CFD Simulation of Free Surface Flows in OpenFOAM

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Research group : 4 PhD, 2 PDRA, 2 KTP. Working on all aspects of CFD (theory, applications); predominantly using OpenFOAM.

Variety of projects including

- Tidal Scour behind bridges (EPSRC)
- Additive Manufacture (InnovateUK)
- Adjoint Optimisation of vortex separators (KTP)
- Floating Wind Turbines (UK/China)
- ML-CFD (EPSRC)

Past projects include Tidal Stream Farm Optimisation, FRMRC-II

OpenFOAM

OpenFOAM is an Open Source CCM code/code library :

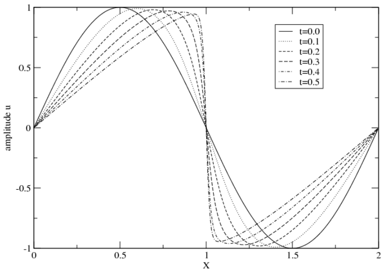
- Written in C++ – Based on FVM on arbitrary unstructured (polyhedral cell) meshes
- Fully featured – covers turbulent flow (LES,RANS), multiphase flow (Lagrangian, Eulerian, FSF), combustion, FSI, parallelisation ...
- Extensive user community – Academic and commercial usage.

OpenFOAM uses the full range of the C++ language – inheritance, polymorphism, templating, operator overloading etc – where appropriate :

Effective result is a high level "language" for encoding CFD.

Example : Burgers equation

$$\frac{\partial \mathbf{u}}{\partial t} + \nabla.(\frac{1}{2}\mathbf{u}\,\mathbf{u}) = \nu \nabla^2 \mathbf{u}$$



Implemented as :

```
fvVectorMatrix UEqn
(
    fvm::ddt(U)
  + 0.5*fvm::div(phi, U)
  - fvm::laplacian(nu, U)
);

UEqn.solve();
```

Advantages

Open Source software development encourages code sharing and information exchange. OpenFOAM's structure and use of C++ is ideal for this and provides a common platform for CFD research.

Basic code designed to make implementing new models simpler (eg. overloading mathematical operators) and more rigorous (physical dimension checking)

Advantages :

- Complete transparency and code availability (vs. "grey box" approach for commercial codes)
- Information exchange with other practitioners at a fundamental level
- CFD use not rationed by license fees.

VOF modelling

Two types of modelling for free surface flow : interface tracking and interface capturing. *Volume of Fluid* implemented in OpenFOAM.

Solve for single (mixture) fluid

$$\frac{\partial \mathbf{u}}{\partial t} + \nabla.\mathbf{uu} = -\frac{1}{\rho}\nabla p + \nu_t \nabla^2 \mathbf{u}$$

and an *indicator function* α

$$\alpha = \begin{cases} 0 & \text{in air} \\ \text{between 0 and 1} \rightarrow & \text{interface} \\ 1 & \text{in water} \end{cases}$$

Continuity equation for α :

$$\frac{\partial \alpha}{\partial t} + \nabla . \alpha \mathbf{u} = S_{\alpha}$$

Given the phase fraction α, construct mixture properties as

$$\mu_m = \alpha \mu_a + (1 - \alpha) \mu_b$$

Substantial effort involved in compressing the region $0 < \alpha < 1$ to localise the interface location.

Other modelling

Also implemented in OpenFOAM :

1. Actuator disk modelling for turbine rotors (several times)
2. Sliding mesh (detailed blade motions)
3. 6 d.o.f modelling/mesh adaption
4. Overset meshing

Relevant Projects

Several projects involving free surface flows + VOF :

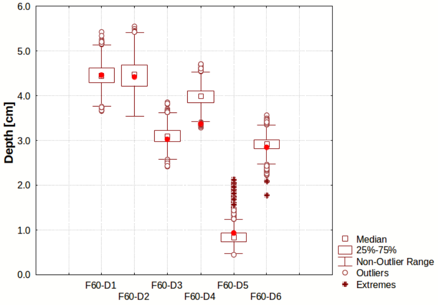
1. FRMRC-II – modelling runoff from road surfaces into gully pots
2. Tidal farm modelling project
3. CCP-WSI – wave-structure interaction
4. Scour behind bridge piers
5. Wind farm optimisation

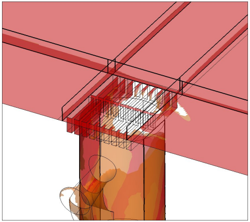
FRMRC-II

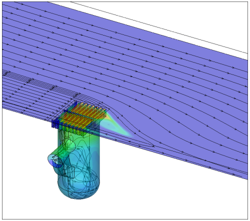
Study water runoff from road surface into gully pot

