The modelling of tidal turbine farms using multi-scale, unstructured mesh models

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Tidal turbine farms

Generation of renewable energy through farms of turbines placed in high tidal currents. Applications of hydrodynamic modelling:

- Energy resource assessment.
- Environmental impact studies.
- Micro-siting, optimisation of farm layouts.

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Challenge to combine turbine scale flow (order 10m) with large scale tidal flow (10s-100s of kms). Gap between idealised 3D CFD modelling and coastal ocean models.

Parameterisation of turbines in large scale model based on outcomes of CFD modelling and lab experiments.

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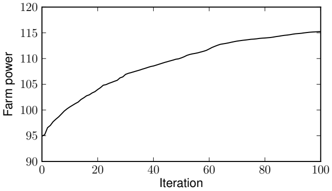
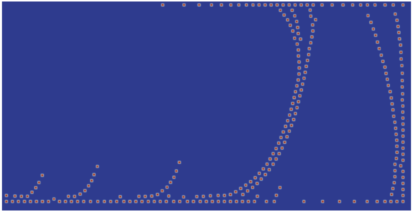
OpenTidalFarm

http://opentidalfarm.org





Automatic optimisation of turbine farm layouts through adjointed shallow water solver.

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EPSRC
Engineering and Physical Sciences Research Council

SuperGen/UKCMER project:
Large Scale Interactive Coupled Modelling of Environmental Impacts of Marine Renewable Energy Farms (LINC)

Imperial College London
Queen's University Belfast
Cefas

http://amcg.ese.ic.ac.uk/fluidity

Open Source Finite Element Modelling framework used for a wide range of Earth science and engineering applications.

Fluidity solves 3D non-hydrostatic Navier Stokes equations, but also depth-averaged 2D shallow water equations. It implements a host of numerical techniques, Continuous and Discontinuous Galerkin methods, and anisotropic mesh adaptivity.

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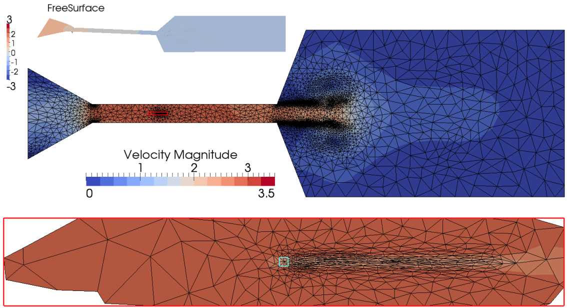

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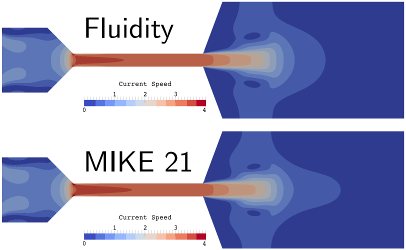
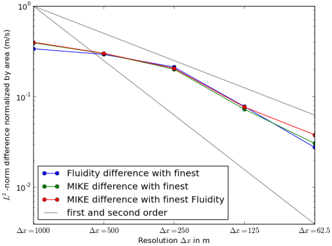
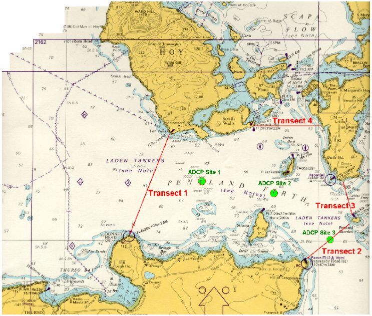
Widely used in marine engineering.

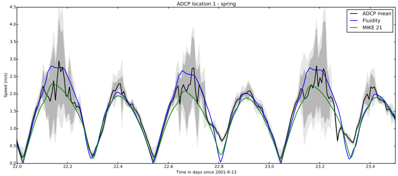
- 3D and 2D capability (MIKE 3, MIKE 21)
- Sediment transport
- Ecological modelling (ECO Lab)
- Wetting and drying
- Structures (including turbines!)

