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

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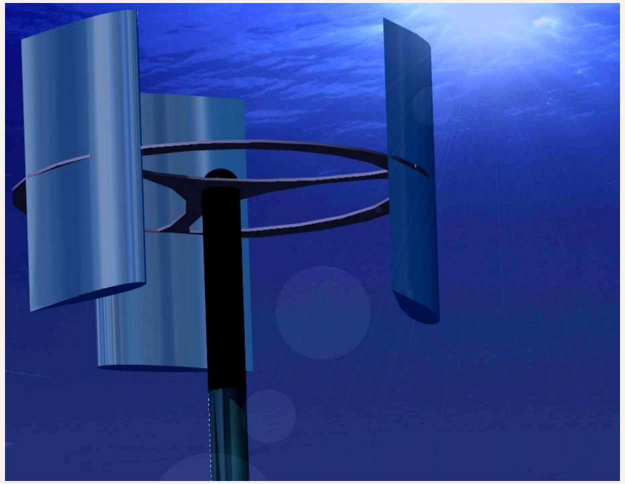
Introduction

- Noticeable increase in renewable energy exploration worldwide.
- Hydrokinetic devices, such as horizontal-axis turbines (HAT) and vertical-axis turbines (VAT), have gained attention for their performance.
- H-Darrieus VATs have advantages over HATs, including easier installation and flow direction independence.



Motivation

- Flow, sediment, and turbine interactions could impact device performance.
- Past studies have been focused on sediment dynamics impact on HATs' performance.
- Interactions among utility-scale VATs, turbulent wake flow, and sediment dynamics remain underexplored.

Objectives

Study Objectives:

- Comparative study of utility-scale VAT performance under rigid and mobile bed conditions;
- Mobile bed evolution due to VAT-induced turbulence;
- Effect of sediment dynamics on wake recovery.

Simulation Methodology:

- A series of coupled LES-morphodynamics simulations were conducted under rigid and mobile bed conditions;
- The simulation results for power production, wake recovery, and sediment dynamics were analyzed to gain insight about VATs' performance.

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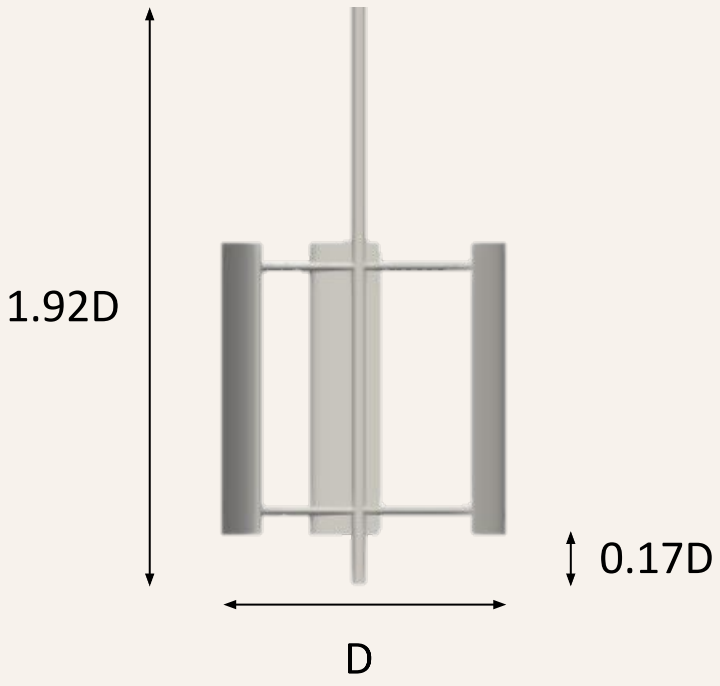
VFS-Geophysics open-source code

- Curvilinear Immersed Boundary Method (CURVIB)
- Turbulence simulation and modeling: DNS, LES, RANS
- Fluid-structure interaction
- Turbine models: geometry resolving, actuator disk, actuator line, actuator surface
- Bed morphodynamics and sediment transport module
- Free surface tracking using level set.
- Turbine control modules
- Hydro- and aero-elastic modules

Computational Details

Turbine Descriptions

Rotor Diameter (m)	D=2
Chord Length (m)	0.5
Airfoil Type	NACA 0015
Solidity	0.24



Computational Details

Variables	Definition	Value
Flow	Number of Computational Nodes	1801×261×229
	Spatial Steps of the Flow Solver Normalized with Rotor Diameter	0.01
		0.0005
	Minimum Grid Spacing in the Vertical Direction Scaled by Inner Wall Units	600
Morphodynamic	Non-Dimensional Time Step of the Sediment Transport Computations	0.05
	Spatial Step of the Morphodynamics Solver Normalized with Rotor Diameter	0.023

