Review of tidal turbine wake modelling methods—state of the art

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Abstract—**Enabling Future Arrays in Tidal (EnFAIT) is an EU Horizon 2020 flagship tidal energy project. It aims to demonstrate the development, operation and decommissioning of the world's largest tidal array (six turbines), over a five-year period, to prove a cost reduction pathway for tidal energy and confirm that it can be cost competitive with other forms of renewable energy. To determine the optimal site layout and spacing between turbines within a tidal array, it is essential to accurately characterise tidal turbine wakes and their effects. This paper presents a state-of-the-art review of tidal turbine wake modelling methods, with an overview of the relevant fundamental theories. Numerical and physical modelling research completed by both academia and industry are considered to provide an overview of the contemporary understanding in this area. The scalability of single device modelling techniques to an array situation is discussed, particularly with respect to wake interactions.**

Keywords—**array, large eddy simulation, RANS, tidal energy, wake interaction, wake modelling**

I. Introduction

THE need for clean and reliable energy sources is increasing rapidly, and renewable technologies with currently low exploitation levels must overcome key technological and financial challenges. Recent developments in energy converter technology are reducing the cost of tidal power, bringing it closer to becoming a competitive industry.

Tidal flows are generated by astronomical forces and as a result are predictable months and even years in advance. The tide is a highly reliable energy source, less dependent on specific weather conditions than solar and wind, although the effect of waves and atmospheric pressure can influence local hydrodynamics. Tidal energy is greater in regions with a large tidal range, and is most concentrated in areas of constrained flow such as between islands. Exploitable resources have been identified in many countries including Canada, Japan, and across Europe. The global tidal resource which could be exploited and converted to electrical power has been estimated at several hundred gigawatts [1], and the UK extractable resource has been estimated at around 22 TWh/y [2].

To increase the power yield of tidal stream sites turbines will need to be operated in large arrays. Enabling Future Arrays in Tidal (EnFAIT) is a €20m, five-year, Horizon 2020 project which began in 2017. As part of this project, Nova Innovation will double the capacity of the Shetland Tidal Array in Bluemull Sound by installing three additional 100 kW seabed-mounted turbines, which will subsequently be repositioned to optimise array output and maximise learning. Figure 1 shows the positions of existing turbines (T1, T2, T3), the proposed initial and final positions of turbines T4, T5 and T6. A concurrent programme of numerical modelling and site measurements led by the Offshore Renewable Energy Catapult (OREC) will provide the first ever full-scale, grid-connected demonstration of the impact of a row of three upstream turbines on the generation potential and cyclic loadings of three turbines downstream. More details of the site resource assessment and modelling can be found in [3].

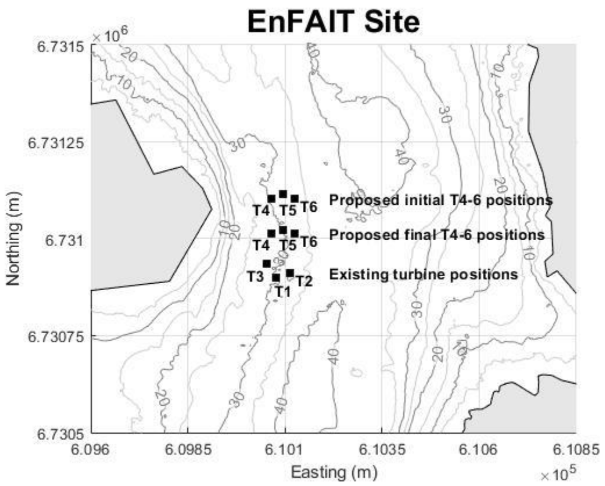

Figure 1. Locations of existing turbines (T1-3) in Bluemull Sound and proposed initial and final positions of T4-6, overlaid on site bathymetry depth contours.

Understanding and predicting wake behaviour is required for array optimisation because upstream wake characteristics will influence the input conditions to downstream turbines in an array. Those conditions will affect the generated power and turbine loading. An

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additional level of complexity arises when devices are positioned such that there is wake-to-wake interaction, altering the process of wake recovery and affecting efficiency even in single row arrays [4].

