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On the Hydrodynamic Analysis of a Vertical Axis MHK Turbine: Investigating Fish Trajectories via large-eddy simulation

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Abstract

Marine hydrokinetic (MHK) turbines offer a robust renewable energy solution to address the challenges of energy scarcity and environmental degradation. However, owing to the potential impact of MHK turbines on the aquatic ecosystem, evaluating the implications of deploying such devices on fish life is essential. Herein, we conducted large eddy simulation (LES) of a vertical axis turbine (VAT) using the turbine geometry-resolving model to gain insights into the relationship between turbulent flow dynamics and fish trajectory. The LES results were validated using experimental data obtained at the Hydro-environmental Research Centre's hydraulic laboratory of Cardiff University, UK. The LES results of the turbulent wake flow field demonstrate meaningful alignment with fish behavioral experimental data, thus serving as a reliable turbulence map for elucidating the trajectories of fish movement within the flow.

Keywords: Vertical axis MHK turbines; Fish turbine interaction; LES; Turbine-Resolving method; Fish behavior

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1. Introduction

The vast potential of marine energy as a renewable resource offers substantial promise in addressing global energy requirements because approximately seventy percent of the Earth's surface is covered by water.

Nomenclature

J	Jacobian of the geometric transformation
U_i	Filtered contravariant volume flux
ξ^j	Component of the transformation metric
u_i	Filtered *i-th* Cartesian velocity component

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ρ	Fluid's density
μ	Fluid's dynamic viscosity
τ_{ij}	Subgrid stress (SGS) tensor
k	Turbulent kinetic energy (TKE)
Re_D	Reynolds number with rotor diameter as the characteristic length
h_0	Water height
U_0	Free stream velocity
D	Rotor's diameter
$u'u', v'v', w'w'$	Reynolds stress component for the fluctuating velocity component in the x,y,z-direction.

Notably, fourteen of the world's largest cities are along coastlines [1]. Hydrokinetic turbines, particularly vertical axis turbines (VAT), have drawn interest for their capacity to exploit the kinetic energy inherent in flowing water without relying on diversion or hydraulic structures to establish a head difference [2]. However, the turbulence generated by these turbines can alter and interact with adjacent ecosystems, potentially affecting aquatic habitats. Despite their importance, the environmental consequences of these hydrodynamic alterations remain relatively understudied [3]. Such modifications in hydrodynamics and wake patterns can influence the movement behavior of fish, especially migratory species that need to migrate between salt and fresh water, as evidenced by studies documenting avoidance behavior in the vicinity of VATs [3-7]. Through the development of computational methods and the availability of high-performance computing resources, researchers have extensively studied the three-dimensional turbulent flow surrounding Marine and Hydrokinetic (MHK) turbines using numerical simulations. These investigations are documented in studies such as those that employed various parameterization techniques and turbine geometry-resolving methods [3, 7]. In turbine-resolving approaches, the flow around turbine blades is directly resolved in numerical simulations using grids fine enough to capture intricate details. This approach reduces the need for extensive modeling and parameterization, allowing for a more detailed examination of the flow physics around individual turbines.

This study employs high-fidelity numerical simulations utilizing a turbine geometry-resolving methodology to examine the hydrodynamics of VAT and explore the relationship between turbulent flow dynamics and fish trajectory using large eddy simulation (LES). By juxtaposing the turbulent flow patterns induced by VATs with observed fish trajectory data obtained from experimental investigations conducted at Cardiff University, our analysis marks a meaningful association between the turbulence map in the wake of vertical axis MHK turbine and the fish trajectories observed in the lab.

2. Methodology

We adopt LES to capture a wide range of turbulent eddy sizes and resolve the instantaneous flow around a lab scale VAT. This choice of methodology is motivated by its capability to accurately replicate real-world conditions, including the intricate details of VAT structures such as the shaft and struts, which significantly influence the turbulence characteristics. The VAT model utilized in our simulations corresponds to that employed at the Hydro environmental Research Centre's hydraulic laboratory at Cardiff University, UK. A depiction of the VAT structure is provided in Fig. 1 to facilitate understanding.

Table 1. Details of hydraulic parameters used in the simulations, including flow depth (h_0), bulk velocity (U_0), Reynolds number based on rotos diameter (Re_D), and rotor diameter (D) which is the characteristic length scale.

Test cases	h_0 $[m]$	U_0 $[m/s]$	D $[m]$	Re_D
Mild flow condition	0.23	0.19	0.12	22,800

In this study, we performed Large Eddy Simulations (LES) of the flow around a Vertical Axis Turbine (VAT) with a rotor diameter of 12 cm. We examined two tip speed ratios: 1.9 and 2.5. The simulations were conducted in a flume domain measuring 30 cm in width and 180 cm in length, with a bed slope of 0.001, representative of marine bathymetry. The simulated flow depth (h_0) was set to 23 cm, with a corresponding free stream velocity (U_0) of 0.19 m/s, replicating conditions from previous tests conducted at [2]. To ensure accurate representation, the system was normalized using the rotor diameter, and the computational grid consisted of 32 million nodes. A stretched grid methodology was employed to maintain uniform 1-millimeter spacing around the turbine, achieving a y^+ value of

Fig. 1. Illustration showing the flume and the designed VAT based on the experiments.

approximately 9 near the turbine blades. This approach enhances the capture of turbulence generated by the blades, facilitating the correlation of trajectories with turbulence metrics.

