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Coupled LES and bed morphodynamics of a utility-scale vertical-axis MHK turbine under rigid- and mobile-bed conditions

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Abstract

We present a coupled large-eddy simulation (LES) and bed morphodynamics study to examine the sediment dynamics around a utility-scale vertical-axis marine hydrokinetic (MHK) turbine under two flume bed conditions: rigid and mobile. Carefully comparing the coupled LES and morphodynamics numerical results under the rigid- and mobile-bed conditions, we attempt to quantify the effect of scour development on the wake recovery and power production of the turbine and to gain insight into the formation, development, and migration of dunes over the mobile bed. The sediment dynamics are obtained using the Exner-Polya equation, which is solved until an equilibrium bed morphology is reached. A mass-balance-based sand-slide module is used to ensure that bed deformation angles are physically accurate. The model's flow and sediment transport results are validated using experimental data of adequate Reynolds numbers representing large-scale tidal farms.

Keywords: Large-eddy simulations, Vertical axis hydrokinetic turbine, Sediment transport, coupled Hydro-morpho dynamic interactions

1. Background

Recently, there has been a noticeable increase in the exploration of renewable energy sources in various parts of the world. Hydrokinetic devices such as horizontal-axis turbines (HAT) and vertical-axis turbines (VAT) have garnered significant attention due to their capacity to generate power. In particular, H-Darrieus VATs have distinct advantages over horizontal-axis turbines, owing to their ease of installation and independence from the incoming flow direction. However, deploying these devices in riverine and marine environments with mobile beds induces complex interactions between sediment particles, devices, and turbulent wake flows, which, in turn, ultimately influences VATs' power output and wake recovery. While past studies have examined sediment processes in rivers [1, 2], and the impacts of sediment transport on HATs [3, 4, 5], there remains a notable gap in the literature regarding the interactions among the utility-scale VAT, turbulent wake flow, and sediment dynamics. High-fidelity numerical simulations using the coupled large-eddy simulation (LES) and bed morphodynamics can be employed to shed light on this gap and address this issue.

2. Objective

This study aims to determine the effect of sediment processes on power production and wake recovery, as well as the deformation and migration of the mobile bed due to VAT-induced influences on morphodynamic processes

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utilizing LES coupled with morphodynamics equations [1]. To achieve this goal, a series of simulations under rigid and mobile bed conditions were conducted to compare VAT power generation, wake recovery, and sediment dynamics. The numerical simulations were carried out using a computing cluster at Stony Brook University.

3. Methodology

In this work, the spatially filtered Navier-Stokes equations within the non-orthogonal, generalized curvilinear coordinate system were implemented as the governing equations of the incompressible flow [6]. Our methodology can accurately capture the large eddies. The turbine structures, including blades, struts, and shafts, are directly resolved using the curvilinear immersed boundary (CURVIB) method [6]. At each time step, the flow field obtained from the LES is utilized to solve the Exner-Polya equation [7] at the interface of the water and sediment to determine the bed deformations. For each step, after obtaining the bed deformations, the sand-slide model [8] is implemented to prevent the slope from exceeding the angle of repose of sand particles (=40°).

The channel's width and length are 5m and 37.5m, respectively. The channel's height (H) is 5m, the flow depth (h) is 3.83m, and the rotor diameter (D) is 2m.

The turbine is located at 6.25D downstream of the inlet (see Figure 1). The angular velocity of the blades (ω) is 6.18 rad/s. The bulk velocity is considered 1.5 m/s, and the Reynolds number ($= \frac{U_0 D}{\nu}$) is 3×10^6. The flow domain is discretized with 91 million computational grid nodes that are uniformly distributed in all directions, obtaining a spatial resolution of 2 cm. We considered a sediment density of 2650 kg/m3, with a porosity of 0.4 and a mean grain size of 1 mm.

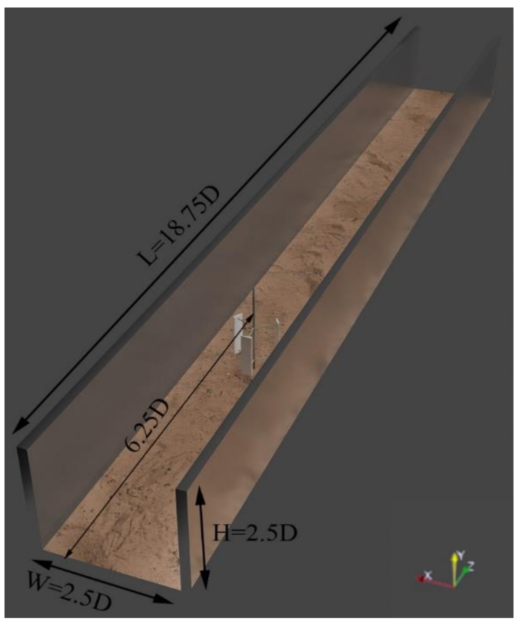

Figure 1: Schematic of the VAT, located 6.25D downstream of the inlet. Dimensions are normalized with the rotor diameter D(=2m).

