A Study of Wake Characteristics of Marine Turbine Arrays

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A Study of Wake Characteristics of Marine Turbine Arrays

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Abstract

As the marine energy industry continues to develop and installations grow from single turbines to small arrays and larger farms, understanding and predicting wake behavior using modeling tools is necessary for array design and optimization. The wake characteristics of upstream turbines, including velocity deficit, wake swirling, tip vortices, wake shape and direction, and flow recovery, influence the inflow conditions experienced by downstream turbines in an array and, subsequently, affect the individual turbine loading and power generated by the array. These wake characteristics are influenced by many factors, including site geography, inflow shear profile, turbulence, waves, the strength of the current resource, gravitational forces, storm surges, and seasonal effects like temperature and wind conditions. Efficient array modeling tools that capture these wake effects and resulting turbine-to-turbine interactions need to be developed to optimize farm layouts and design individual turbines for operation within arrays. Unlike the wind industry, the marine energy research community is largely limited to the use of either numerical tools or tank/flume testing to understand marine turbine wake interactions. This paper will investigate recent advances in numerical and experimental marine turbine wake modeling, with a focus on recent publications and on both axial-flow and cross-flow marine turbines. A summary of recent research on these topics is provided. Additionally, a demonstration of turbine wake interactions using computational fluid dynamics is presented.

Keywords: marine turbine array; wake modeling; wave interaction; tidal farm optimization; marine hydrokinetic turbine

1. Introduction

The net-zero carbon emissions targets established by countries around the world at COP26 stimulated a need for reliable renewable energy sources as well as renewables technologies. Marine energy resources such as river, tidal, and ocean currents can provide abundant, predictable, and clean power to both densely populated and remote communities worldwide. The theoretical global current energy resource (i.e., the energy available in the resource) is estimated to be more than 150 GW, and current energy has been identified as a promising source of energy in countries across North America, Asia, and Europe. In the U.S., the technical resource (i.e., the portion of the theoretical resource that can be captured using existing technology) of river, tidal, and ocean currents has been respectively estimated as 99, 220, and 49 TWh/yr [1]. Increasing interest in marine energy as a renewable energy resource coincides with recent developments that are reducing the costs of marine turbine technologies, making them more competitive with mature clean energy technologies such as solar and wind. Along with understanding and predicting performance and loads of a single-rotor through control co-design and optimization [2] in the design stage to increase reliability, efficiency, and cost-effectiveness, it is also necessary to realize and foresee wake characteristics more accurately to support control co-design and the optimization of individual turbines in a marine turbine array. In combination with a high turbulent inflow condition, the level of complexity of performance and loads for downstream turbines tends to increase due to turbine wake characteristics such as velocity deficit, wake swirling, tip vortices, wake shape and direction, and flow recovery.

This work briefly summarizes the most recent published studies related to wake modeling in a marine turbine array using both numerical and physical modeling, focusing on both axial-flow and cross-flow water turbines. The summary reviews key parameters of wake generation and flow recovery and influential factors for wake behaviors, all of which are discussed in prior studies. A high-fidelity computational fluid dynamics (CFD) simulation was conducted as part of this study to demonstrate initial wake characteristics of a marine turbine array with three Reference Model 1 (RM1)

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turbines [3]. Different streamwise spacings between consecutive turbines were investigated to show the effects of an upstream turbine's wake on a downstream turbine's performance and loads.

2. Literature review

This section briefly reviews key parameters of wake-related behaviors as well as numerical and physical modeling for a marine turbine array, focusing on axial-flow and cross-flow water turbines.