2.1. Governing equations

We solve the spatially filtered Navier-Stokes equations that describe incompressible flows within non-orthogonal generalized curvilinear coordinates. Employing the compact Newton notation, which assumes summation over repeated indices, the equations are expressed as follows (i, j, k, l = 1,2,3) [8]:

$$J\frac{\partial U^i}{\partial \xi^j} = 0 \tag{1}$$

$$\frac{1}{J}\frac{\partial U^i}{\partial t} = \frac{\xi_l^i}{J}\left\{\frac{\partial}{\partial \xi^j}\left(U^j u_i\right) + \frac{1}{\rho}\frac{\partial}{\partial \xi^j}\left(\mu\frac{g^{jk}}{J}\frac{\partial u_i}{\partial \xi^k}\right) - \frac{1}{\rho}\frac{\partial}{\partial \xi^j}\left(\frac{\xi_i^j p}{J}\right) - \frac{1}{\rho}\frac{\partial \tau_{ij}}{\partial \xi^j}\right\} \tag{2}$$

For quantifying turbulence, we use TKE (Turbulent Kinetic Energy) which measures the increase in kinetic energy of a system due to turbulent fluctuations in the flow. It is defined as follows:

$$k = \frac{1}{2}\left(\overline{u'u'} + \overline{v'v'} + \overline{w'w'}\right) \tag{3}$$

The energy in the flow is coupled with the energy expended by the fish. Therefore, TKE can be a good predictor of fish trajectory [2, 9].

3. Results and discussions

3.1. Relation of turbulence and different fish behaviors

Fish tend to avoid swimming in environments characterized by significant temporal velocity fluctuations. In such areas, high turbulent shear stress acts on the fish's body, negatively impacting their physiology and overall well-being. Conversely, fish may also harness turbulence flow to swim, propelling themselves upstream or maintaining their position. So, fish will show different behaviors by being in a turbulent area. In case of the duration spent in distinct areas, regardless of flow conditions and turbine operation, fish predominantly remained downstream of the channel, indicating that avoidance behavior is consistently dominant. In the downstream section, fish spent most of their time near the side wall, especially at the furthest downstream location. In case of attraction to and avoidance of specific areas, the results demonstrate avoidance behavior, which appears to be independent of the turbine's operating conditions [2, 9]. All these behaviors can be addressed by the analysis of the turbulent flow.

Fig. 2 (a) and (b) illustrate the time-averaged and instantaneous velocity magnitude contours on the horizontal plane at mid-depth. The lateral expansion of the wake is evident, attributed to the convection of large-scale vortices. Additionally, a distinct shear layer, originating from the turbine wake, is discernible. Asymmetry in the wake is also observed, resulting from the Magnus effect induced by the rapid rotor rotation, a phenomenon previously explored in studies on the flow around rotating cylinders [10]. Fig. 2 (c) and (d) depict the out-of-plane vorticity magnitude and iso-surfaces of Q-criteria, highlighting the vortical structures generated by the VAT. Out-of-plane vorticity highlights regions where the motion is rotational, indicating flow separation and the presence of shear layers. Q-criteria reveals regions where rotational motion (vortices) dominate over shear strain, helping to understand the coherence and organization within the turbulent flow, and showing how energy and momentum are transported by these structures. Fig. 2 (e) and (f) show the turbulent kinetic energy (TKE) and Reynolds stresses. TKE indicates areas where turbulence is more intense, identifying zones of high mixing and energy dissipation, and visualizing the structure of the turbulent flow. Reynolds stresses reveal how momentum is transferred by turbulence within the flow, highlighting regions of high turbulent shear stress and the anisotropic nature of turbulence, showing different levels of turbulent intensity in different directions.