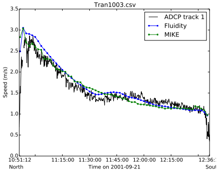
Comparison MIKE 21 vs Fluidity

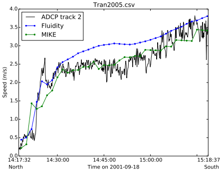




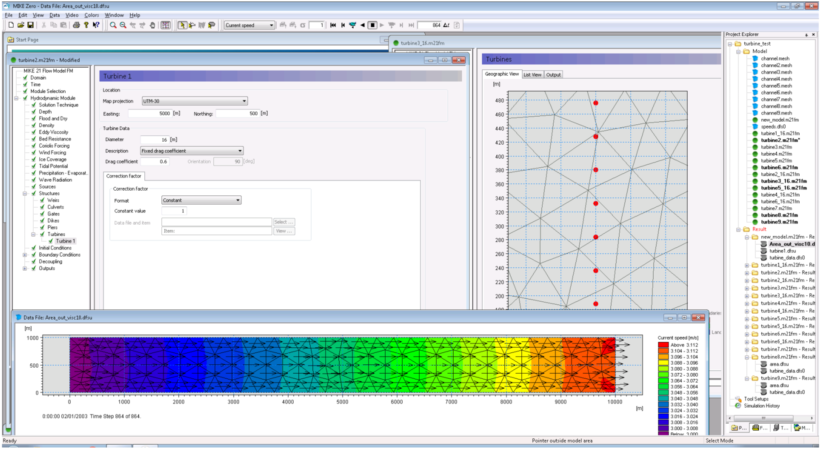






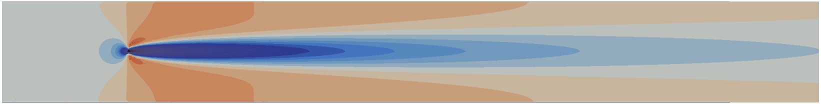


Turbines in MIKE 21

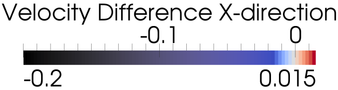


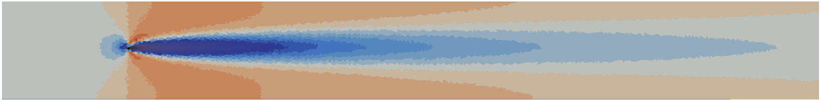
Turbines at coarse resolution are represented as point momentum sources. Implemented as enhanced bottom drag in cell that contains the turbine location.

Turbines in Fluidity and MIKE



Fluidity

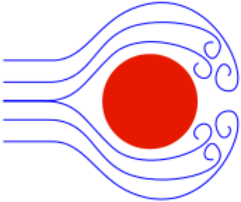




MIKE 21

Visualisation of wake by velocity deficit (difference between solution with and without a turbine). Wake length depends on mixing, typically parameterised through turbulence model. Here, we use a fixed eddy viscosity.

Parameterisation of turbines in SWE models



Total body drag force on turbine:

$$\vec{F}(\vec{u}) = \tfrac{1}{2}\rho_0 C_D(u) A_{\text{cross}} \|u\| \vec{u}$$

Represented as a momentum source $\vec{f}(\vec{u})$:

Depth avg. momentum eqn.: $\rho_0 \dfrac{\partial \vec{u}}{\partial t} + \rho_0 \vec{u} \cdot \vec{\nabla} \vec{u} + g \vec{\nabla} \eta + \cdots = \vec{f}(\vec{u})$