This work investigates the state-of-the-art in tidal turbine wake modelling, focusing on the most recent publications and on horizontal-axis tidal turbines (HATT). The topic of this paper is wake characterisation and array interaction modelling (AIM); the prior art includes several published works summarising research on hydrodynamic modelling for marine energy more generally [1]–[4]. A brief introduction to tidal turbine wake theory is given, followed by a review of numerical and physical modelling of individual turbine wakes, and finally an investigation into modelling of wakes within device arrays.

II. Turbine and Wake Theory

The wake of a turbine is the area downstream of the turbine which experiences disturbed flow characterised by reduced flow speed, increased turbulence and swirl. In this section wake-related behaviours and the theoretical representation of tidal turbines are discussed.

A. Wake Generation and Flow Recovery

The main behaviours and characteristics of a tidal turbine wake are described in the following sections.

1) Velocity Deficit

Due to the extraction of momentum from the flow by the turbine, water speed is reduced and so the flow downstream of a turbine is slower than that upstream. Velocity deficits due to wakes can often be observed up to [9] or further than [10] 20 times the turbine rotor diameter (20D) downstream of the turbine.

2) Wake Swirl

Turbine wakes also swirl—an equal and opposite torque is generated in the fluid to match that in the turbine. As a result, the fluid behind the turbine rotor rotates in the opposite direction to the turbine blades.

3) Tip Vortices

The rotation of turbine blades causes the formation of tip vortices which are then shed into the flow downstream of the turbine, adding further complexity to the wake.

4) Wake Shape and Direction

Whilst wind turbine wakes are generally considered to be axisymmetric, tidal turbine wakes tend to be asymmetric due to influences of the seabed, free surface, and the turbine supporting structure. This has been shown both in physical [11] and numerical models [12]. Wake meandering—large-scale changes in direction of the wake—can be caused by proximity to boundaries and is influenced by turbulence, waves, and other wakes. Several studies have investigated this [13]–[15] and found that meandering tends to begin after 4D downstream and is characterised by high levels of mean velocity fluctuation.

5) Flow Recovery

A shear boundary layer is formed between the low energy wake region and the surrounding ambient flow field. As mixing occurs between the slow and fast regions, momentum is transferred from the flow field back into the wake. With distance the wake is dissipated through this re-energisation process and the flow field recovers lost velocity. This recovery process is enhanced by turbulence.

B. Factors Influencing Wake Behaviour

The wake created is dependent on the power extracted from the flow and ambient flow speed and direction can be used to crudely predict turbine power output and wake characteristics. In practice there are many other influencing factors which must also be understood such as water depth, flow blockage, turbulence, waves and ocean currents.

1) Site Geography

The depth and bathymetry of a tidal site affects the resource available, as does the width of a channel. The distance between the turbine and the seabed, water surface and channel walls all influence how wakes can expand or meander. Deeper channels have been shown experimentally to lead to faster wake recovery in comparison to a shallow flow [16].

2) Flow Shear Profile

Water flow through a channel has a natural shear profile due to the bottom friction induced by the seabed in comparison with the free region at the water surface. Flow velocity differs at the top and bottom of the turbine swept area, affecting the energy extracted and hence the wake generation and recovery. Shear profiles can differ significantly with tidal height and flow direction.

3) Turbulence

The turbulent characteristics of a flow have a significant effect on wake generation and flow recovery. Turbine loading, fatigue and power outputs are also affected [17], [18]. Generally, ambient turbulence is seen to increase wake recovery [1], with large coherent structures specifically seen to produce a shorter wake [19]. Turbulence can be described in terms of its intensity (TI), and length scale. TI is the root-mean-square of turbulent velocity fluctuations over the mean velocity, as a percentage. Turbulence length scale is a dimensional value describing the size of large turbulent eddies. As with shear profile, TI can vary with velocity, tidal state and with geographical location within a single tidal site.

4) Waves

Waves have an influence on the tidal current and turbulence. Scale experiments have found that waves do not affect average loading but do cause oscillations [20], [21] and that these variations increase with wave amplitude and decrease with frequency [22]. These oscillations increase peak loading, driving turbine design.

