CFD Analysis and Optimisation of Tidal Turbine Arrays Using OpenFOAM

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Tidal Farm modelling at Exeter

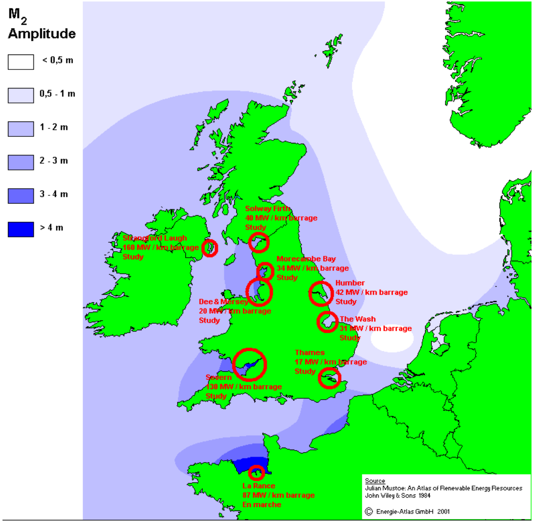
EPSRC-funded grant; *Optimal Design of Very Large Tidal Stream Farms: for Shallow Esturine Applications*. Also funded by Laing Foundation (PhD: Matt Berry)

Involves; P.I. Prof Mike Belmont

CFD	Flood Risk	Optimisation
Prof Gavin Tabor	Prof Slobodan Djordjevic	Prof Dragan Savic
Dr Mulualem Gebreslassie	Miriam Garcia-Oliva	Dr Michele Guidolin
Matt Berry		Dr Helena Mala Jetmarova
Ben Ashby		Ogaday Willers Moore

Joint with Edinburgh – Prof Ian Bryden, Dr Tom Bruce (FloWave facility)

Background: Esturine tidal energy



Significant power available in esturine tidal sites

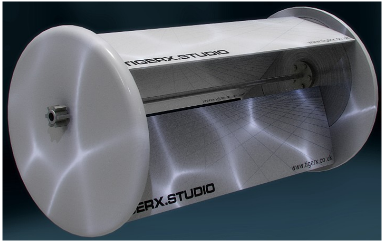
- Less challenging environment than marine sites.
- Closer to land
- Shallow water ≡ large farms of small installations.

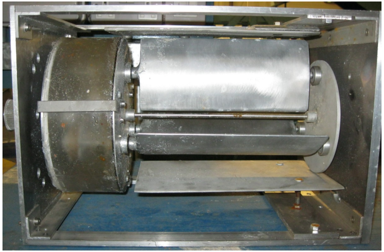
Background: Lift/Drag Turbine

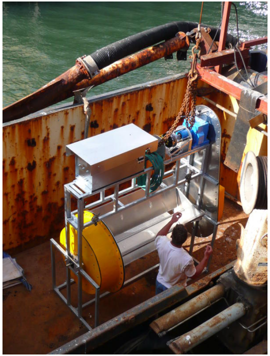
Lift/Drag turbine : Novel design for tidal turbine based on cycloidal turbine involving complex rotating airfoil blades

- Blades act in drag mode on one side; rotate (0.5Ω) to develop lift on other side
- Unit operates as cross-flow turbine
- Energy extracted through volume – high efficiency (measured efficiency of $\sim 50\%$)
- High blockage factor

Significant CFD challenge in simulating individual turbines – also want to simulate and optimise farms (of 10's or 100's of units)







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Project aims

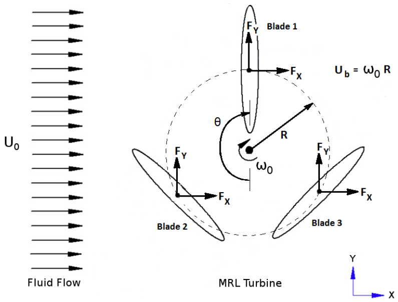
- Full sliding mesh (GGI) simulations undertaken - very expensive, but able to probe blade/flow interaction
- Developed new Immersed Body Force technique to represent turbine :
  - LES turbulence formulation – need to examine large scale transient motions
  - VOF – free surface important for turbine behaviour
  - Simulate multiple turbines within array
- Develop surrogate model for turbine positioning
- Optimise array using GA and compare with experiment
- Investigate flood risk (theoretical and specific case study – Solway Firth)

