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Wake characteristics of a *TriFrame* of axial-flow hydrokinetic turbines

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ABSTRACT

An effective way to develop arrays of hydrokinetic turbines in river and tidal channels is to arrange them in TriFrame™ [1] configurations where three turbines are mounted together at the apexes of a triangular frame. This TriFrame can serve as a building block for rapidly deploying multi-turbine arrays. The wake structure of a TriFrame of three model turbines is investigated using both numerical simulations and experiments. In the numerical part, we employ large-eddy simulation (LES) with the curvilinear immersed boundary method (CURVIB) for fully resolving the turbine geometry details to simulate intra-turbine wake interactions in the TriFrame configuration. First, the computed results are compared with the experiments in terms of mean flow and turbulence characteristics with overall good agreement. The flow-fields are then analyzed to elucidate the mechanisms of turbine interactions and wake evolution in the TriFrame configuration. We found that the wake of the upstream TriFrame turbine exhibits unique characteristics indicating presence of the Venturi effect as the wake encounters the two downstream turbines. We finally compare the wakes of the TriFrame turbines with that of an isolated single turbine wake to further illustrate how the TriFrame configuration affects the wake characteristics and power production in an array of TriFrames.

1. Introduction

Marine and hydrokinetic (MHK) resources are gaining much interest as an emerging source of renewable energy in recent years. One way to harness MHK energy from rivers and tidal streams is by using current driven hydrokinetic turbines, which are modular and scalable in nature. A turbine array is usually employed to maximize the power extraction from any MHK site. To reduce the installation and maintenance efforts of the turbines underwater, an effective way to develop arrays of hydrokinetic turbines in rivers and tidal channels is to arrange them in conjunction. To optimize the performance of turbine arrays, a better understanding of turbine wake characteristics and turbine-turbine wake interaction is needed. In this work, we employ both numerical and experimental methods to investigate the wake characteristics of three turbines mounted in a triangular frame (TriFrame) configuration (as shown in Fig. 1).

Many published works studied the nature of the turbulent wake downstream of a hydrokinetic turbine [1–10], as well as arrays of wind turbines and effects of intra-turbine spacing within arrays [11–15] using theoretical, experimental and/or computational tools. However, there have been relatively fewer studies on arrays of hydrokinetic turbines. A brief review of experimental and numerical efforts of turbine array studies are presented first. Myers et al. [16] performed a set of scaled experiments to mimic an array of marine turbines in a laboratory setting. A porous disc was used to model the turbines in the experiments. They investigated several intra-turbine spacings in the array and concluded that wake interaction can result in undesirable effects of reduced power and increased fatigue loading for downstream turbines in the array. Using similar tools, Daly et al. [17] investigated effects of marine turbines in a split tidal channel. Stallard et al. [18] studied the wake structure and recovery of multiple axial-flow hydrokinetic turbines in several configurations. Their experiments indicated that the wake recovers 80% at 10 rotor diameters downstream of the turbine. The effect of lateral spacing on the shape of the wake was also discussed.

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[1] TriFrame is a trademark of Verdant Power Inc.

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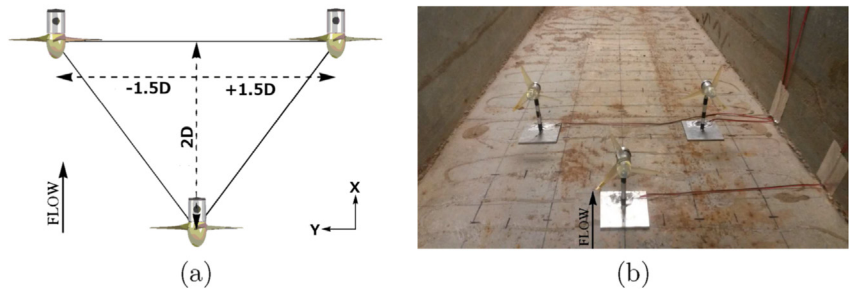

Fig. 1. (a) Sketch of TriFrame geometry used in the experiments and computations (D = turbine diameter = 0.15m); (b) TriFrame of small scale model turbines placed in the laboratory flume at Saint Anthony Falls Laboratory (SAFL).

