Simulating the Environmental Impact of Tidal Turbines on the Seabed

Lada Vybulkova
University of Glasgow
Glasgow G12 8QQ, United Kingdom
E-mail: l.vybulkova.1@research.gla.ac.uk

Marco Vezza
University of Glasgow
Glasgow G12 8QQ, United Kingdom
E-mail: marco.vezza@glasgow.ac.uk

Richard Brown
University of Strathclyde
Glasgow G1 1XJ, United Kingdom
E-mail: richard.brown@strath.ac.uk

***Summary*—Recent proliferation of marine renewable energy installations has inspired a number of researchers to study the possible impact of the technologies on the marine environment. The impact of tidal turbines on the flow downstream of the rotor and their effect on sediment transport from the seabed over the lifetime of the devices is of particular concern, given the potential damage to the seabed, the habitats of marine life and submarine power cables used to connect the devices to the coast.**

Previous computational studies of the environmental impact of tidal turbines have, however, focused predominantly on large-scale one and two dimensional modelling. Resolution of the three-dimensional nature of the flow through the rotor of the turbine proves to be crucial if the mechanism whereby these devices entrain sediment from the seabed is to be properly understood.

The three-dimensional phenomena occurring in the flow through the rotor of the turbine have been found to profoundly affect how the sediment is lifted from the seabed and transported downstream in the wake of the device. The physics of sediment transport due to the rotor of a tidal turbine in a tidal current have been investigated using high resolution three- dimensional computational simulations of the hydrodynamics of the rotor wake. The direct impact of the turbine on the seabed has been found to be confined to an area that extends no further than two rotor diameters downstream of the turbine. The maximal values of shear stress, which indicate the extent of the impact, vary with the distance between the rotor hub and the seabed.

I. Introduction

The efficiency and design of various forms of tidal turbines have been the focus of both experimental and computational studies. The computational studies have generally adopted a physical model of the turbine geometry and relied on such a model to produce a comprehensive assessment of the performance of the device. In contrast with the growing number of experimental investigations of the effect of such technologies on the habitats of marine flora and fauna, a relatively small number of studies have attempted to assess the potentially harmful impact of tidal turbines on the marine environment by means of computer modeling. The main impact of a tidal turbine on its environment arises from the possibility that the turbine might interact hydrodynamically with the seabed, alter erosion rates of the sediment, damage the power cables and disturb the marine environment in the long term.

The models used to assess the environmental impact of tidal turbines have usually been constructed by introducing some form of simplified representation of the effects of the turbine into an existing hydrodynamical model for the background flow [1], [2], [3]. The hydrodynamic models used in past studies have usually represented the flow on the scale of the turbines as either one-dimensional or two-dimensional (i.e. depth-averaged). The three-dimensional phenomena occurring in the wake of a turbine in a tidal current have thus not been properly captured. The present study shows that detailed three-dimensional computational modelling of the fluid dynamics of the interconnected turbine-environment system is required to fully understand the interaction between tidal turbines and the seabed.

II. Methods

A series of high-resolution computer simulations have been conducted using the Vorticity Transport Model (VTM). The VTM provides a detailed representation of the fluid dynamics within the wake of a rotor or turbine. In the VTM the temporal evolution of the vorticity ω and velocity $\mathbf{v}$ of an incompressible fluid is calculated by advancing through time the *Vorticity Transport Equation* [4]

$$\frac{\partial \omega}{\partial t} + (\mathbf{v} \cdot \nabla)\omega - (\omega \cdot \nabla)\mathbf{v} = S_\omega \tag{1}$$

where $\omega = \nabla \times \mathbf{v}$.

When a blade tip vortex approaches the seabed, the velocity that is induced parallel to the ground rises substantially. Individual vortices can create significant unsteady shear stresses on the ground, in some cases exceeding twice their time-averaged values [5]. The dimensionless Critical Bed Shear Stress, θ_{cm} was used as the threshold condition for initiation of sediment motion. Sediment particles are assumed to leave the seabed when $\theta \geq \theta_{cm}$. The excess bed shear stress $\xi = \theta/\theta_{cm} - 1$ [6] indicates the impact of the turbine on the seabed. The effect of the presence of the seabed on the dynamics of the flow has been modelled in the VTM using the *method of images* [7].

Tab. I provides details of the rotor of a representative three-bladed horizontal-axis device,

R	N_b	Aerofoil	θ_0
5m	3	NACA0012	3°

TABLE I
Parameters of the tidal turbine

which has been exposed to inflow that varies with water depth, as depicted in Fig.1.