2.1. Wake-related behavior parameters

Several parameters are integral to the characterization of marine turbine wakes and wake effects: velocity deficit, tip vortices, wake shape and direction, yawing, site geography, turbulence, waves, and flow alignment [4-5]. The first of the parameters is velocity deficit, which refers to a slower flow downstream of a turbine caused by energy extraction. Chen et al. [6] found that significant kinetic energy recovery happens alongside wake expansion and turbulence dissipation once shear-induced turbulence reaches the wake's core region. Turbulence affects not only wake behavior and flow recovery, but also turbine loading and power output [4]. Yet, tip vortices stimulate turbulent mixing of the downstream wake. Rotating blade tips shed vortices from the blades into the downstream wake, which add and complicate turbulence in the flow field. In large-eddy simulation (LES) of an axial turbine, Posa and Broglia [7] observed that turbulence was dominated by tip vortices that went from stable upstream to unstable downstream. Instability marked the onset of turbulent mixing and momentum transfer from the outer freestream into the wake. In another instance, wake expansion and turbulence dissipation were limited until the onset of shear-induced turbulence in the wake's core [6]. As the wake length indicates the downstream distance from the rotor plane at which the velocity and turbulence intensity recover [4], the wake itself is an important consideration for marine turbine arrays. Turbulence, waves, and boundaries such as the seabed and the free water surface make turbine flow asymmetric. Such asymmetry results in a downstream meandering wake. In a geometrically resolved marine turbine simulation [8], the interaction between the blades and nacelle starts a swirling motion that becomes unstable as it precesses downstream. In a numerical implementation of yaw, Galloway et al. [9] recorded that yaw significantly influenced the range of the other study parameters. As flow depth, channel width, and local bathymetry influence wake meandering and flow recovery, site layout itself is a fundamental consideration for the site-specific optimization of marine turbine arrays. Even though improved power output is possible for turbines deployed near a riverbed, the implementation of a depth-varied velocity profile should lower power extraction so that shallow turbines extract more energy than deep turbines [10]. Even for simple experimental and numerical models, complex terrain is a common consideration for turbine arrays that challenges shear layer approximations and attached parallel flows [11]. Waves add another layer of complexity, as their oscillations cause variable turbine performance in accordance with their amplitude and frequency [9]. Weerakoon et al. [12] measured an increased efficiency with increasing wave period in an experimental study on cross-flow turbines. The last of the parameters, flow alignment, refers to different configurations of turbines: axial-flow turbines and cross-flow turbines, with the latter being of special interest. Cross-flow turbines are distinguished by their rotational axis that lies normal to the freestream instead of parallel to the freestream. Whereas axial-flow turbines extract energy more efficiently than cross-flow turbines, cross-flow turbines are more practical for shallow water and for array layout [4, 13-14]. In consideration of all these parameters, wake modeling should be concentrated on collective optimization instead of individual optimization, as too much focus on the latter leads to worse performance of turbines in a group [4].

2.2. Numerical methods for wake modeling

To reduce the computational cost of simulating arrays of marine turbines, numerical methods such as the blade element momentum (BEM) method and actuator models in CFD have been adopted to simplify simulations without sacrificing too much accuracy. The actuator disk (AD) is the simplest actuator model. Within AD, momentum loss is applied over a circular region in the streamwise direction. One limitation of AD is that it does not include rotational effects, as the turbine blades are replaced by a disk representing the turbine's swept area. In simulations with AD and the Reynolds-averaged Navier-Stokes (RANS) method, Tian et al. [15] acknowledged shortcomings such as underprediction of turbulence intensity. BEM and AD can be combined into blade element momentum theory (BEMT) wherein blades are subdivided into independent airfoil sections, and elements along the blade length are modeled as annular sections around a disk. Galloway et al. [9] detected differences between wind turbines and tidal stream turbines within BEMT, and Zhang et al. [16] cautioned that BEM excludes tip vortices in the same way as AD. Nevertheless, both BEM and AD can accurately predict marine turbine performance in steady and low-turbulent flows [16], and BEMT can guide blade design for more efficient energy extraction and less vulnerability to cavitation [14]. An increase in complexity and accuracy from the AD method is the actuator line (AL) method where the momentum sink is radially distributed along lines to represent the turbine blades. AL can more fully predict the wake meandering region than AD by accounting for turbine rotation effects and by resolving blade tip vortices [8]. Together, LES and AL can resolve swirling details in the near-wake of a velocity profile. Yet AL does not perfectly replicate a geometrically resolved marine turbine's wake behavior. AL suffers the same problem as AD in that the simplified geometry hinders the predictive capability for turbine wake characteristics such as velocity deficit in the near wake and wake meandering and turbine intensity in the far wake [1]. For a more geometrically accurate actuator model, Yang and Sotiropoulos [17] proposed the actuator surface (AS). As in AL, forces on the turbine blades are computed with BEM, but more complex geometries in AS imply force distributions at different radial locations. The nacelle is included as another surface in AS for higher geometric resolution, and thus higher accuracy of wake predictions. With few exceptions, the time-averaged streamwise velocity was comparable between AS and wall-resolved LES of a flow field with periodically placed nacelles [17]. Moreover, AS could reasonably predict turbine wake behavior for geometry-resolved turbines [8]. Overall, the actuator methods balance a lower computational cost with a reasonable but not exact prediction of wake behavior.