CFD undertaken with OpenFOAM - Flood risk with Mike21/Mike3D

Detailed CFD

Tank-scale model

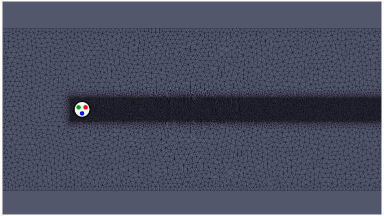
- Turbine radius, R = 0.055m
- Blades: 0.095m chord → 0.050m chord
- $U_0 = 0.875\text{m/s}$
- No free surface
- Two-dimensional simulation
- Variation of BSR: 0.1-1.0

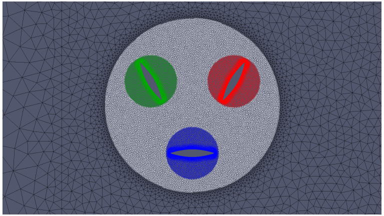


Computational Details

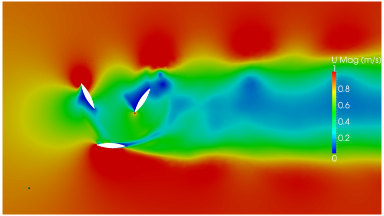
Mesh generated with Pointwise – 2d simulations

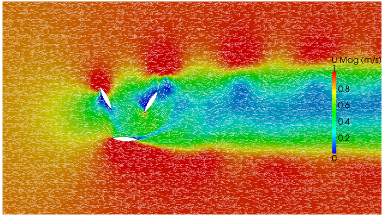
- Swept turbine diameter = 0.14m – 2d calculation
- $k-\omega$-SST model wall resolved ($y^+ \sim 1-2$)
- 100,000 cells; 5 GGI regions; gradual mesh inflation
- RANS with $k-\omega-SST$ model

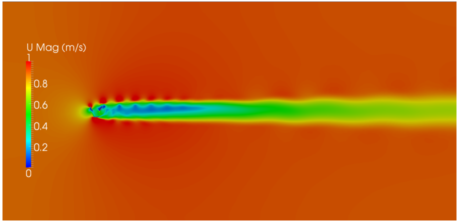




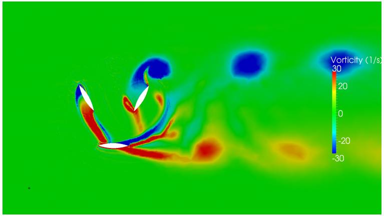
Results – 50cm chord

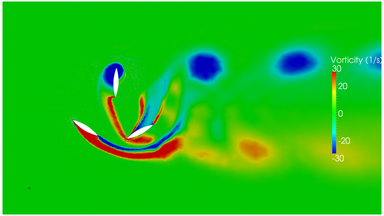


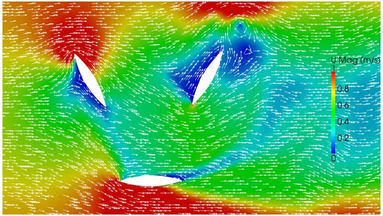




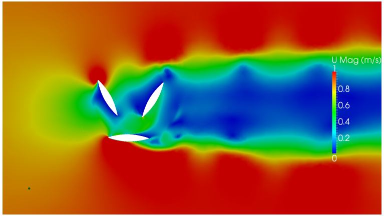
Vorticity

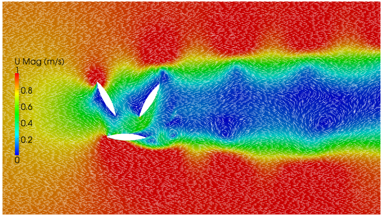

Vorticity (1/s)
30
20
0
-20
-30

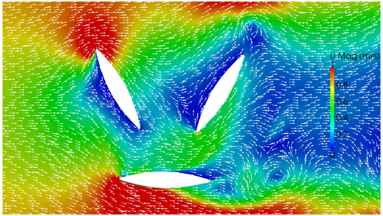

Vorticity (1/s)
30
20
0
-20
-30


U Mag (m/s)
1
0.8
0.6
0.4
0.2
0

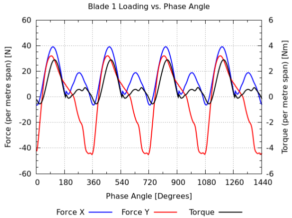
85cm chord

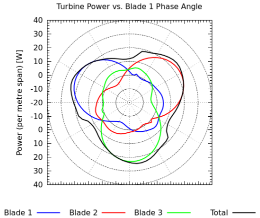


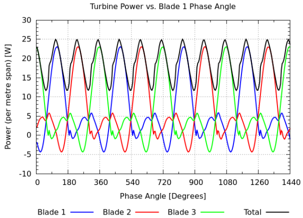


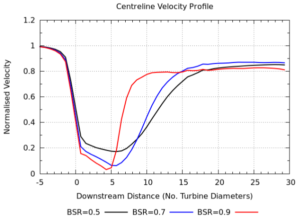


Force loadings + wake (BSR=0.5)