It has also been observed that waves can double the magnitude of velocity fluctuation in the upper half of the wake [23]. Numerical models have predicted that waves will enhance local turbulence and fluid mixing behind the turbine, ultimately penetrating through the wake and influencing recovery [24]. If wave interaction is expected then an appropriately incorporated free surface is needed in any computational fluid dynamics (CFD) model [25].

5) Tidal Energy Resource

The tidal energy available will vary at each site, and the tidal range will vary geographically across a large site. Additionally, the local tide varies fortnightly on a neap–spring cycle, and the extent of the neap–spring cycle varies seasonally between the equinoxes. Flow speeds and the shear profile will change as this occurs, affecting the turbine response and hence the wake generated.

6) Other Effects

Although tidal energy is driven primarily by gravitational forces, the resource at tidal sites can be affected by storm surges and seasonal effects such as changing temperature and wind conditions.

C. Turbine Representations

Modelling of tidal turbines can be done numerically or via scale experiments in flumes or tow tanks. Simplified representations of tidal turbines are often utilised to reduce the complexity and cost of modelling. With these simplifications some of the details of turbine behaviour and wake characteristics can be lost. The most commonly used turbine representations are described below.

1) Actuator Disk

Linear momentum actuator disk theory (LMADT) assumes that the loss of pressure across a turbine rotor is due to work done in extracting energy from the flow. Actuator disks (AD) can be considered an idealised turbine and are the simplest turbine model. In computational models this can be represented as a momentum sink over a given area in the streamwise direction [26]. In experimentation the porosity of a disk is set dependent on the thrust coefficient [19]. Momentum loss is modelled but the wake flow, swirl and turbulence are not captured. ADs can be tuned to agree with downstream wake predictions of resolved turbine geometries, but are sensitive to input turbulence length scales [27].

2) Tuned Actuator Disk

More recently a tuned actuator disk (TAD) was developed for numerical methods. It uses a simplified disk grid with fewer elements, tuned to match known thrust and power profiles with the aim of more easily allowing simulation of multiple turbines [28]. However, this approach neglects the effects of wake swirl and turbulence.

3) Blade Element Method

The blade element method (BEM) has been developed as an extension to the AD to include effects of non-uniform loading across the rotor swept area. Averaged loads are represented across concentric bands, usually via forcing terms in the Navier-Stokes equations [29], [30], [31].

4) Actuator Line Model

The actuator line (AL) method includes the effects of non-uniform loading and extends BEM to distribute loads along rotating lines which represent blades, rather than average them over an area [12], [32], [33].

5) Fully-resolved Geometry

The most accurate method is full representation of the rotating turbine blade geometry. For numerical modelling applications this is computationally expensive and not always feasible. Representing turbine geometry at small scale for physical modelling also has challenges associated with the change in Reynolds number.

III. Physical Modelling of Turbine Wakes

Physical modelling of turbines in test tanks at lab-scale provides insight into turbine behaviour at lower cost and risk, supporting turbine design and development and the validation of numerical modelling.

D. Tank Requirements and Scaling

Tank geometry and depth should be representative of in-stream conditions as far as practicable (e.g. proximity of free surfaces and channel walls, turbulence conditions, flow speed). When designing open channel tanks Froude & Reynolds numbers (*Re)* are both important, as the effect of gravity close to a free surface and the viscous forces close to the sea bed both influence the flow. It has been asserted that it is acceptable to have full-scale and model *Re* within the same turbulent classification, and maintain Froude similarity [11]. The performance of turbine blades depends upon the chord *Re* of the blades, so the thrust & torque characteristics of scaled rotors is different to full scale [6]. Specifically, the turbulent boundary layer increases with *Re*, causing the fluid to remain attached to more of the blade [34].

In scale experiments the chord *Re* needs to be considered, however the velocity and chord length which should be used to calculate the *Re* is debated. It has been suggested that the point most influential to power production (0.7R—the near-tip power is decreased by tip losses) would most influence wake velocity reduction [34] [35]. The maximum lift to drag ratio and hence the torque developed is also important, and blade design of scale models needs to account for this to arrive at suitable thrust coefficients and peak power coefficients [36]. It can also be difficult to achieve Reynolds similarity due to flume velocities. To match tip speed ratio (TSR) of full scale devices would require excessive rpm, introducing tip vortices dissimilar from those in a full scale wake [37]. Such turbine scaling effects are most noticeable in the near wake as they are a function of blade hydrodynamics [35].