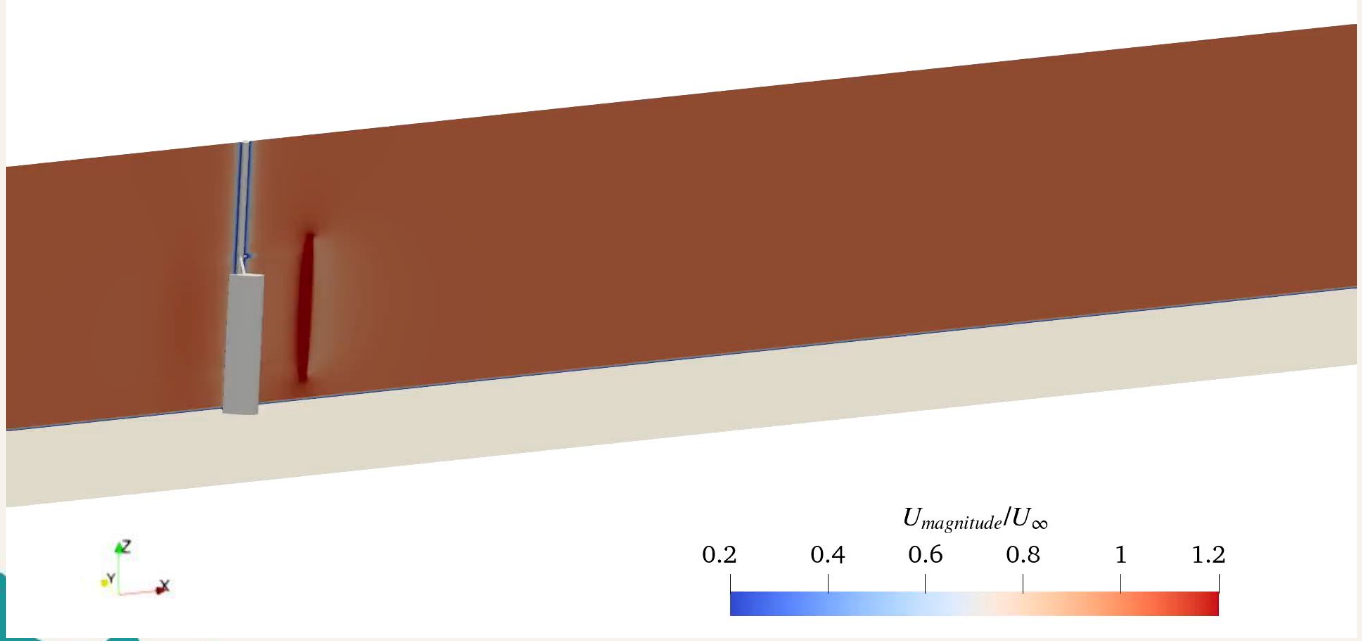
Test Cases Description

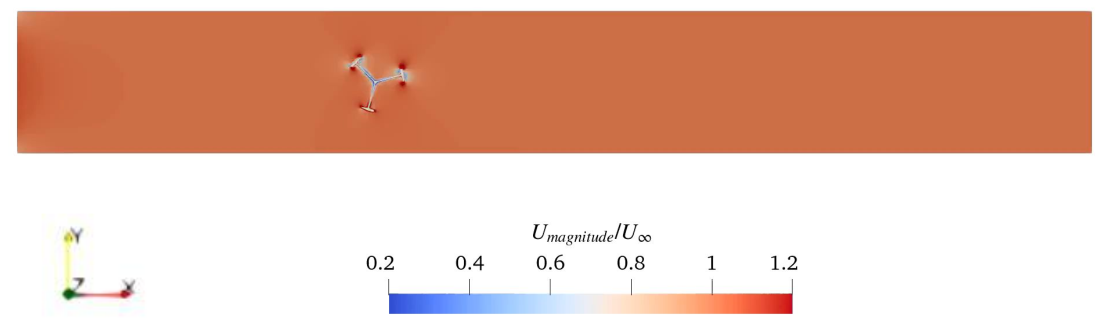
Case #	Water Depth (m)	TSR	Bed Load Layer Thickness (mm)	Incoming Velocity (m/s)	Reynolds Number
0 (Rigid Bed)	3.84	2.0	-	1.5	
1	3.84	2.0	3	1.5	
2	3.84	2.0	5	1.5	
3	3.84	2.0	10	1.5	