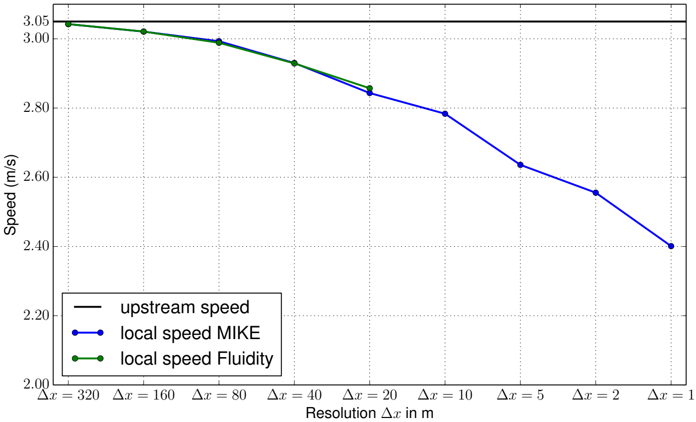
Applied over some horizontal area A, we need:

$$\int_A \vec{f}(\vec{u}) = \int_A \frac{\vec{F}(u)}{AH} = \int_A \frac{\rho_0 C_D(u) A_{\text{cross}}}{2AH} \|u\| \vec{u}$$

Therefore, we end up with a quadratic "bottom" drag force:

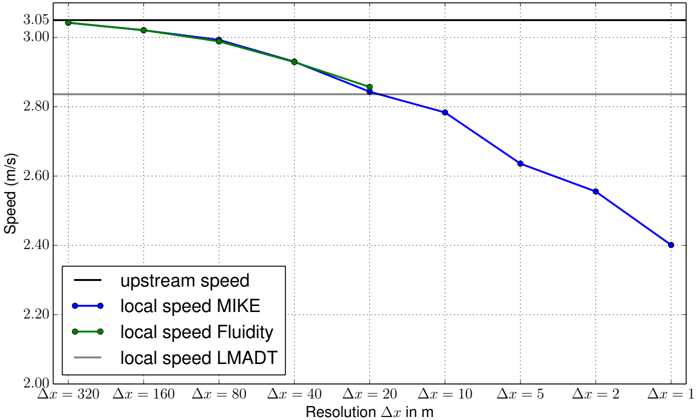
$$\vec{f}(\vec{u}) = \frac{\rho_0 C_D(u) A_{\text{cross}}}{2AH} \|u\| \vec{u}$$

Drop in local velocity



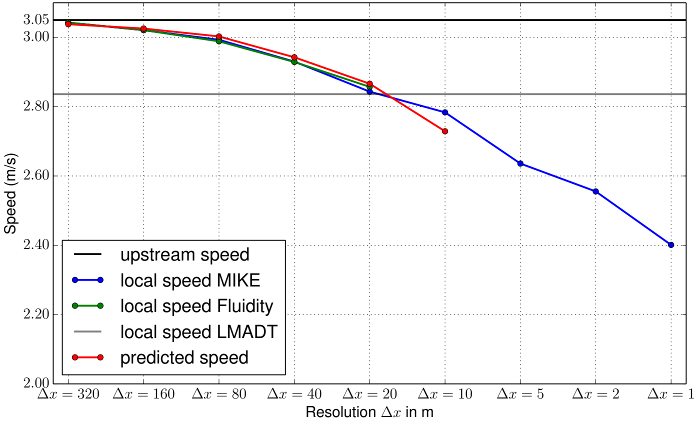
Local velocity in cell containing the turbine, drops significantly with increasing resolution. This local velocity is used to compute the drag force to be applied.