The InSTREAM project examined the differences between turbulence in tanks and tidal channels and developed a method of scaling this flow. This can assist in creating appropriate tank conditions to represent a given site, to validate and support numerical modelling [38].

E. Measurement Techniques

Measurement devices are required in physical modelling to verify the operating conditions and to measure the turbine's response and the downstream flow field. The devices required will depend on the information of interest—some studies focus on turbine loading, whilst those of most interest to the current work focus on wake behaviour. Acoustic or Laser Doppler Velocimeters (ADVs, LDVs) are commonly used to measure downstream velocities and wake behaviour in test tanks. These measure single points in the flow field, and often several instruments will be used. Particle Image Velocimetry (PIV) has also been used more recently [34], [35], [39], [40]. One key advantage of this over ADV and LDV methods is better measurement of large turbulence.

For testing in the marine environment, Acoustic Doppler Current Profilers (ADCPs) are used to characterise the flow through the whole water column. These can also provide coarse measurements of TI. Seabed and vessel-mounted ADCPs and ADVs have also been used to analyse wakes of full scale turbines [41], [42] but the outcomes of such work are often considered commercially sensitive and not made public.

F. Prior Studies and Findings

A good summary of experimentation prior to 2013 is given by Tedds et.al [43]. Due to tank size limitations, the blockage ratio (turbine swept area to channel cross section) in experiments can exceed that in a potential operational site, which can influence both turbine performance and the wake structure. A study which tested a cross flow turbine, a HATT, and porous plates at different blockage ratios [44] found that higher blockage ratios resulted in reduced momentum loss through the devices. Wake expansion was also reduced in the region measured (<2D downstream).

Work has demonstrated that tidal turbine supports have a significant impact on the near wake [9], but are unlikely to influence the wake >4D downstream [36]. In considering a shared support for offshore wind and tidal turbines, the presence of a large cylinder was seen to further increase the far wake (>6D) velocity deficit by around 12-15% [45].

Studies investigating the impact of waves on scale turbines have primarily focused on loading rather than on wake response. Tow tank tests have shown that regular waves create a wider wake and affect the structure of tip vortices, but momentum deficit and wake growth were similar with and without waves by 2D downstream [34], [35].

High TI does not reduce mean turbine performance but does cause significant fluctuations [46]. Power and thrust can increase with TI by up to 10%, whilst increased turbulence length scale has the opposite effect [47]. Mycek et al.'s comparison of low and high TI (3% and 15%) [48] showed that turbine performance and power outputs were slightly affected, and the turbine wake was much shorter in the 15% case. With a TI of 15% the velocity deficit at 10D was <5%, with a TI of 3% the respective figure is 20%.

It has been seen that increased turbulence levels persist for longer in the wake of scale turbines than is the case for ADs [43], likely due to the addition of swirl effects [9]. Turbine TSR has been found to affect the form and speed of a 6-bladed turbine's near-wake [49], whilst a study examining large scale motions (close to rotor radius in size) in the wake of a 3-bladed model turbine to quantify wake recovery found these to be independent to TSR [13]. In circulating channel tests using a 5-bladed turbine the slipstream expansion reached a maximum at the TSR corresponding to maximum power. This was at around 90% of the theoretical prediction using the Betz theory [40].

Studies have focused on wake behaviour over a range of distances from 2D [34], [35] to 20D [9] downstream of the turbine. Near wake studies have demonstrated that rotation in the near wake [36] has a circumferential velocity of up to 20% of the streamwise velocity, with a significant impact on near wake mixing [9]. Experimental tests have shown strongly anisotropic near-wake turbulence, indicating that near-wakes cannot be accurately modelled with isotropic turbulence [43]. Additionally, tip vortices have been seen to have a significant influence within 3D for the top of the turbine only [13]. In far wakes TI and Reynolds shear stress spread laterally but less so depth-wise, which would affect downstream turbines [9]. Wake meandering has also been observed in tank tests from >4D downstream [13].