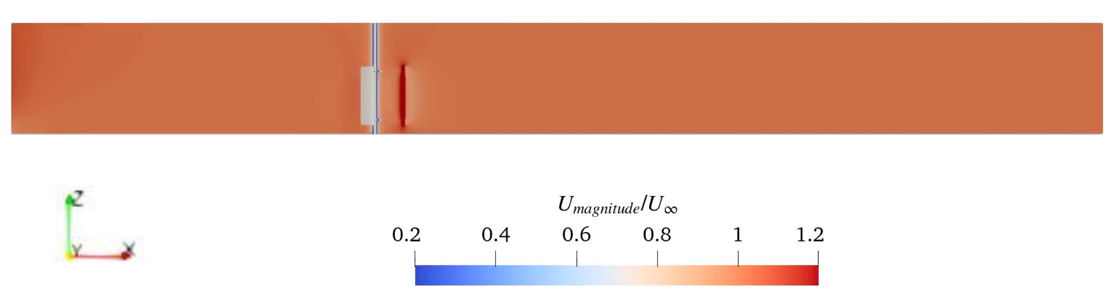
Simulation Results

Case 0 - Rigid Bed - Instantaneous

$\times \frac{1}{6}$

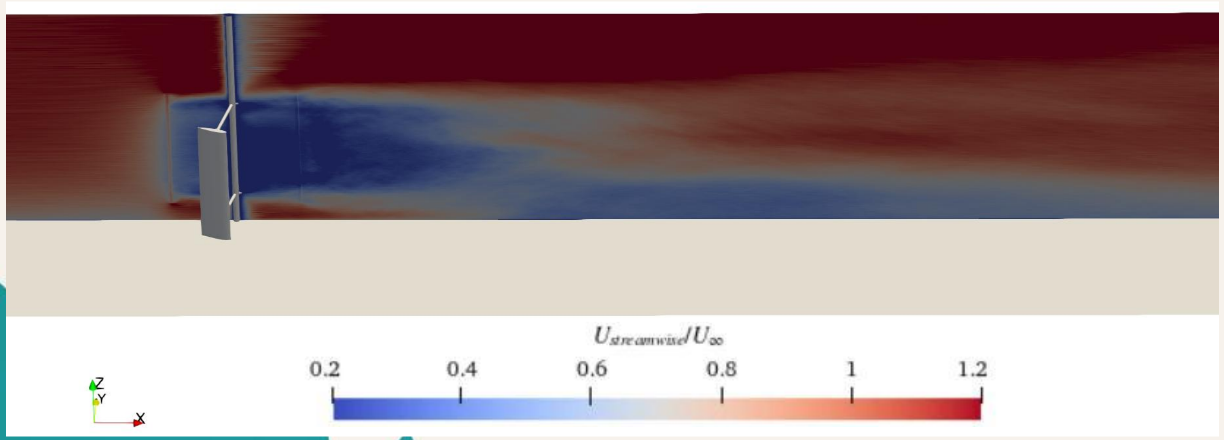


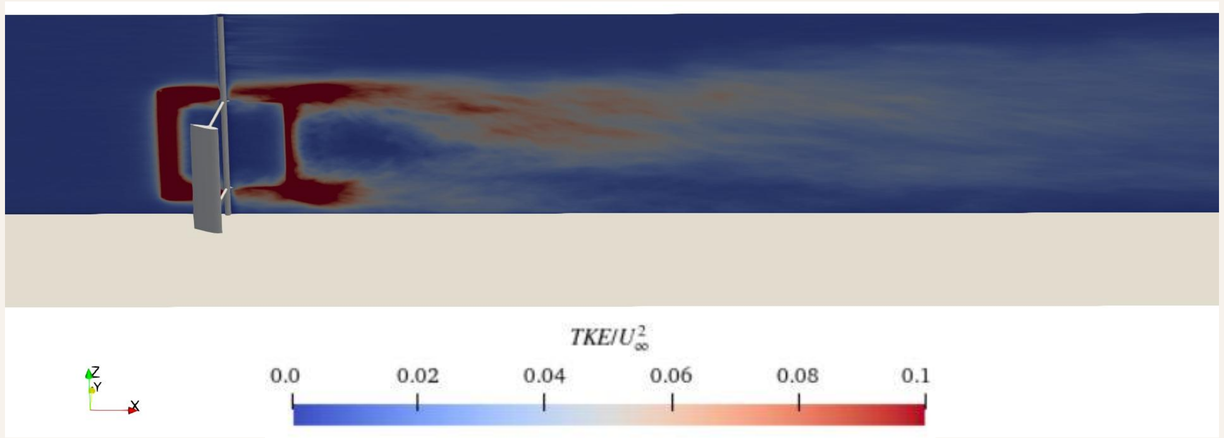




Case 0 - Rigid Bed - Time-Averaged

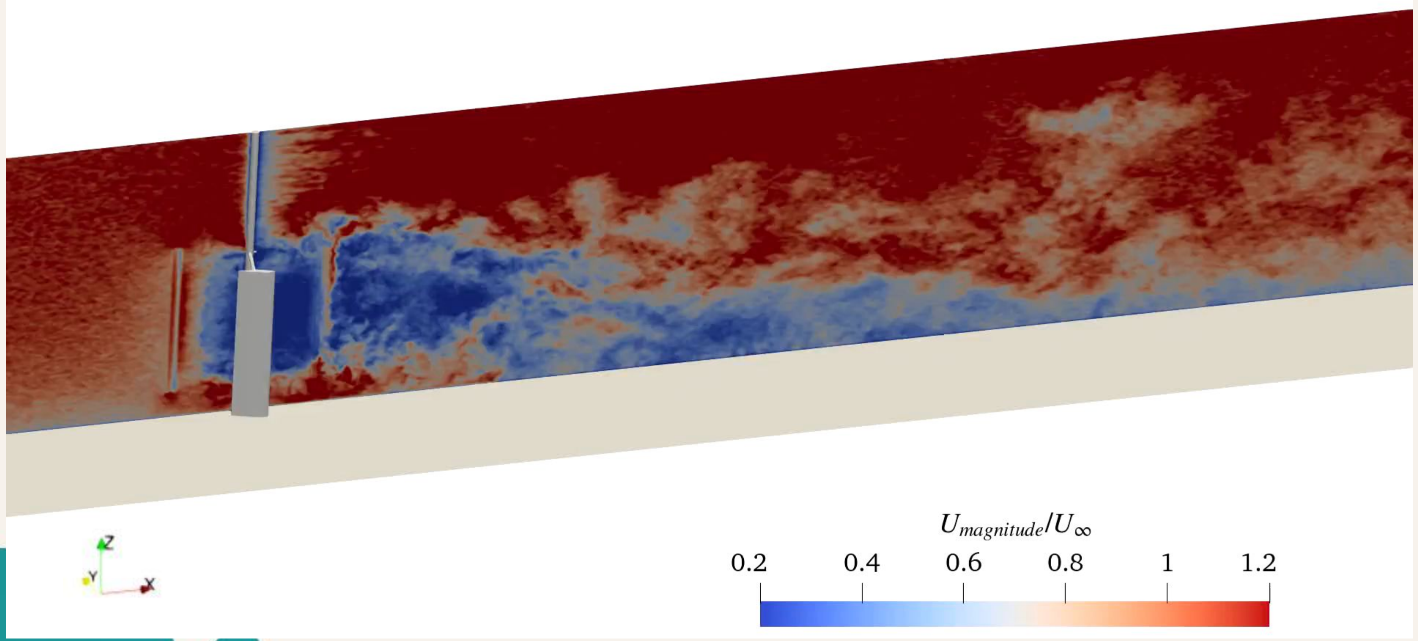
- High momentum region and elevated turbulence in the near bed region cause the following changes:
  - Increase in sediment transport and bed deformations
  - Impact on power production and wake recovery