Drop in local velocity

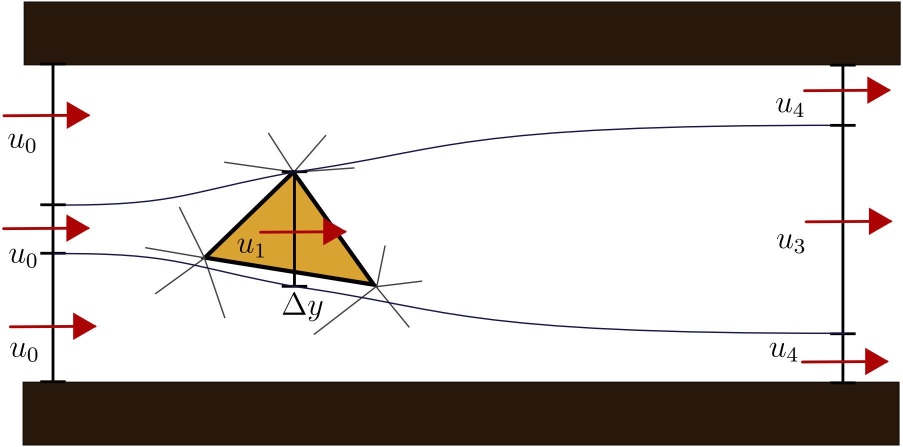


For resolution near the turbine scale (turbine diameter here is $D = 16$ m), the local velocity in cell matches the local turbine velocity predicted by actuator disc theory (LMADT).

Drop in local velocity



For resolutions larger than the turbine scale, the local velocity can be predicted by a modified actuator disc theory taking into account the length scale, Δx, over which the force is applied.



Adjust actuator disc theory (see Garret and Cummins '07), to take into account that the drag force $F = \frac{1}{2}\rho_0 C_D(u) A_{\text{cross}} u^2$, is not applied over the width of the turbine (diameter D), but over the width, Δy, of the cell the drag is applied within.

Correction in drag coefficient

Using the modified theory we can express the drag as a function of the local cell velocity instead of the upstream velocity:

$$F = \tfrac{1}{2}\rho_w C_T \frac{4}{\left(1+\sqrt{1-\gamma}\right)^2} A_{\text{cross}} \|u_{\text{local}}\|^2,$$

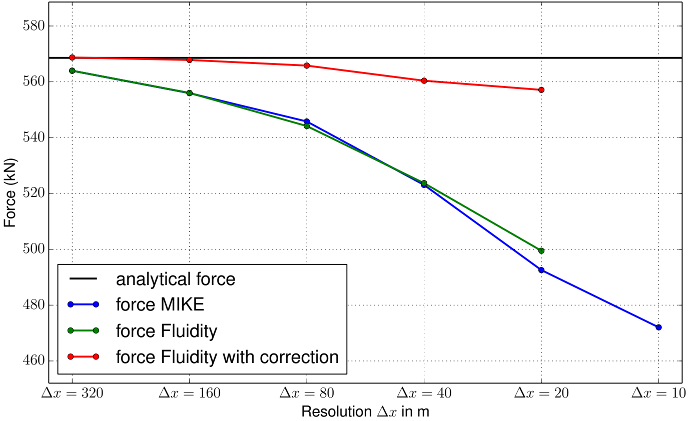
where

$$\gamma = C_T \frac{A_{\text{cross}}}{\Delta y H}.$$

Here $\Delta y H$ is the modified cross section, the product of the cell width Δy and water depth H.

In 3D, if we ignore the difference between the cell width and the turbine diameter, we have $\gamma = C_T$ and we recover the correction by Roc et al. '13. This assumes we resolve the turbine scale.

Correction in drag coefficient



Without correction, the drag force applied in the model drops significantly with resolution (up to 15%). With correction the change in applied force is limited (less than 2%).

Conclusions:

- There is a large difference between turbine scale and large scale tidal flow. Unstructured mesh models provide more flexibility to narrow down that gap, but simplification and parameterisation of turbine effects is still necessary.
- Parameterisation of turbines in under-resolved hydrodynamic models can be improved through a modified actuator disc theory that takes into account the width over which the force is applied numerically.
- A lot of work needs to be done to improve the turbulence parameterisation to achieve realistic wakes.