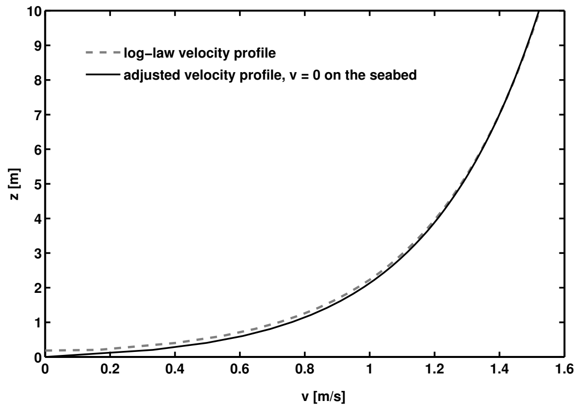

Fig. 1. Inflow velocity profile

III. Results

The vorticity induced by the presence of the device on the seabed has been modelled by the VTM. The simulation was initiated from an impulsive start, which has generated a strong vortex bound to the rotor blades. The starting vortex has then been transported by the flow down-stream of the rotor. Further from the rotor, the concentrated vortices have started to disintegrate and, since the starting vortex has now dissolved, the simulation at this point was considered to represent a quasi-steady state. Fig. 4 illustrates the evolution of the wake induced vorticity field. Each blade of the turbine trails a sheet of vorticity into the flow. These sheets roll up immediately behind the rotor to form a sequence of concentrated vortex filaments, yielding a helical structure to the wake as it convects into the flow downstream of the turbine. The velocity profile causes the helical structure to incline due to the vertical gradient of the inflow velocity. The inclination of the induced vorticity field contributed to its eventual disintegration into a 'cloud' of vorticity fragments. The vorticity fragments are elevated from the seabed by the inflow.

Fig. 2. Side view of the induced vorticity field during the development of the turbine wake. Top: 42s, bottom: 189s after an impulsive start to the rotor. ($v_{hub} = 1.25$ m/s.)

The evolution of the induced vorticity field has been simulated for a number of positions of the rotor subjected to the velocity profile presented in Fig.1. The velocity at the rotor plane is illustrated in Fig.3.

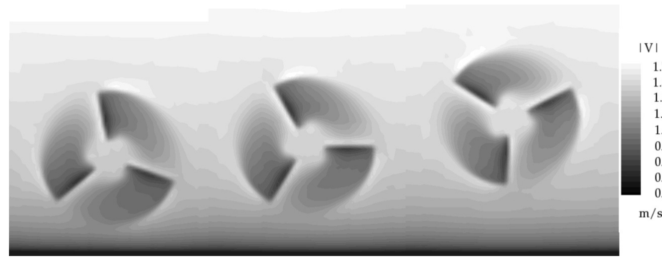

Fig. 3. Velocity field at the rotor plane for three different positions of the rotor hub, from the left to the right: $1.4R$, $1.6R$ and $2R$

Tab.II contains the velocity at the rotor hub for each of the chosen positions, where the corresponding values of the vertical gradient of the inflow velocity is represented by the difference

$$\Delta v_{2R} = v_{fs}(z_{hub} + R) - v_{fs}(z_{hub} - R),$$

.

z_{hub} $[m]$	6.0	7.0	8.0	9.0	10.0
v_{hub} $[m/s]$	1.35	1.40	1.45	1.49	1.52
Δv_{2R} $[m/s]$	0.80	0.61	0.50	0.43	0.38

TABLE II
Position of the rotor hub in the velocity profile

The velocity gradient increases when the turbine is placed closer to the seabed. The influence of the velocity gradient on the induced vorticity is apparent in Fig.4.

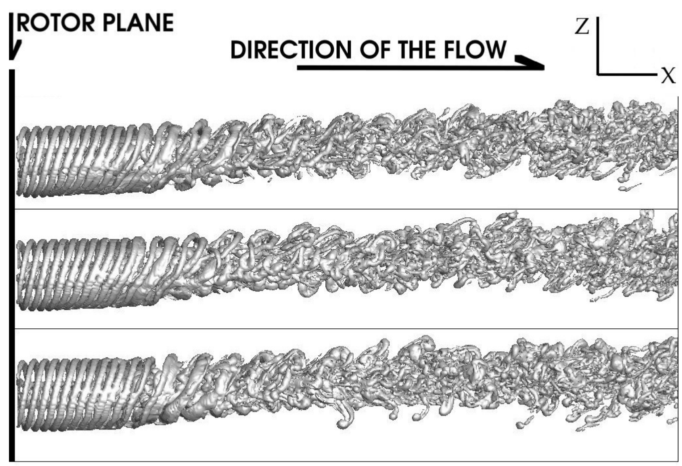

Fig. 4. Wake induced vorticity field for three different positions of the rotor hub, from the top to the bottom: $z_{hub} = 1.4R$, $1.6R$ and $2R$, all at $t = 112$ s

The inclination angle of the vorticity loops in the helical structure down-stream of the rotor is greater when the turbine is closer to the seabed. For all studied rotor positions the vorticity is elevated from the seabed by the flow further than $2R$ down-stream of the rotor. The vorticity induced by the flow affects the velocity near the seabed, which is crucial for the uplift of sediment into suspension. The excess shear stress on the seabed is driven by the velocity just above the surface, since $\xi = \theta/\theta_{cm} - 1 = |\mathbf{v}_{fs}|^2/v_t^2 - 1$. Fig. 5 shows the spatial distribution of the excess bed shear stress for the studied positions of the rotor above the seabed.