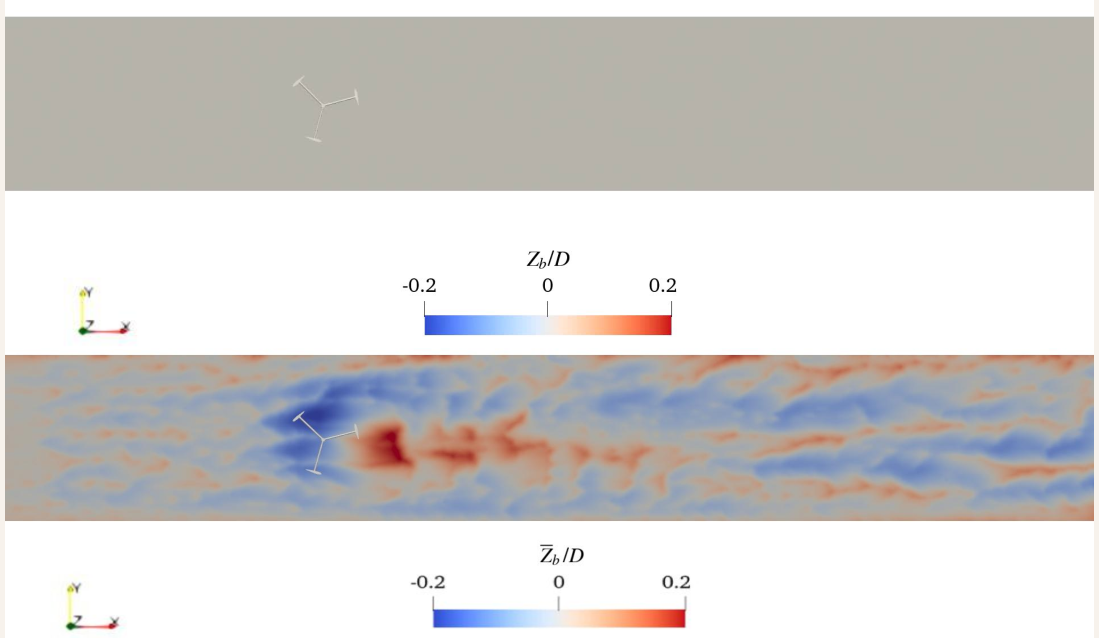




Case 1 - Mobile Bed - Instantaneous

$\times \frac{1}{6}$





Case 2 - Mobile Bed - Instantaneous

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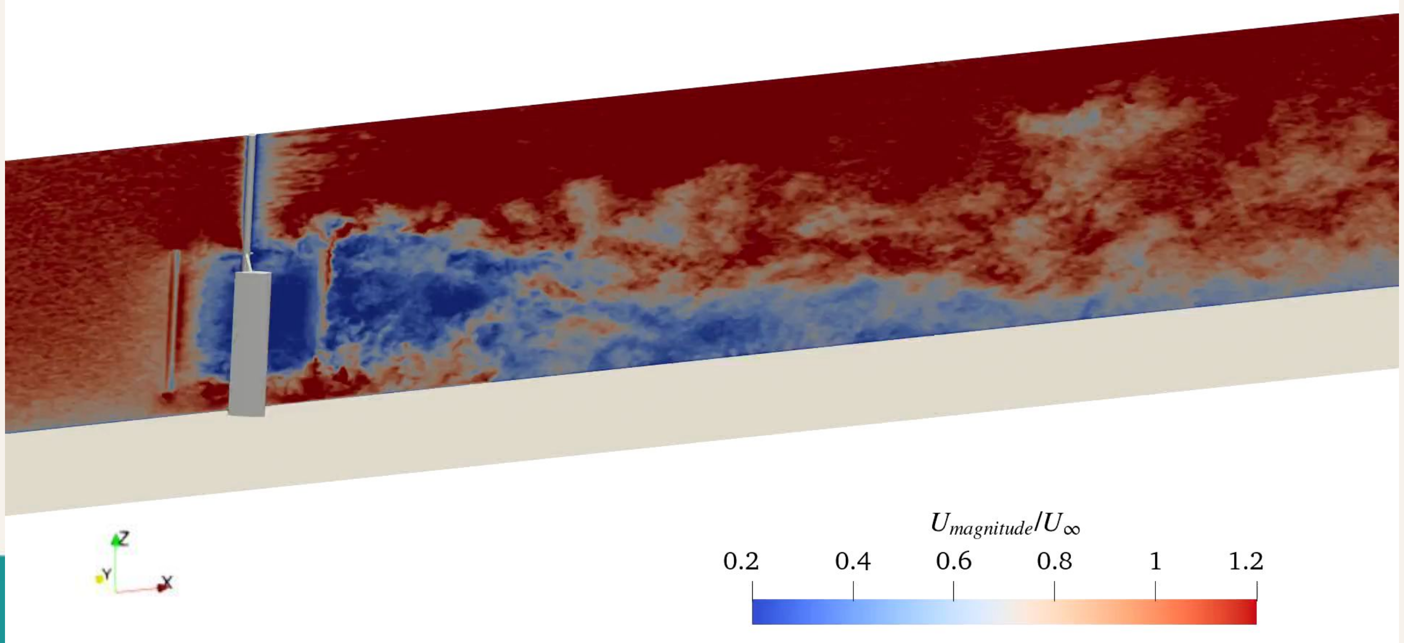