IV. Numerical Modelling of Turbine Wakes

Methods of numerical modelling are described in the following section, focusing on their ability to represent wake behaviour. The Turbulence in Marine Environments (TiME) project's guidance on the characterisation and representation of turbulent flows [50] is a useful reference for implementation of the below.

G. Blade Element Momentum Theory

Blade element momentum theory (BEMT) combines LMADT and BEM by subdividing the blades into independent aerofoil sections. Elements along the rotating blade's length are modelled as annular regions across a disk. One drawback is that its standard form does not account for tip vortices and swirl, however methods of accounting for tip and hub losses have been developed.

Several of these methods have been compared to models in DNV-GL's Tidal Bladed software, and to a lifting line theory model to develop a robust approach for prediction of turbine loading [51]. A comparison of BEMT, BEM-CFD and blade resolved CFD modelling approaches found that BEMT thrust predictions agreed well with experimental findings and results of BEM-CFD [10]. BEM-CFD was able to capture wake dynamics observed in the geometry resolved model, however both models may underpredict turbulence. Recently an extension to BEMT to account for blockage due to tidal channel constraints was developed [52]. BEMT has also been modified to account for waves and yawing flow with respect to the turbine, finding increases in cyclic loading and fatigue [53]. It appears from the literature that BEMT is better suited to modelling of turbine loading and power outputs than to modelling of wake behaviour.

H. Computational Fluid Dynamics

CFD modelling is often utilised to model turbine behaviour in a given flow regime. The Navier-Stokes equations can be solved via various methods, and a review of prior art has found that numerous solutions to turbulence closure have been implemented in combination with the aforementioned turbine representation methods.

1) Reynolds Averaged Navier-Stokes

The Reynolds-averaged Navier-Stokes (RANS) method uses time-averaged equations to solve fluid flow. Various turbulence models can be implemented to solve the nonlinear Reynolds stress (R_{ij}) term. Although turbulent eddies are smoothed and approximated, these methods are sufficient for a lot of industrial flows.

1) k-epsilon model and variants

The k–ε turbulence model is a two-equation turbulence closure model, which considers turbulent kinetic energy (k), and rate of dissipation (ε). A single length scale is considered. An equilibrium between R_{ij} and mean rate of strain and turbulence isotropy are assumed. The model is most applicable when there are no large pressure gradients present and does not work near solid boundaries. It has been used when turbine performance and downstream wake were of greater interest than the near wake [54] [55].

RANS simulation using k–ε has been used to compare the accuracy of AD and BEM turbine models [31]. Turbine generated turbulence included as source terms for the AD has been found to be more accurate than using a k–ω SST model, which under-predicted eddy-viscosity and hence wake recovery. The BEM approach is preferable for arrays, as wake and power predictions are more accurate, and it does not require turbulence source terms.

Other studies have found that if a turbine is in close proximity to the water surface then the wake cannot expand along its top edge [54], and that acceleration in the flow direction increases the rate of wake recovery [55].

Modelling of a full size (20m) turbine via an AD method was found to be very sensitive to mesh and grid density. Further work is needed, but such a method could be applied in a larger scale model to examine regional flow effects on turbine performance, where fully-resolved geometry would be computationally unfeasible [56].

Re-Normalisation Group methods have been used to develop the k–ε RNG model, which accounts for a range of turbulent length scales. This is useful if performance is of most interest [54] or if the flow structure of the near wake region is less important than the far wake [57]. The k–ε RNG model has been used in RANS modelling of a BEM turbine representation, and further developed to use Prandtl's lifting line theory. This modifies simulation towards the hydrofoil tip to better reflect tip vortices [57].

2) k-omega model and variants

The k–ω model (ω = specific dissipation rate) is used in cases with boundary proximities and adverse pressure gradients. The shear stress transport (SST) modification uses k–ε in the free stream, and k–ω near boundaries to model the far wake without tuned correction terms [58].

Comparison of AD and AL turbine representations using a URANS k–ω SST model has been run in Fluidity [59]. Results of experiments on a 3-bladed turbine [48], [60] were used for validation. Wake velocity and far wake turbulence agree with experimental results in both cases whilst the near wake region is better represented with the AL model. AL is shown to slightly underpredict the velocity deficit at 2–4D, but turbulence predictions are more accurate. Neither model exactly represents the blockage or bypass velocities. An AL model is around 50 times more computationally intensive to run.