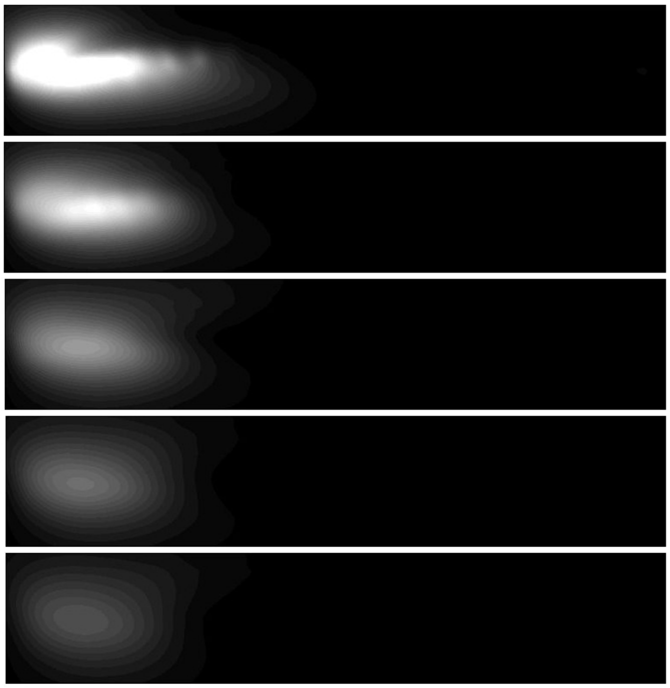

Fig. 5. Excess bed shear stress 10 cm above the seabed, from the top to the bottom $z_{hub} = 1.2R$, $1.4R$, $1.6R$, $1.8R$ and $2R$

The excess bed shear stress contains high values in the region immediately down-stream of the rotor for all investigated positions of the turbine. The maximal value of the excess bed shear stress depends on the proximity of the turbine to the seabed. Furthermore, the excess bed shear stress has been averaged over the computational domain and the time period of the quasi-steady state. The temporal mean of the averaged excess bed shear stress has been compared for the investigated positions of the rotor above the seabed. A relation between the mean averaged excess bed shear stress (MAEXSS) and the position of the turbine is apparent from Fig.6 and has been approximated by a quadratic function, Eq.2.

$$\bar{\xi} = \xi_2 z_{hub}^2 - \xi_1 z_{hub} + \xi_0 \quad (2)$$

The coefficients are $\xi_2 = 9.96$, $\xi_1 = 42.13$ and $\xi_0 = 48.02$. Goodness of the quadratic fit, expressed by the coefficient of determination, is 0.993.

The relation between the mean averaged excess bed shear stress (MAEXSS) and the vertical gradient of the inflow velocity is presented in Fig.7 and has been approximated by an affine function Eq.3.