2.3. Experimental studies

To complement and corroborate results from numerical methods, experimental studies can be done to examine the effects of turbine array parameters on wake behavior. Chen et al. [6] conducted flume experiments with a porous disk and acoustic Doppler velocimetry to examine the spatial evolution and kinetic energy recovery of a tidal current turbine's wake. Alongside laboratory experiments, acoustic Doppler instruments were deployed in the field for site assessments of velocity, turbulence intensity, and power density [4]. Zhang et al. [18] investigated the effect of ambient turbulent intensity on a tidal turbine's wake behavior in a recirculating water flume by measuring the wake's velocity deficit, turbulence intensity, and Reynolds stress data. By studying the impact of yaw variation on marine turbine parameters, Zhang et al. [19] observed a decrease in the thrust forces on the turbine in the streamwise direction, which could lower loads on downstream turbines in an array [19]. Bachant and Wosnik [20] evaluated the effects of waves and turbulence on two helical cross-flow turbines' performance in a tow tank and in a wave tank. Waves lowered the threshold of tip speed ratios for power output, as the streamwise velocity fluctuation caused by wave activity led to higher induction in the turbine. Although experimental results can guide turbine design and array considerations, experiments by themselves may not fully capture wake effects at utility scale because laboratory results may not scale accurately [5]. Therefore, it is advisable to combine experimental and numerical approaches for cross-validation. Chawdhary et al. [21] executed geometry-resolving LES with CURVIB with experimental validation to compare wake behavior between an individual turbine and a tri-frame array. Array layout affected the wake behavior; for example, the Venturi effect shortened the upstream turbine's shear layer, and the downstream turbines displayed higher turbulent kinetic energy in the near-wake region. Cross-validation with experimental and numerical studies is crucial to check that results are not only capable of predicting wake behavior in marine turbine arrays but also consistent with each other in the wake characteristics that they indicate.

3. Simulation approach

The high-fidelity CFD code, STAR-CCM+, was utilized to study the wake of three RM1 turbines in an in-line arrangement considering different spacings between adjacent turbines. An implicit, three-dimensional, incompressible, unsteady RANS model was applied herein. The shear stress transport (SST) k-ω model was chosen to model the turbulence in the CFD domain. The volume of fluid method was also used to model the interface between air (ρ_{air} = 1.225 kg/m^3) and water (ρ_{water} = 1000 kg/m^3) at the free surface. To reduce the computational mesh complexity while maintaining an acceptable accuracy for the turbine and wake, an actuator line approach was implemented to represent the turbine instead of a blade-resolved model. A tip-loss correction was included to account for losses due to higher local inflow near the tip. The simulation employed a time-accurate approach that tracks blade motion and adds hydrodynamic lift and drag forces to corresponding cells with a source term.

In the current study, the single RM1 turbine with diameter (D) of 20m was used to demonstrate and investigate turbine wake interactions. The RM1 turbine is a dual, variable-speed, variable-pitch axial-flow type with a rated power of 500 kW per rotor at a rated inflow speed of 1.9 m/s. In this study, the water depth was assumed as 50 m, and the RM1 hub center was assumed as 25 m below the water level. The computational domain's streamwise dimension was bounded at 3 diameters (3D) upstream from the first turbine and 10D downstream from the last turbine in the array. An extended length of 50 m was established in the lateral direction from the turbine center location, which results in a blockage ratio of 6.3%. A trimmed cell mesh technique was used to generate a high-quality grid, particularly for the air-water interface as well as the wake regime. Mesh refinement of the wake regime was performed from the first turbine to the last. Locally refined domains at the turbine were developed to generate good mesh resolution around the turbine blades (shown in Fig. 1). More than 100 cells were uniformly distributed in the blade radius direction and more than 4 cells were used for the actuator line thickness.