A k–ω SST Volume of Fluid (VoF) approach applied to a BEM turbine has shown that surface waves increase mixing and modify the position of wake velocity deficit in the water column [24]. The k–ω SST model has also been used with fully-resolved geometry to show that an increase in distance of turbine rotor from a flume bed increases wake recovery and reduces wake width. However, near wake CFD results differ from experimental findings [61].

3) Other Methods

Other turbulence models which have been implemented in RANS include another two-equation model, Mellor-Yamada [62] and the more complex seven-equation Reynolds stress model (RSM) [63].

2) Large Eddy Simulation

Even RSM RANS models cannot provide a reliable solution for all cases [64] and so turbulence modelling methods have been developed which seek to solve the largest length scales of turbulence via filtering the Navier-Stokes equations, such as Large Eddy Simulation (LES). Comparison of LES and RANS modelling of a full-scale turbine in Code_Saturne has demonstrated that a LES model is capable of simulating blade-generated turbulence not possible with a RANS model [18]. However, the wake flow was under-resolved in comparison with field data for the 1MW turbine, and a single turbine rotation took a day for the RANS simulation and a week for the LES simulation. One method of reducing computational time is to run a RANS k–ε simulation to develop initial conditions for the LES model [65]. The synthetic eddy method (SEM) has also been used to develop turbulent conditions for LES

[66]. This was integrated into 3D Vortex Method software [67], [68], and demonstrated to represent wake behaviour.

LES models have been implemented with AD, AL and fully-resolved turbine geometry. AL has been shown to be more accurate than AD, though it is not as capable as fully-resolved [14]. One study has shown that the inner (hub) wake shows more stability and less interaction with the shear layer in AL models than in fully-resolved simulations. Turbulence and wake size can also be underestimated, and wake rotation continues farther downstream [46]. Good correlation with experimentation has been achieved using an AL LES modelling approach, particularly at around 3–4D downstream [69].

A study of turbulence length and TI on AD wakes has shown an increase in wake width with inlet TI. Near wake velocity deficit is increased, wake recovery is faster and far wake velocity deficit is reduced with higher TI. Increasing turbulence length scale has a similar effect of causing higher velocity deficit closer to the AD, but reduces downstream deficits due to mixing [65]. Another study of the influence of TI, using AL turbines, has shown that an increase in TI moves the peak downstream TI closer to the turbine. From 6D downstream solutions merge, and TI is higher than that upstream, suggesting that additional downstream turbulence is due to tip vortex breakdown [46]. It has been found that in turbulent conditions the wake mixes within 2D downstream, although this study did not consider hub geometry [70].

Other LES modelling work has found that meandering begins near the point where the spiralling inner hub wake intercepts the outer shear layer [14], and that seabed dunes can increase recovery in the far wake (>4D) due to dune-induced turbulence [15].

3) Hybrid Solutions

LES is the most common scale resolved solution (SRS) however a range of hybrid RANS-LES methods have also been developed and applied to modelling of tidal turbines. This is partly to reduce the cost and complexity of running LES simulation of the full domain, and partly to effectively model regions where small-scale turbulence has a significant influence (e.g. near-wall regions).

A detached eddy simulation (DES) hybrid RANS-LES turbulence model which has been validated against scale experiments showed significantly improved prediction of wake recovery versus a 2-equation RANS model. Wake sensitivity to turbulence lengths which is not seen with the RANS model was shown using the DES approach, with higher lengths resulting in reduced wake recovery, likely due to reduced mixing. It was also hypothesised that in the model a very large turbulence length greater than the turbine diameter could give a surge of higher speed with no change to the wake recovery [71].

An improved scale-adaptive simulation (ISAS) method has been developed. The ISAS method replaces the grid size turbulence length scale method used in DES with the second order term (von Karman) used in scale-adaptive simulation (SAS) [72]. The result is more efficient than SAS and without the grid sensitivity of DES. Initial tests of flow over a cylinder indicate that ISAS represents shear layers well, and investigation of this model on a turbine or actuator disk would be very interesting.