Early computational efforts modeled MHK turbines in an array as single energy extraction points in a 2D domain. James et al. [19] used a modification of the Environmental Fluid Dynamics Code (EFDC) developed at Sandia National Laboratories (SNL) to simulate the changes to marine environments caused by an array of MHK turbines. Harrison et al. [20] and Malki et al. [21] employed the Reynolds-Averaged Navier-Stokes (RANS) equations and the Blade Element Method (BEM) to simulate an array of tidal turbines, respectively. Harrison et al. [20] observed faster wake recovery when compared to the actuator disc parametrization of turbine. No comparison with experimental data was made in both papers [20,21]. Colby and Adonizio [22] at Verdant Power studied turbine-turbine interaction and its effect on marine ecology using ANSYS CFX. However, the simulations didn't resolve the full turbine wake and hence under-predicted the strength of wake. Bai et al. [23] also studied multi-row arrays of turbine wakes using Fluent with an actuator disc model but no validation of the model was provided. Olczak et al. [24] assessed the accuracy of BEM and RANS in predicting the thrust coefficient and wake velocities using commercial CFD package StarCCM+. It was found that the predictions worsens with the increasing number of turbines in the array with worst prediction for turbines in downstream rows of the array. The National Renewable Energy Laboratory (NREL) created a framework for simulating MHK turbine arrays in natural waterways [25]. The effect of incoming turbulence on the wake characteristics was studied in an artificial straight channel. Ten different configurations including counter-rotating and co-rotating turbines modeled as actuator discs were investigated. It was found that for non-staggered co-rotating case, increasing streamwise spacing between rows improved array performance. Staggering turbines downstream in the row also resulted in improved performance. However, the published numerical data were not verified with any experimental measurements. Yang et al. [26] developed a computational framework to perform large-eddy simulation (LES) of MHK turbine arrays in natural waterways. The turbine blades were parameterized using actuator lines. This framework was employed to analyze the wake of aligned arrays of MHK turbines with various intra-turbine spacing in a straight channel flow. More recently, Stansby and Stallard [27] exploited the self-similarity of the wake in order to obtain optimized inter-turbine spacing in an array. The depth-averaged wake model of turbines in an array was obtained by superposition of velocity-deficit for a single turbine wake obtained from measurements (and applying self-similarity [10]).

In the above mentioned computational works, turbine parametrization was used to save computational cost involved in resolving the detailed geometry of a turbine. However, it was shown by Kang et al. [8] that the classic actuator disc and actuator line models without a model for the nacelle cannot accurately predict the velocity deficit in the near wake and wake meandering and turbulence intensity in the far wake. The geometry-resolving model using the curvilinear immersed boundary (CURVIB) method, on the other hand, captures the turbine wake dynamics for both near- and far-wake regions, and the computed results agree well with the measurements.

In this work, we employ the same numerical method, i.e. LES with the CURVIB method resolving every geometrical details of the turbine, as in Kang et al. [8], together with experiments to study a TriFrame of turbines, or simply a TriFrame, which is defined as a layout where three turbines are mounted together at the apexes of a triangular frame (Fig. 1 (a)). The resulting arrangement is equivalent to two rows in a staggered fashion. The objective of this work is to study the wake characteristics of the three turbines in a TriFrame configuration and evaluate the feasibility of using such system as a building unit for turbine arrays.

This paper is organized in the following fashion. Section 2 describes numerical methods used to perform the computational portion of this work. In Section 3, the experimental and computational setup is described. This is followed in Section 4 by discussion of the results obtained. Finally, Section 5 concludes the findings of this work.

2. Numerical methods

The CURVIB method [28,29] is employed to simulate the turbulent flow past the TriFrame of axial flow turbines. The governing equations are the spatially filtered continuity equation (Eq. (2.1)) and Navier-Stokes equation (Eq. (2.2)) in generalized curviliear coordinates, which read as follows:

$$J\frac{\partial U^i}{\partial \xi^i} = 0, \tag{2.1}$$

$$\frac{1}{J}\frac{\partial U^i}{\partial t} = \frac{\xi^i_l}{J}\left(-\frac{\partial}{\partial \xi^j}\left(U^j u_l\right) + \frac{1}{\rho}\frac{\partial}{\partial \xi^j}\left(\mu \frac{g^{jk}}{J}\frac{\partial u_l}{\partial \xi^k}\right) - \frac{1}{\rho}\frac{\partial}{\partial \xi^j}\left(\frac{\xi^j_l p}{J}\right) - \frac{1}{\rho}\frac{\partial \tau_{lj}}{\partial \xi^j}\right), \tag{2.2}$$

where ξ^j is the jth curvilinear coordinate, J is the Jacobian of the geometric transformation, ξ^i_l are the transformation metrics, g^{jk} is the contravariant metric tensor, U^i are the contravariant volume fluxes, u_i are the Cartesian velocity components, p is the pressure, μ is the dynamic viscosity, ρ is the density and τ_{ij} is the subgrid-scale (SGS) stress tensor of the LES method. U^i, u_i and p are filtered quantities. Time averages of cartesian velocity components in the X, Y and Z directions are denoted as U, V and W later in the discussion. Equations are expressed using Einstein's notation for tensors where repeated indices imply summation. The SGS stress (τ_{ij}) which appears after applying the spatial filter to the curvilinear Navier-