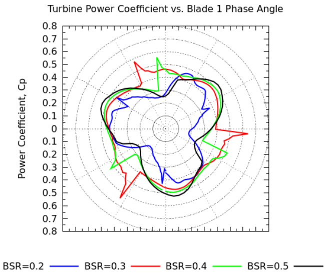


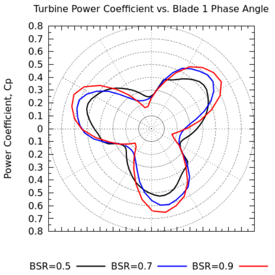






Force loadings – variable BSR=0.5





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Analysis

Full turbine calculations significantly challenging – transient stall effects and complex mesh motion. Some points to note :

- 3d effects most likely to be important for wake recovery. Working on code speedup and full 3d simulation for comparison with detailed tank tests
- Power, wake recovery significantly affected by turbulence properties. Have implemented $k - \omega$–SST turbulence model with sustain terms (Spalart and Rumsey) to keep turbulence level at an appropriate level
- GGI rotation specifies a constant input rotation speed. Actual turbine – rotation speed consequence of forces, probably not constant. Working on modifying GGI to evaluate torques and calculate Ω

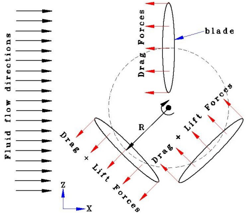
Turbine modelling – simplified

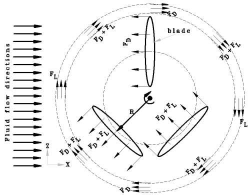
Immersed body force method :

- Blades represented by body forces

$$\overline{\mathbf{F}} = \overline{\mathbf{F}}_D + \overline{\mathbf{F}}_L$$

- Compromise between accuracy and efficiency
- Capable of representing large scale vortexes





Governing Equations

LES governing equations

$$\frac{\partial \overline{u}_i}{\partial t} + \frac{\partial}{\partial x_j}\left(\overline{u}_i \overline{u}_j\right) = -\frac{1}{\rho}\left(\frac{\partial \overline{p}}{\partial x_i} + \delta_{i1}\frac{\partial \langle P \rangle}{\partial x_1}\right)$$
$$+2\nu \frac{\partial}{\partial x_j}\overline{S}_{ij} - \frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i + \overline{F}_D + \overline{F}_L$$

$$\frac{\partial \overline{u}_i}{\partial x_i} = 0 \qquad \overline{S}_{ij} = \frac{1}{2}\left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i}\right)$$

SGS Modelling

One Equation Eddy Viscosity model adopted (`oneEqEddy`)

$$\tau_{ij} = \frac{2}{3} k_{sgs} \delta_{ij} - 2\nu_t \overline{S}_{ij} \qquad \text{where} \qquad \nu_t = C_k \overline{\Delta} \sqrt{k_{sgs}}$$

and

$$\frac{\partial k_{sgs}}{\partial t} + \overline{u}_i \frac{\partial k_{sgs}}{\partial x_i} = -\tau_{ij} \frac{\partial \overline{u}_i}{\partial x_j} - C_c \frac{k_{sgs}^{3/2}}{\overline{\Delta}} + \frac{\partial}{\partial x_i} \left(\frac{\nu_t}{\sigma_k} \frac{\partial k_{sgs}}{\partial x_i} \right)$$

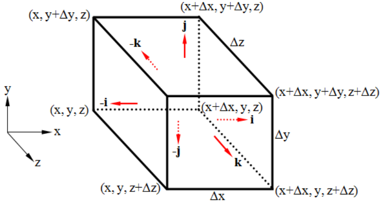
$C_k = 0.094,\ C_c = 1.0$, and $\sigma_k = 1.0$