The majority of recent published work has described CFD modelling studies. There are, however, other modelling methods and theories such as the lifting line approach and the boundary integral equation method (BIEM) which can potentially be applied to tidal turbine applications. A new method of implementing BIEM, with a viscous-flow correction model, has been developed to represent a tidal turbine [29]. This could be used with RANS, LES or DES models. Results from a RANS/BIEM study overestimated the wake velocity deficits, so further development of this approach is still required.

V. Array Interaction Modelling

The EnFAIT project will be the first project to perform and validate full-scale numerical modelling of a 6-turbine grid-connected tidal turbine array. Previous studies have been carried out both experimentally on scale turbines or actuator disks, and numerically via various methods. Of the numerical studies, only some of these specifically examine wake interaction.

I. Physical Array Interaction Modelling

Physical AIM has been performed with ADs, porous fences, and scale turbines.

AD studies have been performed in single and two-row arrays. Comparison of 1:120th scale ADs with a 1:15th scale turbine show similar results in the far wake, where swirl and device generated turbulence should no longer be significant, thus validating the AD approach if conditions such as turbulence, thrust, length ratios are appropriate [73]. A 2-disk single row array showed no merging of wakes when disks were 1.5D apart, and flow between the devices was accelerated [74]. A 5-disk fence displayed increased thrust and faster wake mixing for closely spaced devices [75]. This increase is lower than predicted in a theoretical study of this concept—potential efficiency increases from the Lanchester-Betz limit of 0.593 up to 0.798 with increased blockage, then decreases as choking effects reduce the flow through an array [76]. A two row 3-disk array displayed merging of all three wakes before 10D downstream [74]. The upstream disk wakes were deflected due to the third disk. The streamwise distance between rows was 3D, which may be closer than on full-size arrays for practical reasons, even ignoring any performance effects. Another study looking at two disks, with 7D streamwise separation showed that the persisting wake velocity deficit reduces available energy to the downstream disk [73].

Arrays of porous fences have been used to investigate the effects of multiple wakes on downstream fences. For an unstaggered array, the wake of the first fence contains turbulence peaks at the top and bottom of the fence within the mixing layer, whilst the downstream fences affected by this wake had most TI at the wake centre, due to the changed inflow conditions promoting faster mixing [37].

Two axially-aligned scaled turbines tested with spacing of 2D–12D indicated that downstream turbine power is reduced with closer device spacing, but that higher TI can reduce this effect [60]. With 3% TI, downstream turbine power output was just 50% of the upstream turbine, whilst an increase in TI to 15% gave a power output 90% of upstream with device spacing >6D. The wakes of up to 10 3-bladed scale turbines arranged in 1–3 rows showed that turbine wakes in a single row with lateral spacing of 3D differed little from those of individual turbines [23]. With 1.5D lateral spacing, wake recovery rate was slower (particularly for central turbines), and downstream TI was increased. In situations with low ambient turbulence (TI 2%), the TI 20D downstream of a single turbine was 8%, indicating that turbine generated turbulence will have a significant impact on downstream turbines [77].

J. *Numerical Array Interaction Modelling*

Numerical studies of array interaction have utilised a wide range of the models discussed in Section V. RANS, LES [32] and DES [78] methods have all been applied to the problem, using AD, AL, BEM and geometry resolved turbines. Comparison of existing wake models to tidal arrays (in efforts to find simplified methods) have shown an error in wake velocity of 7–10% between a Jensen model and a RANS AD array, suggesting that this method is not appropriate [79].

It is anticipated that downstream turbines in an array will be subject to reduced input flow speeds and produce less power. Whilst this has been demonstrated via various modelling methods [27] [12], one initial study of wakes in tidal arrays showed no significant difference in centreline velocity deficit of two ADs at streamwise separation of 5D and 8D [1]. Studies have demonstrated that staggering rows increases power and efficiency [31], [76], however a RANS simulation of arrays of 4, 7 and 8 ADs by Hunter et al [81] found that a non-staggered array would give maximum power extraction. The latter study considered the influence of tuning operating conditions within an array based on the flow conditions each turbine experiences, which may be the reason for this difference.