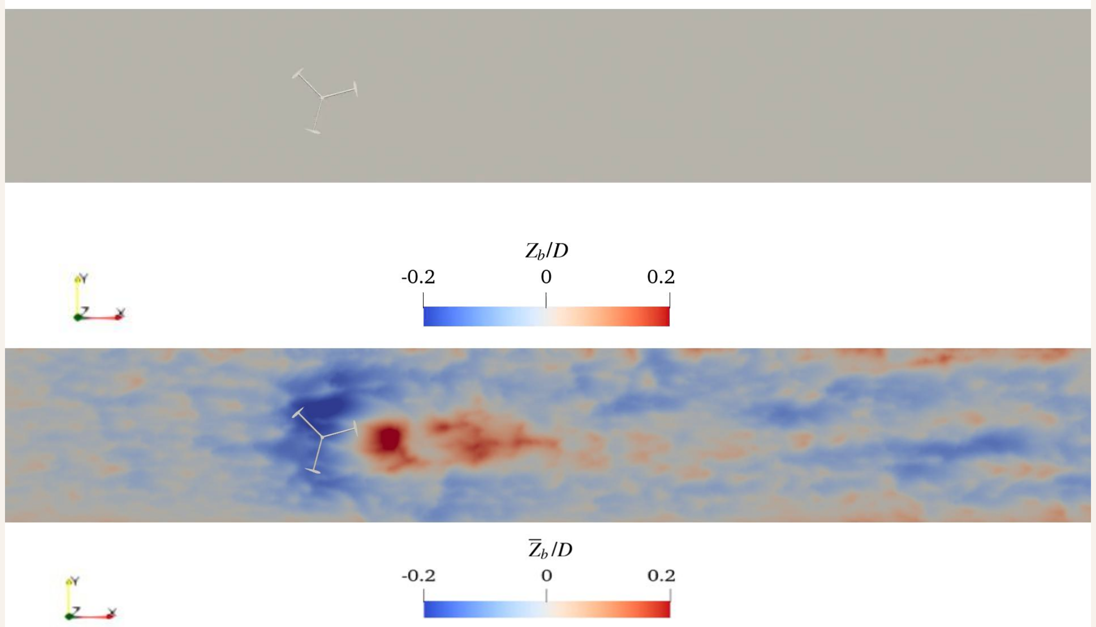

Case 3 - Mobile Bed - Instantaneous

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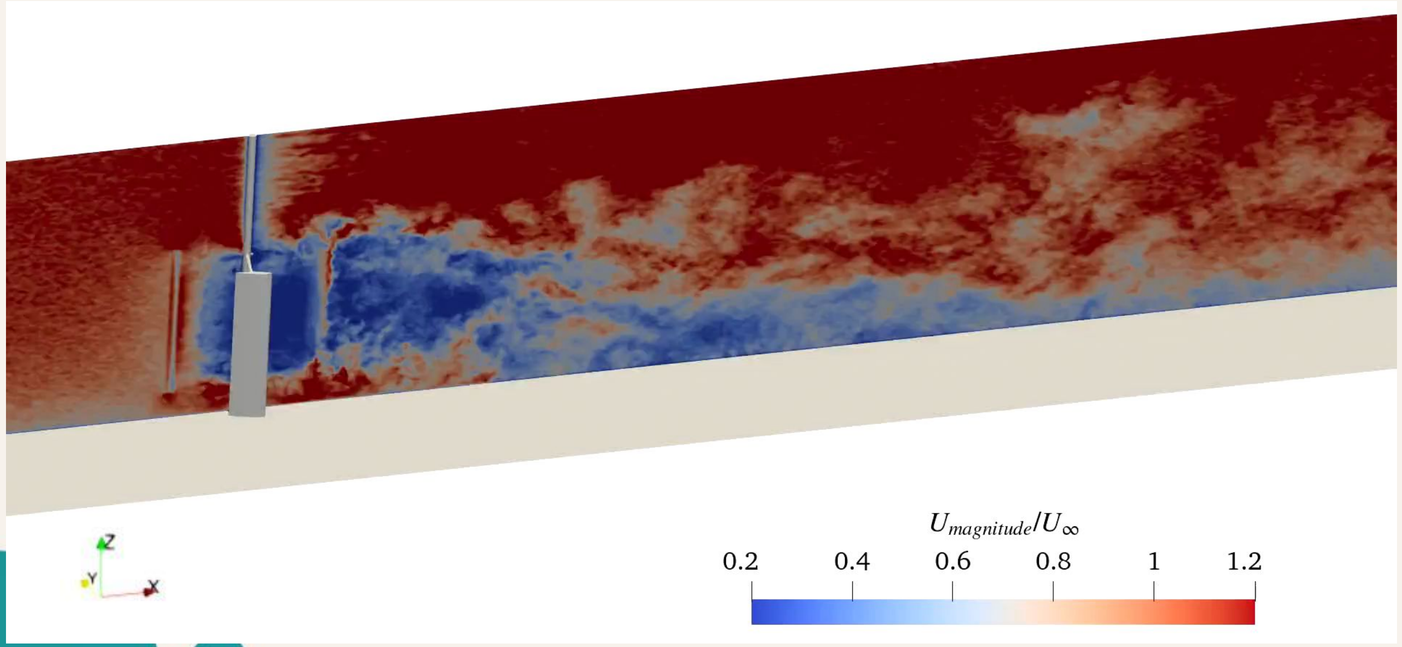

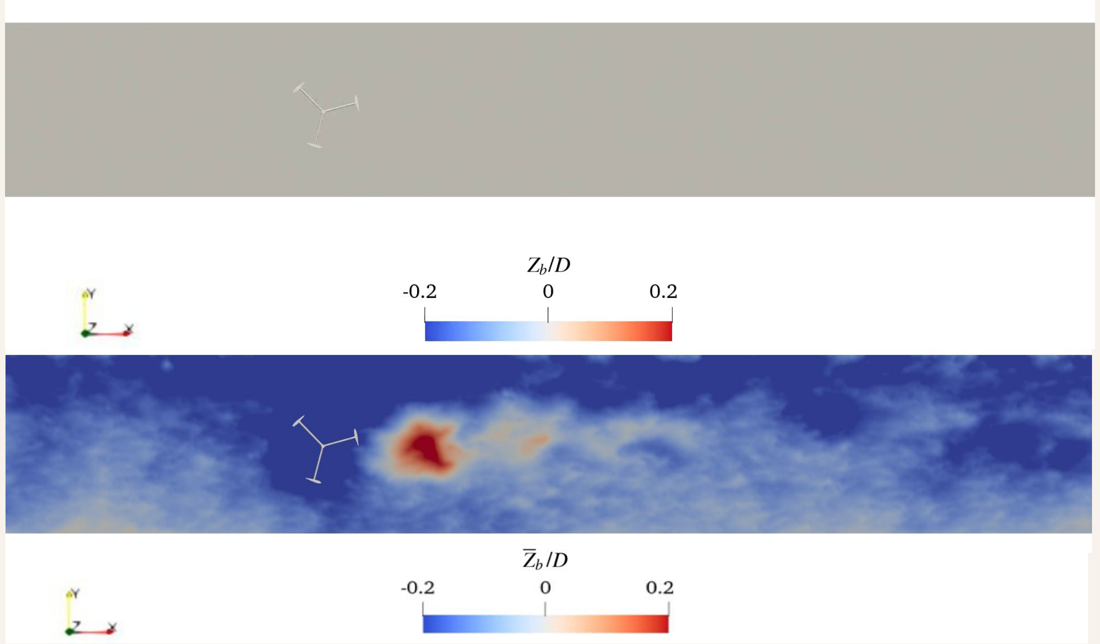

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Time-Averaged Streamwise Velocity