4. Results

In Figure 2, we plot the LES-computed results of the flow field under rigid bed conditions. As seen, there is a high momentum region in the near-bed region downstream of the turbine, caused by the blades' rotation. The elevated turbulence at this region suggests the potential for increased sediment transport and bed deformations in the near field, which could also impact power production and wake recovery of the turbine.

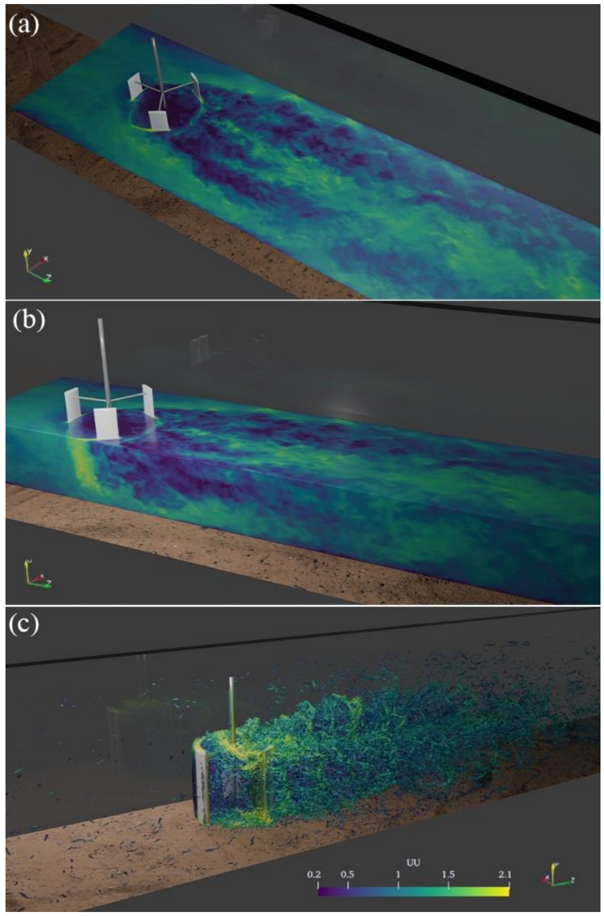

Figure 2:) LES-computed instantaneous flow field past the vertical axis turbine in 3D views. (a) marks the color map of velocity magnitude on a horizontal plane 0.8D above the bottom of the channel. (b) shows the color map of velocity magnitude on horizontal and vertical planes around the turbine. (c) depicts iso-surfaces of Q-criterion (=75) colored with the velocity magnitude.

5. Conclusions

This study utilizes a series of coupled morpho-hydrodynamic simulations to investigate the impacts of sediment transport on VAT's power generation and wake recovery. Likewise, we attempt to evaluate the effects of turbulence induced by the blades' rotation on the bed morphodynamics past the turbine. Through rigorous examination of the nig data obtained from these high-fidelity simulations, the present study aims to provide insights essential for optimizing VAT performance under diverse environmental scenarios.

Acknowledgments

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References

[1] Khosronejad, A., Limaye, A. B., Zhang, Z., Kang, S., Yang, X., & Sotiropoulos, F. (2023). On the morphodynamics of a wide class of large-scale meandering rivers: Insights gained by coupling LES with sediment dynamics. *Journal of Advances in Modeling Earth Systems*, 15, e2022MS003257.

[2] Khosronejad, A., & Sotiropoulos, F. (2014). Numerical simulation of sand waves in a turbulent open channel flow. *Journal of Fluid Mechanics*, 753, 150–216.

[3] Aksen, M., Flora, K., Seyedzadeh, H., Gholami Anjiraki, M., Khosronejad, A. (2023). On the impact of debris accumulation on power production of marine hydrokinetic turbines: Insights gained via LES. *Theoretical and Applied Mechanics Letters,* In review.

[4] M. Musa, C. Hill, M. Guala, (2019). Interaction between hydrokinetic turbine wakes and sediment dynamics: array performance and geomorphic effects under different siting strategies and sediment transport conditions. *Renewable Energy*, 138, 738–753.

[5] X. Yang, A. Khosronejad, F. Sotiropoulos, (2017). Large-eddy simulation of a hydrokinetic turbine mounted on an erodible bed. *Renewable Energy* 113, 1419–1433.

[6] S. Kang, I. Borazjani, J. A. Colby, F. Sotiropoulos, (2012). Numerical simulation of 3d flow past a real-life marine hydrokinetic turbine. *Advances in Water Resources*, 39, 33–43.

[7] Paola, C., Voller, V. R., (2005). A generalized Exner equation for sediment mass balance. J. *Geophys. Res*., 110, F04014.

[8] Khosronejad, A., & Sotiropoulos, F. (2017). On the genesis and evolution of barchan dunes: Morphodynamics. *Journal of Fluid Mechanics*, 815, 117–148.