirl's omission, and against actuator BEM, the exclusion of the tip vortexes. Support structures may carry visible effects in the near wake but not in the far wake region.

Overall, we confirm CFD methods (actuator BEM, actuator line, blade resolved) predict accurately tidal turbine performance in given flow conditions: steady and low turbulent flows. Considerable progress has been gained in turbulent and wave-current flow. Despite the advance of flow-modelling techniques, the parameters leading to wake formation and interference with adjacent turbines are not yet fully understood, therefore, accuracy of wake profiles may be variant on the downstream distance range. And as we know from wind turbines, the turbulent onset flow characteristics are

transported to the downstream flow. Turbulence causes force and torque variance, but the changes in the mean performance characteristics are similar to the steady flow condition.

In waves and current, the mean properties of the wake and turbine output have been reported as the same; namely the velocity deficit and thrust and power but not the turbulence intensity. Models increase in complexity by accounting the surface effects and the flow acceleration. According to BEM-CFD simulations, the wake length shortens with waves, and given effect increases with increasing convective acceleration.

Overall, the k-$\omega$ SST model appears to be the most suitable model for the far wake region considering the modelling accuracy and computational resources. Although, what is not yet clear is the impact of modified turbulent models on the properties of the wake. Further experimental work is needed to correlate the turbine prediction output in arrays. Preliminary studies assume the farm power output may be greatly altered by the local blockage caused by turbine close arrangement, up to 10%. Array studies have demonstrated a poorness in the CFD's wake predictions of inter, closely-aligned turbines, and this may be due to the treatment of the rotor thrust and turbulent flow nature. Another possible area of future work would be to determine how floating foundations affect turbine functioning.

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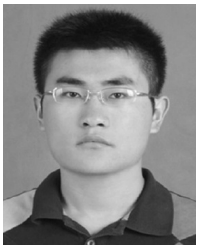

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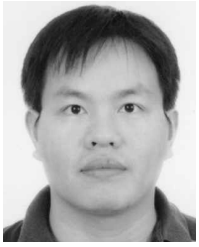

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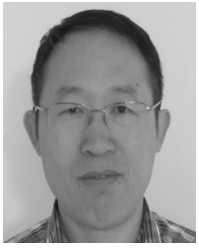

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