CFD modelling of a single row AL array showed clear distinct wakes at 4D which were still evident at 12D, however similar experiments saw wake merging by 8D (although this discrepancy may partially have been due to high TI in the flume experiments) [12]. One approach to modelling a single-row array was to vary the domain width, with a smaller domain width indicating tighter spacing, and resulting in faster wake mixing [80]. Whilst computationally efficient, this modelling approach doesn’t fully represent all the complexities of a row of turbines.

RANS modelling of multi-row arrays has underpredicted the velocity deficit downstream (between 4D and 8-12D) using various approaches [12] [82]. Use of an SST eddy viscosity limiter (SST + S_k model) has been demonstrated as being beneficial in preventing overprediction of wake recovery in RANS AD arrays for streamwise row separation of <10D, with comparison to k–ε and SST models [83]. For row distances >10D, k–ε would be sufficient—indeed k–ε has been shown to better predict wake recovery >4D than k–ε realisable, k–ω SST and RST models [12].

RANS BEM models use turbulence terms at the rotors [82] [80] to account for tip generated turbulence and to introduce swirl. Studies have found that lateral spacing >2D allows optimisation of an array and power increase of 10% [84], and alternatively that lateral spacing of 1.5D is most efficient, with accelerated flow around the turbines and an increase in kinetic energy of up to 22% [85].

An LES study coupled with an actuator line method assessed array behaviour in two methods. An initial LES of wide tidal channel was run in order to develop a model of turbulent inflow without turbines present. This data, saved over a series of timesteps, was then used as inflow conditions for a simulation with a turbine array introduced to the domain. The array was modelled as two infinitely wide rows, and in this situation staggering rows increased efficiency [32]. OpenFOAM has been used to perform RANS (k–ω SST) of a 4-turbine, fully geometry resolved array, using the finite volume method. Upstream turbines experienced faster wake recovery. Turbine support structures were not accounted for in this method [86].

K. *Array Optimisation Modelling*

There have also been numerous works investigating the mathematical optimisation problem of the tidal turbine array, several of these within OpenTidalFarm. These will not be covered in detail here as the focus of this work is to understand turbine wake interaction, but approaches include: Bayesian optimisation [87] surrogate models [88], [89], an adjoint approach [90], and optimising financial return incorporating operating costs [91]. Farms have been represented as turbine density functions [92], and LES studies have been used to test varying blockage ratios in a channel to obtain maximum power per turbine [93]. Yet further methods still include a 3D unsteady Lagrangian vortex method & panel method [94], optimisation using volume flux conservation [95], and tuning individual turbines to modify the array resistance via an adaptive operating strategy [96]. Whilst these approaches do not fully simulate turbine wakes, they may be appropriate for larger arrays when developing an operating strategy or assessing expected array power outputs.

VI. CONCLUSIONS

From the literature reviewed, there are a wide variety of approaches to modelling tidal turbine wake behaviour and wake interaction within an array. Each model has strengths and weaknesses, and some are more sensitive than others to certain input data—e.g. AD models are very sensitive to the input TI level [27].

To select a modelling approach the overall aims of the work should be considered—are the outputs intended to aid understanding of fatigue life, far wake velocity, or full wake structure and behaviour? It has been asserted that the variances expected in a turbine wake (swirl angle, vortices shed) are relevant to the first 5D downstream, and that swirling is not what creates reenergisation [11]. This may mean that the detail of fully-resolved blade geometry is not required for modelling of wake behaviour within arrays. Wake behaviour must be sufficiently characterised that downstream velocity and turbulence are accurately predicted.

One potential approach is to run a very detailed model of a single turbine and use this to validate a simpler model for use in AIM. The detailed model would capture turbine and stanchion geometry, boundary conditions, and turbulence behaviour. Wake behaviour could then be used to calibrate a less complex model (such as an AD RANS model). Turbulence sources at the rotor could be added to represent tip generated turbulence.

A key challenge to date has been the lack of field data to validate array models against. Whilst scale models in test tanks and flumes provide a good indication, scaling of the turbine characteristics can be challenging. The EnFAIT project will allow validation of models against real site data and will enable the testing of multiple array layouts at full scale in a world-first.

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