$$\bar{\xi} = \tilde{\xi}_1 \Delta v_{2R} - \tilde{\xi}_0, \quad (3)$$

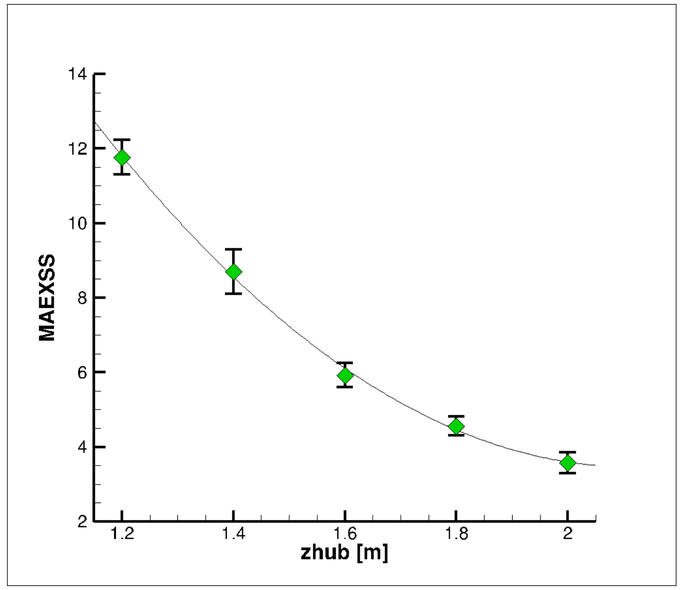

Fig. 6. Temporal mean of the AEXSS

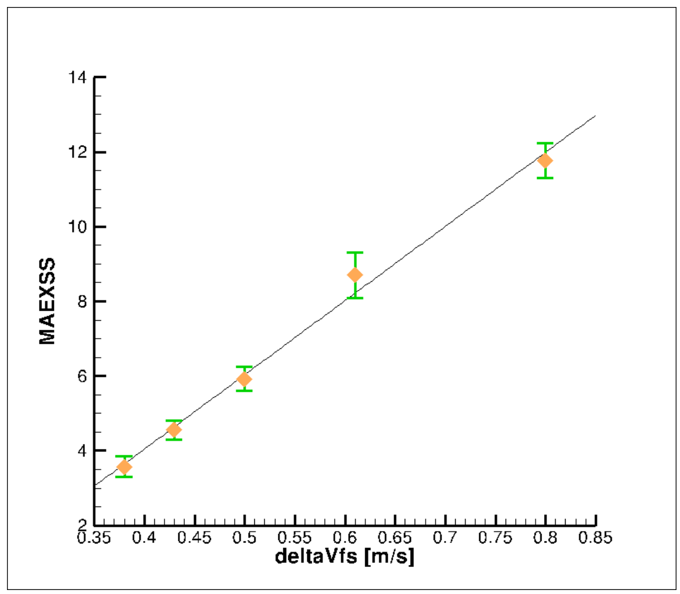

Fig. 7. Dependence of the temporal mean of the AEXSS on the inflow velocity gradient

where the coefficients are $\tilde{\xi}_1 = 19.87$ and $\tilde{\xi}_0 = 3.90$. The precision of the approximation is given by the coefficient of determination, which is 0.986.

IV. Conclusion

The physics of sediment transport due to the rotor of a tidal turbine in a tidal current have been investigated using high resolution three-dimensional computational simulations of the hydrodynamics of the rotor wake. In the process of extracting power from the tidal stream, each blade of the turbine trails a sheet of vorticity into the flow. These sheets roll up immediately behind the rotor to form a sequence of concentrated vortex filaments, yielding a helical structure to the wake as it convects into the flow downstream of the turbine. This structure interacts with the seabed, resulting in localised increases in bed shear stress that are responsible for the entrainment of sediment into the flow. The ordered structure of the rotor wake decays rapidly downstream of the device and, if the inflow varies with depth, the wake lifts clear of the seabed some distance downstream of the turbine. As a result, the region of elevated excess bed shear stress, and thus the direct impact of the turbine on the seabed, is confined to an area that extends no further than two rotor diameters downstream of the turbine. The positioning of the rotor in a tidal flow influences the maximum shear stresses on the seabed. The impact of the turbine on the seabed expressed as the mean average excess bed shear stress increases when the distance between the rotor and the seabed decreases. The relationship between the position of the device and the mean averaged excess bed shear stress is approximately quadratic. The mean averaged excess bed shear stress is related to the vertical gradient of the inflow velocity, which is resposible for the inclination of the induced vorticity field, by a simple affine function. The results suggest that the positioning of power-extraction devices closer to the seabed requires prior examination of the flow conditions to mitigate potential damage to the seabed, supporting structures and underwater electrical installations.

References

[1] Ahmadian, R., Falconer, R. and Bockelmann-Evans, B. "Far-field modelling of the hydro-environmental impact of tidal stream turbines", *Renewable Energy, Volume 38, Issue 1, Pages 107-116* February 2012.

[2] Neill S.P., Litt, E.J., Couch, S.J., Davies, A.G . "The impact of tidal stream turbines on large-scale sediment dynamics", *Renewable Energy, Volume 34, Issue 12,Pages 2803-2812* December 2009.

[3] Neill S.P., Jordan, J.R., Couch, S.J. "Impact of tidal energy converter (TEC) arrays on the dynamics of headland sand banks", *Renewable Energy, Volume 37, Issue 1, Pages 387-397* January 2012.

[4] Brown, R. E., and Line, A. J. "Efficient High-Resolution Wake Modelling Using the Vortex Transport Equation," *AIAA Journal, Volume 43, Issue 7, Pages 1434–1443.* 2005

[5] Lee, T.E., Leishman, J.G. and Ramasamy, M. "Fluid Dynamics of Interacting Blade Tip Vortices With a Ground Plane", *Proc. Annual Forum of the American Helicopter Society* 2008.

[6] van Rijn, L.C. *Unified View of Sediment Transport by Currents and Waves, I:Initiation of Motion, Bed Roughness, and Bed-Load Transport*, 2007

[7] Whitehouse, G.R and Brown, R.E. "Modelling Rotor Wakes in Ground Effect", *Journal of the American Helicopter Society, Volume 49, Issue 3, Pages 238-249* July 2004.