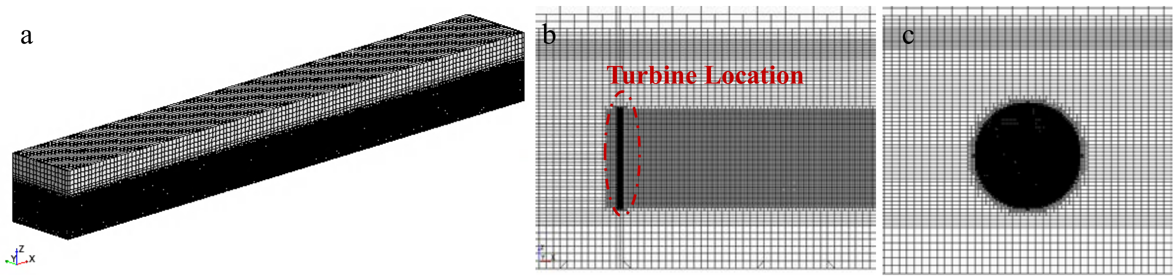

Fig. 1. (a) Full CFD domain; mesh resolution in (b) sideview direction and (c) flow direction

4. Simulation results and discussion

A CFD simulation of a marine turbine array including three in-line RM1 turbines was conducted at rated conditions of 1.9 m/s inflow and 11.5 rpm rotating speed. Streamwise spacings of 7D and 10D were simulated to investigate wake effects on turbine performance, with an emphasis on the downstream turbines' performance.

Figure 2 illustrates the wake development within the marine turbine array. The cross-section plane displays axial fluid velocity of both the air and water phases. The tip vortices shown by the vorticity iso-surface are illustrated by their magnitude. The upstream turbine's wake was not fully mixed before reaching the downstream turbines. Complex wake behaviors and interactions can be observed behind each turbine, particularly for the downstream turbines.

Quantitatively, the turbine-wake interactions led to significant power (or torque) and hydrodynamic load reductions, as shown in Fig. 3. While the first turbine's hydrodynamic thrust and torque remain constant, both downstream turbines exhibit high fluctuations. Similar to wake behavior in a wind farm, wake meandering, which can be described as a low-frequency modulation of the entire wake, potentially contributes to the downstream turbines' power and load fluctuations.

Differing wake effects caused by turbine spacing are also examined in this study. The effects of streamwise spacings of 7D and 10D on rotor torque and thrust are compared in Fig 3. If the transient period of wake development is neglected, the downstream turbines' hydrodynamic performance and loading show smaller amplitude fluctuations as well as higher mean values for the 10D spacing than the 7D spacing.

5. Conclusions

In this study, a literature review was conducted on state-of-the-art marine turbine array modeling, considering both physical and numerical approaches. A summary of recent studies on wake modeling and wake behavior in marine turbine arrays was presented, covering both axial-flow and cross-flow turbines. A study of turbine wake characteristics and wake effects on the performance and loading of downstream turbines was conducted with high-fidelity CFD simulations. Significant power (or torque) and hydrodynamic load reductions and fluctuations were observed due to turbine-wake interactions for an array of three in-line RM1 turbines. Additionally, lower amplitude fluctuations and higher mean loads were observed for a streamwise spacing of 10D than a spacing of 7D. Future studies will focus on detailed wake analysis related to relevant wake behavior.