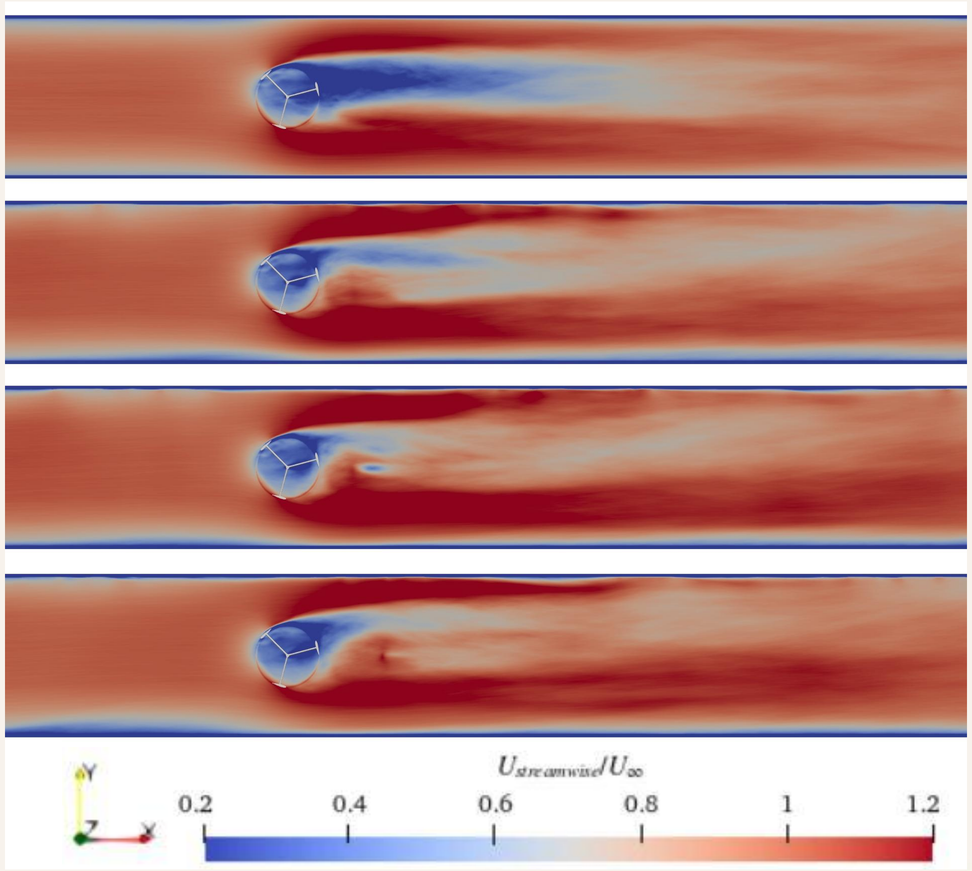
- There is an asymmetric effect of sediment transport on wake flow.
- The sand bars' signature appears downstream of the turbine in Case 2 and Case 3.
- The difference could be significant in an array of VATs.