Free surface modelling with VOF

Turbine Modelling

- No blade motion $\equiv$ cannot directly evaluate mechanical power
- Conservation of Linear Momentum across a control volume around the turbine

$$
\begin{aligned}
T = & \int_{A_{yz}} \left[(p)|_x - (p)|_{x+\triangle x} \right] dA \\
& + \int_{A_{yz}} \left[(\rho u_x u_x)|_x - (\rho u_x u_x)|_{x+\triangle x} \right] dA \\
& + \int_{A_{xz}} \left[(\rho u_y u_x)|_y - (\rho u_y u_x)|_{y+\triangle y} \right] dA \\
& + \int_{A_{xy}} \left[(\rho u_z u_x)|_z - (\rho u_z u_x)|_{z+\triangle z} \right] dA
\end{aligned}
$$



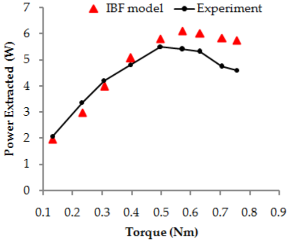
- Power = Thrust $\times$ average u over turbine

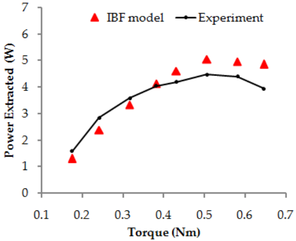
Validation

Laboratory testing carried out in flow channel; flow rate and turbine rotation under a range of mechanical torque conditions :

- Flow rate measured with rotormeter
- Torque output using mechanical system
- Rotation rate recorded optically.

Compared with functionally equivalent CFD simulations.





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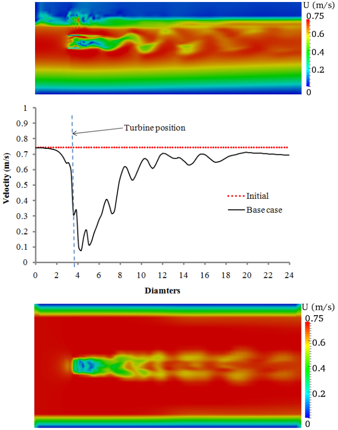
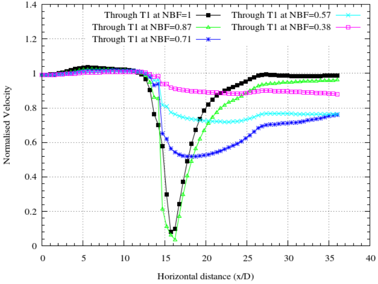
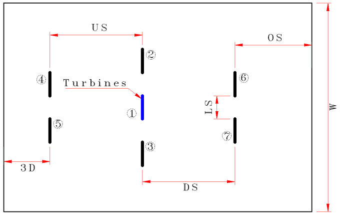
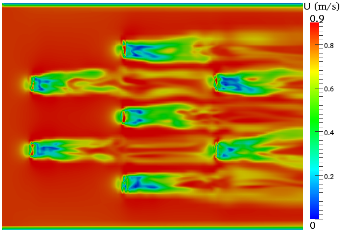
Single Turbine with IBF



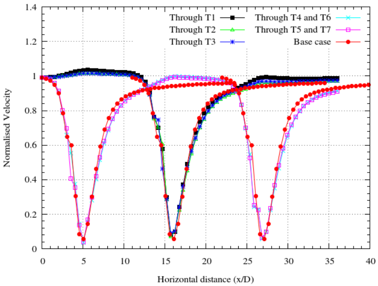


Multiple Turbines





Able to compute power, wake recovery for different turbine loadings within a farm.



Farm Modelling

Ultimate aim to optimise farm of 10's or 100's of devices

Optimise based on position, loading factor etc. Targets; power output, cost

Most suitable technique – *Genetic Algorithm*.

- Create population of models
- Calculate "fitness" + cull less fit
- Generate new population through mutation and genetic recombination

Capable of exploring complex N-d parameter space and reliably identifying optimum (Pareto front). However does require 1000's of evaluations. Cost implications

Surrogate modelling

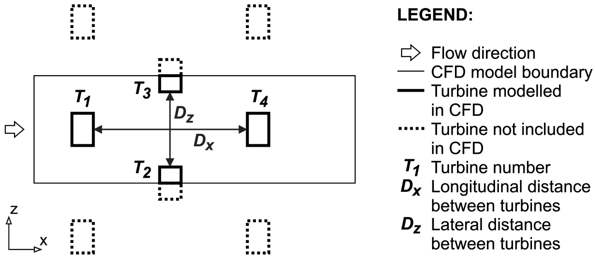
Case	Details	Spec	Time
GGI	160k cells, 30 revolutions	16 cores	5 days
IBF	1 turbine, 148k cells	12 cores	17 hrs
IBF	7 turbines, 1M cells	12 cores	44 hrs

Need to develop *surrogate model* – run 10's of simulations and use *Artificial Neural Network*, *Kriging* to mine results and create correlation.