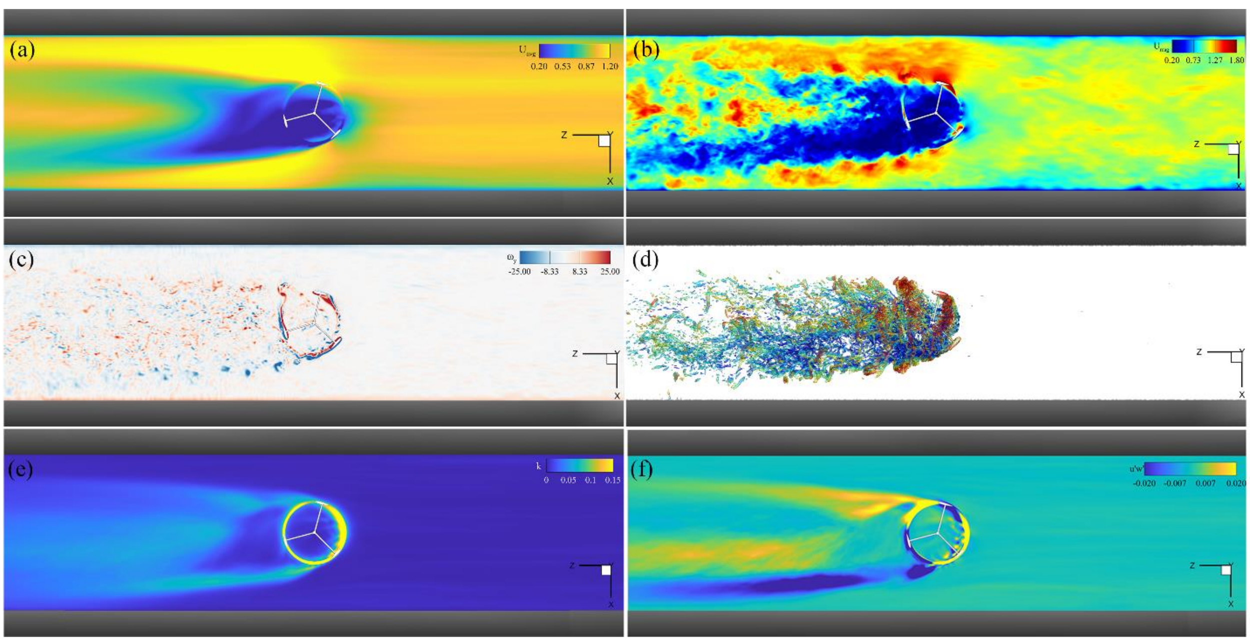

Fig. 2. (a) LES-computed color map of time-averaged velocity magnitude; (b) instantaneous velocity magnitude; (c) instantaneous out-of-plane vorticity magnitude; (d) Iso-surfaces of Q-criteria, colored by the velocity magnitude; (e) turbulent kinetic energy; and (f) Reynolds stress. In all the figures, we plot the top view of the flow at mid-depth. The turbine spins in the counterclockwise direction. The flow direction is from right to left.

In case of fish actions such as entering the rotor area, transitioning to the upstream region, and attempting passage, strategies employed by fish to avoid collision with the turbine should be considered. These strategies can be explained in the context of fish-friendly eddies. These eddies aim to create water flow conditions that can protect fish from injury or death as they navigate through areas with potential hazards, such as turbine intakes or spillways. Fish-friendly eddies should create mild, non-violent turbulence so that fish can navigate without injury. This helps in dissipating the energy in the water without creating high-velocity zones that could harm fish. While turbulence is inherently chaotic, creating more predictable flow patterns within certain areas can help fish anticipate and react to changes in water movement, making it easier for them to avoid hazards. The size and frequency of the eddies should be suitable for the species of fish present. Smaller fish may benefit from smaller, less intense eddies, while larger fish might be better adapted to handling bigger, more powerful eddies.

In addition to these hydrodynamic insights, the turbulence data obtained can facilitate the mapping of fish movement trajectories. From the experimental study [2, 9], fish showed avoidance behavior in the turbine vicinity, irrespective of turbine operation or flow conditions. Analysis of experimental results reveals a clear tendency for fish to avoid traversing the turbine wake, primarily influenced by the Magnus effect-induced wake asymmetry.

3.2. Mechanisms by which turbulent eddies might save fish

One of these mechanisms is avoidance behavior: Fish are known to sense changes in water flow and turbulence using their lateral lines, a sensory organ that detects vibrations and pressure changes in the water. Increased turbulence near turbines might signal danger to fish, prompting them to swim away from the turbulent regions and avoid the turbines. Another important mechanism is the velocity gradients: Turbulent eddies create varying velocities within the water column. Fish may find refuge in areas where the water velocity is lower, helping them to navigate around high-risk areas near the turbines. In addition, energy dissipation is the other important factor. Turbulence can dissipate the energy of the flowing water, potentially reducing the force with which fish might be pushed into the turbine blades. This could decrease the severity of injuries to fish that do come into contact with turbines [5, 11, 12].

4. Conclusion

We carried out LES of a lab-scale VAT to gain insight into the intricate flow dynamics surrounding the device and to reveal the potential connection between the fish trajectories and the turbulence map of the flow field. Our findings underscore the ability of LES to capture turbulent hydrodynamics and effectively correlate them with fish trajectories. Specifically, our results shed light on the hydrodynamics of VATs, including wake generation and expansion, while establishing meaningful connections between turbulence induced by these turbines and fish trajectories, thus bridging the numerical results with fish behavioral experimental data. Employing LES coupled with the turbine geometry resolving method, we successfully resolved all aspects of VAT geometry, enabling a comprehensive understanding of flow dynamics. This study enhances our comprehension of VAT hydrodynamics and highlights the potential of CFD simulations in elucidating the interaction between marine turbines and aquatic ecosystems.

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