Case 0

Case 1

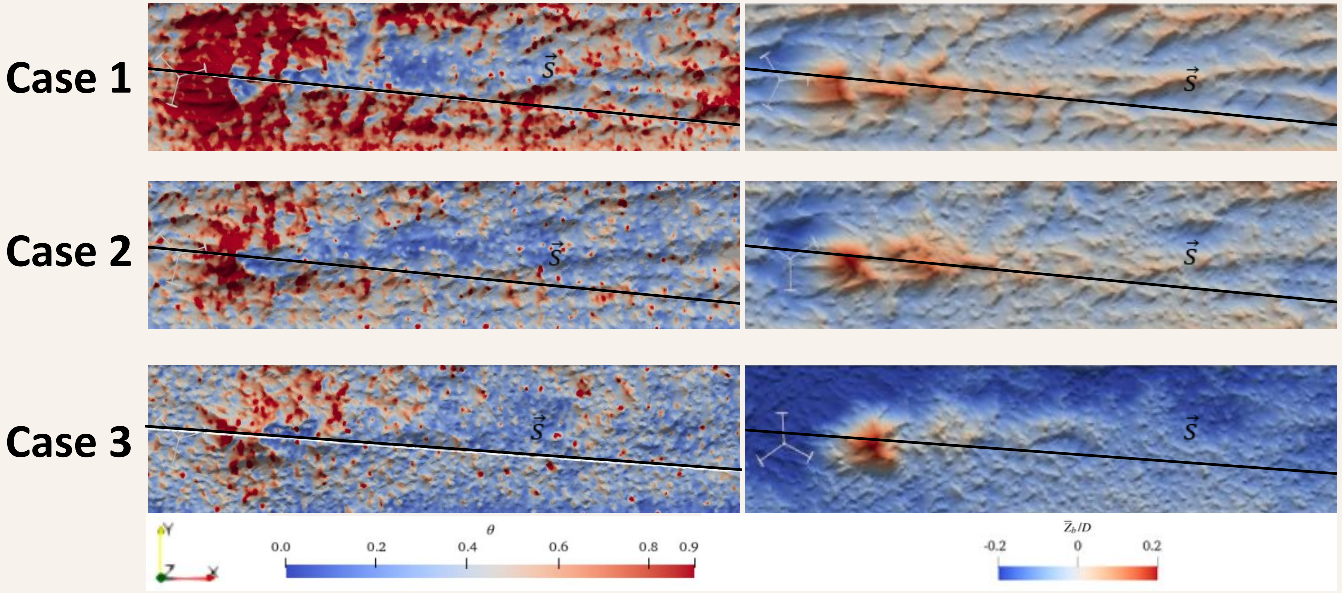
Case 2

Case 3



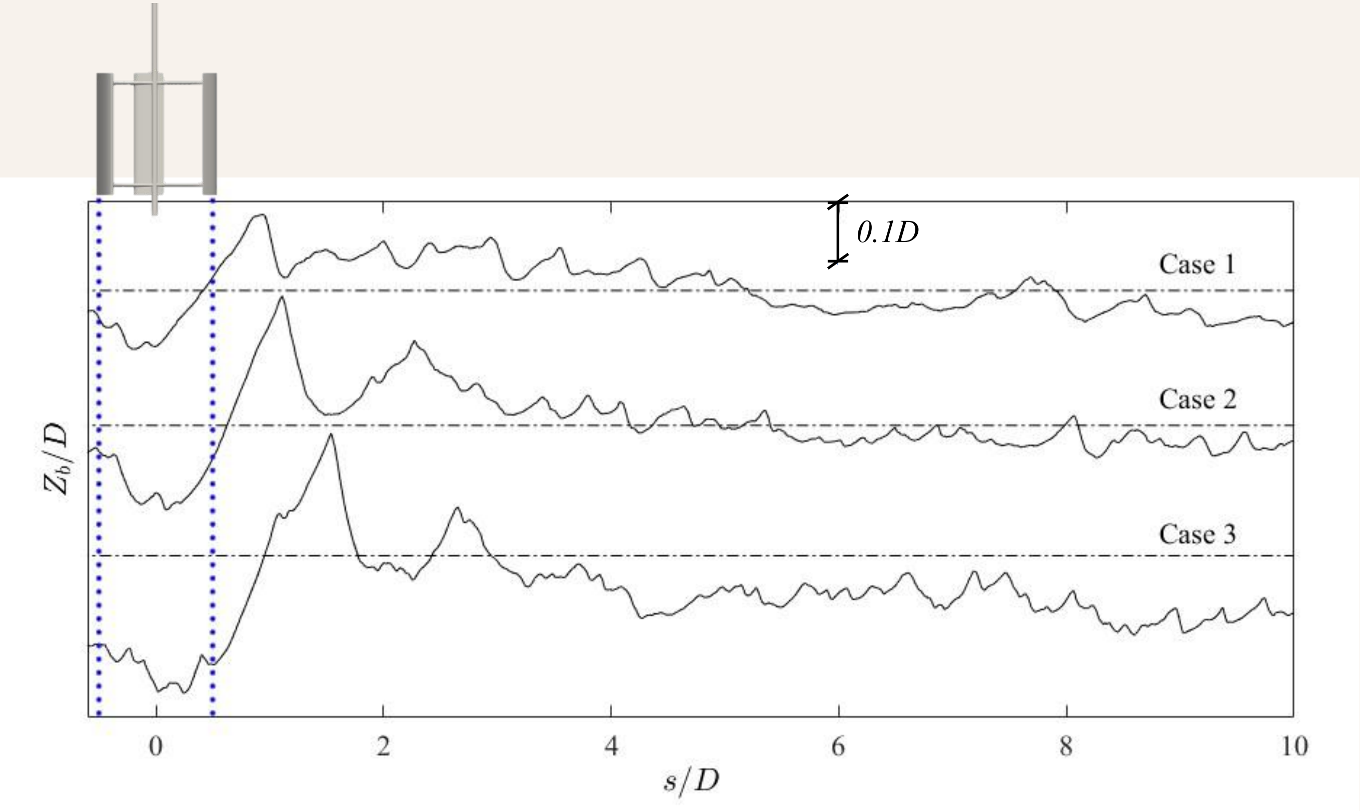
Bed Shear Stress - Bed Deformation

- Effect of asymmetric wake (due to the rotating blades) on migration of sand waves.
- The line along which a part of the major sand waves form and migrate is denoted as vector 's'.
- The greater spatial variations of non-dimensionalized instantaneous bed shear stress (θ) lead to greater bed deformations which align with vector 's'.