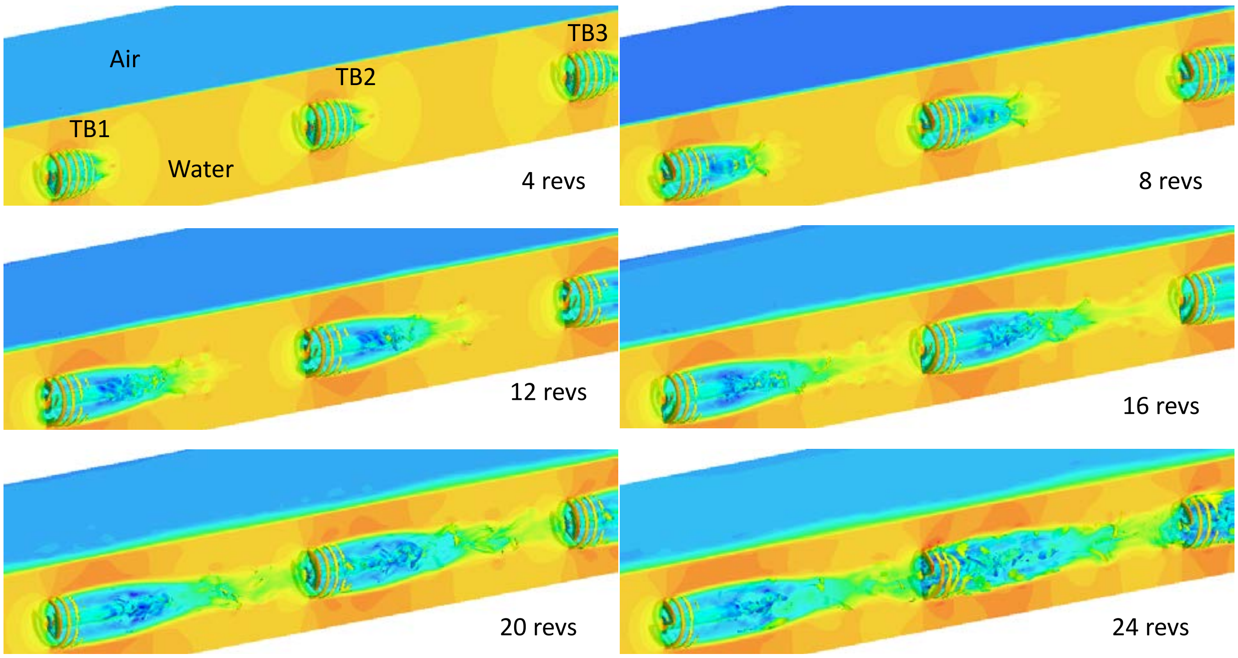

Fig. 2. Wake development of an array of three in-line RM1 turbines (7D distance) illustrated by tip vortices (iso-surface of vorticity) and axial velocity at a cross section centered on the rotors

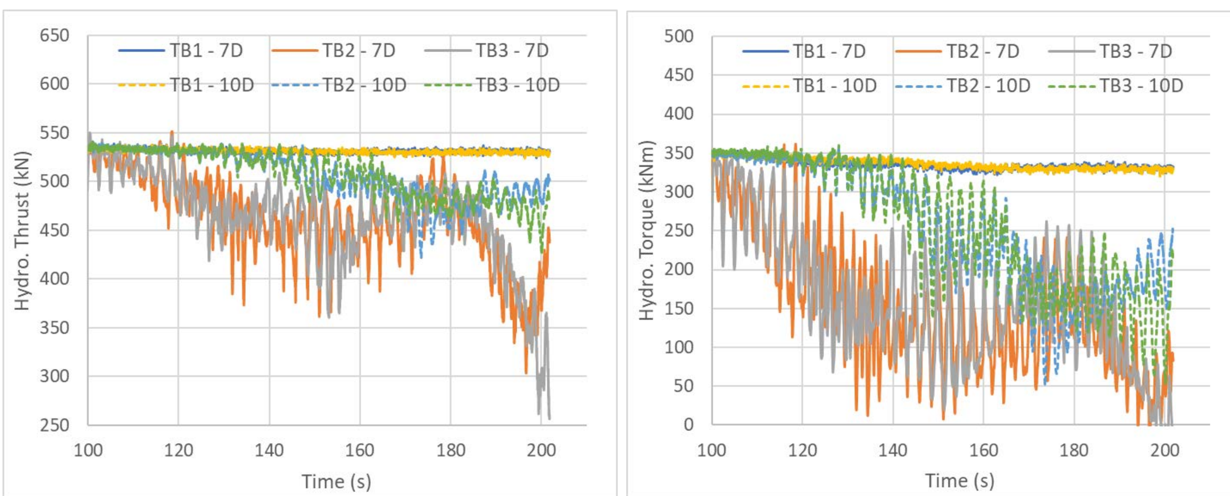

Fig. 3. Unsteady hydrodynamic thrust and torque of three RM1 turbines in an in-line array, simulated with different streamwise spacings (7D vs. 10D)

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