Surrogate modelling

Represent CFD results by a simpler *surrogate model* – ANN, Kriging, k-NN

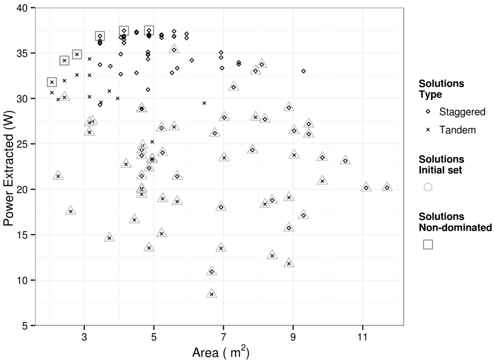
- Tune (train) on a limited subset of data – 10N for N-dimensional parameter space
- Simulations make use of symmetry in CFD to represent infinite farm
- Parameterise in terms of separations, loadings – discrete or continuous parameterisations
- Can update surrogate between generations



Optimisation

Initial results :

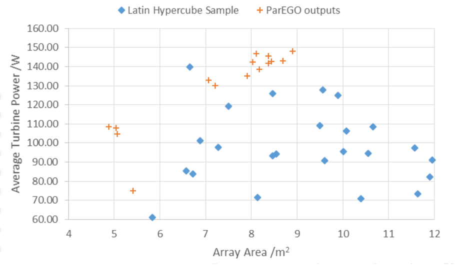
- 3 row farms – 2 alignments (staggered/tandem)
- 6 parameters (592704 layouts in total)
- Surrogate model based on initial sample of 30 solutions (per alignment) – create using Latin Hypercube sample
- Optimisation – GA evaluation using surrogate – evaluate new solutions using farm model



HAWT results

UG research project (B.Ashby) looking at HAWT turbines :

- Similar modelling methodology – farm array of small scale (lab scale) turbines
- Infinite array simulated by symmetry conditions.
- Parameterisation based on separation and load
- Investigate ParEGO optimisation (serial v. parallel)



Conclusions

Results from CFD work :

- GGI simulations detailed but very expensive. Characterised variation of wake and power with various factors (including turbulence)
- Heuristic IBF method cheaper alternative – still not cheap enough
- Development of cheaper surrogate farm models
- Development of optimisation techniques for full farm
- Flood risk analysis

Currently working on :

- Full experimental farm validation (Edinburgh flow tank)

Acknowledgements

Experimental Prof Ian Bryden, Dr Tim Bruce (Edinburgh)

Optimisation Prof Dragan Savic, Prof Slobodan Djordjevic, Dr Michele Guidolin

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Papers

"CFD Simulations for Sensitivity Analysis of Different Parameters to the Wake Characteristics of a Tidal Turbine", M.G.Gebreslassie, G.R.Tabor, M.R.Belmont, *Open Journal of Fluid Dynamics* **2** pp. 56 64 (2012).

"Numerical modelling of a new class of cross flow tidal turbine using OpenFOAM I:calibration of energy extraction", M.G.Gebreslassie, M.R. Belmont, G.R.Tabor, *Renewable Energy Journal* **50** pp.994-1004 (2013).

"Numerical modelling of a new class of cross flow tidal turbine using OpenFOAM II: investigation of turbine to turbine interaction", M.G.Gebreslassie, M.R. Belmont,G.R.Tabor, *Renewable Energy Journal* **50** pp.1005-1013 (2013).

Papers

"Investigation of the performance of a staggered configuration of tidal turbines Using CFD", M.G. Gebreslassie, G.R.Tabor, M.R.Belmont. *Renewable Energy Journal* **80** pp. 690 698 (2015).

"A New Modelling Language for Describing Interacting Arrays of Complex Hydrodynamic Objects Illustrated by Tidal Stream Farms" M.R.Belmont, M.Garcia, G.R.Tabor, M. Gebreslassie, A.D. Gilbert S.Djordjevic, D.Savic, I Bryden, Submitted to : *Renewable Energy Journal*.

"The impact of tidal energy extraction is estuaries: analysis of the influence of channel geometry". M. Garcia-Oliva , S. Djordjevic, G. R. Tabor, Submitted to : *Renewable Energy Journal*.