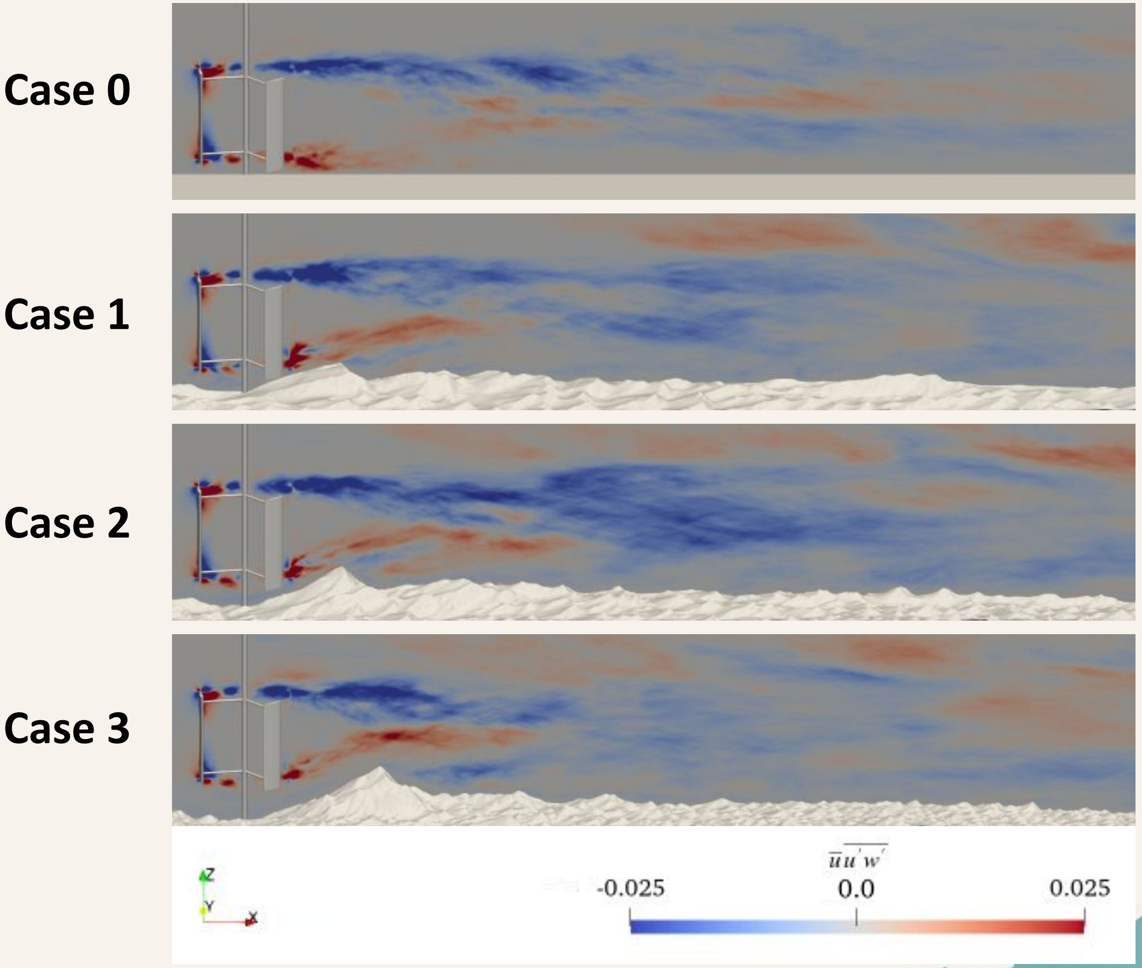
Bed Elevations

- The scour and deposition part of each profile near the center and near field show the effect of rotating blades.
- Maximum scour depth occurs near the center of the VAT.
- Maximum deposition height occurs at $s/D < 2$ for all cases.
- Mean normalized wavelength of sand waves= $0.2D$
- Mean normalized amplitude of sand waves = $0.06D$



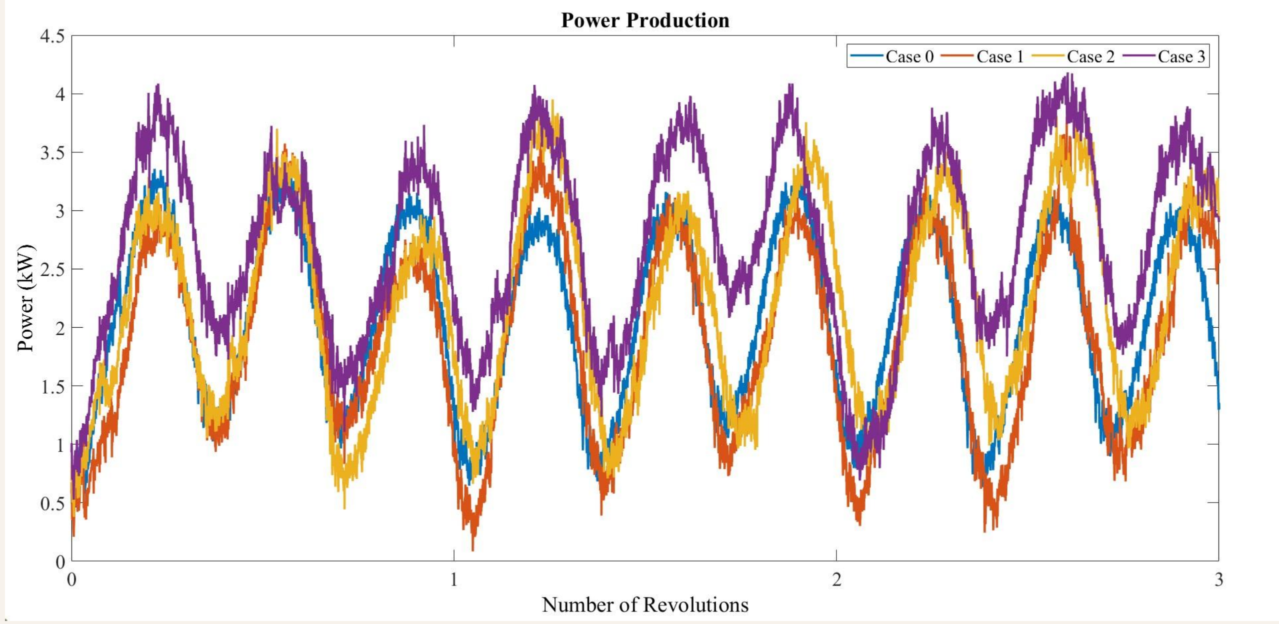
Wake Analysis

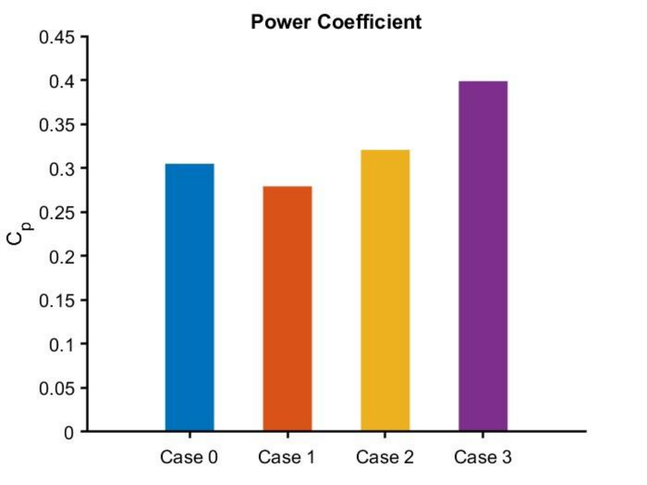
- Turbulence convection along vertical planes intersecting with shaft is plotted.
- Positive terms imply that the mean kinetic energy moves through the top part of the flume.
- Negative terms imply that the mean kinetic energy moves through the bottom part of the flume.
- Effect of mobile bed on turbulence convection is visible.
- More energetic region in near fields of cases with mobile bed.



Power Production

- Two power-related quantities are plotted for all cases:
  - Instantaneous Power Production
  - Power Coefficient
- By increasing the bed load layer thickness in cases 2 and 3, a slight growth of power coefficient is seen compared to case 0.
- This might be the effect of bed deformations in near field of the turbine, causing a jet flow in this region.





Conclusion

- The high momentum region and elevated turbulence in the near field of VAT lead to increased sediment transport and bed deformations;
- Effects of the rotating blades on morphodynamic processes cause deep scour beneath the VAT and relatively high deposition in the near field;
- Asymmetric wake flow, due to the rotation of the blades, makes the sand waves' migration asymmetric. These effects can impact the output of one turbine as well as an array of turbines;
- Sediment erosion and deposition around the center and the nearfield of VAT make jet flows. The resulting jet flows in the near field of VAT cause energy entrainment in this region;
- The power coefficient of the VAT changes as -2.6% for case 1, +1.6% for case 2, and 9.4% for case3.

Thank You!
Questions?

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