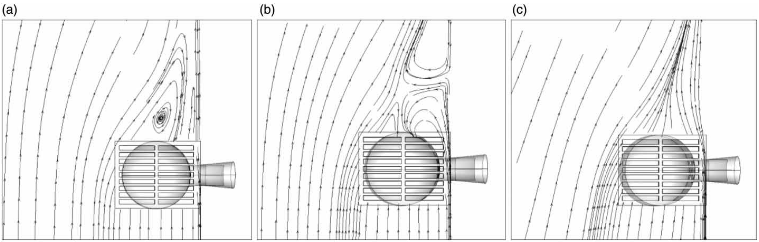
CFD used to extend flood modelling for drainage network model

Comparison of observed and simulated depths



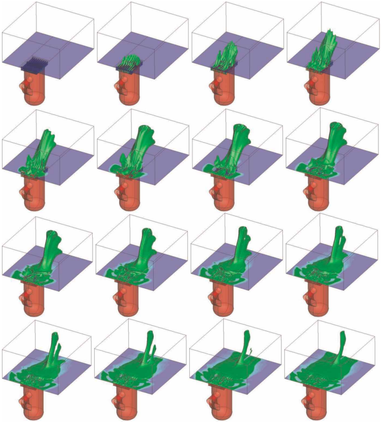




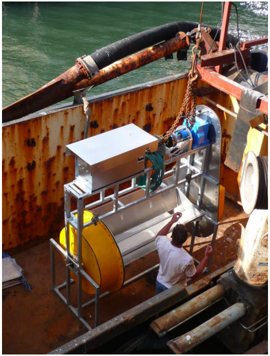


$S_L=1/200,\ S_T=1/200$ $S_L=1/200,\ S_T=1/60$ $S_L=1/200,\ S_T=1/20$

Surcharging

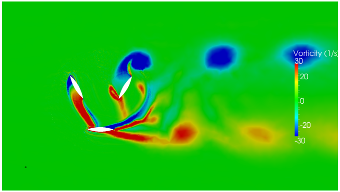


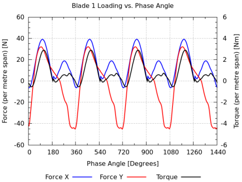
Tidal turbine project



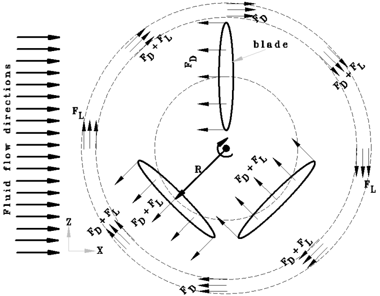
Project investigating estuary-based tidal turbines (+ arrays) based on novel lift/drag design.

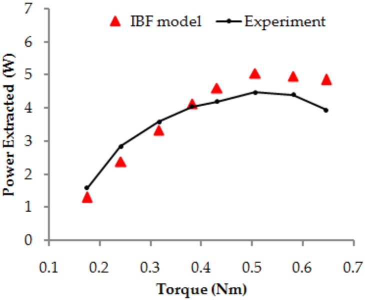
Detailed blade modelling and simplified body force model constructed

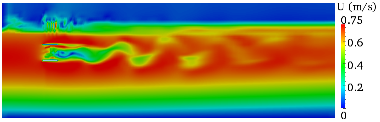




IBF Model


Fluid flow directions
blade
F_D
$F_D + F_L$
F_L
R
Z
X


IBF model
Experiment
Power Extracted (W)
Torque (Nm)
0
1
2
3
4
5
6
7
0.1
0.2
0.3
0.4
0.5
0.6
0.7

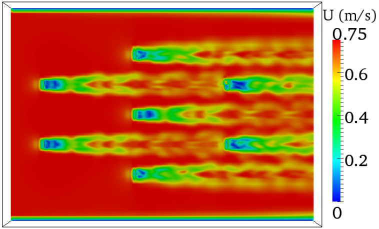

U (m/s)
0.75
0.6
0.4
0.2
0

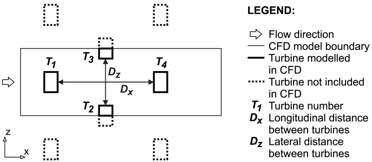
Farm Modelling

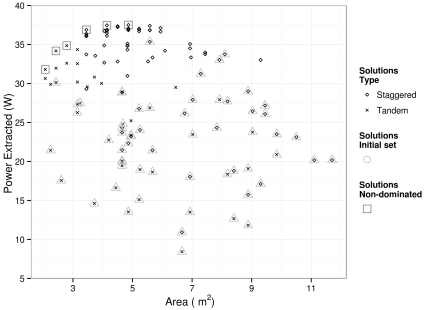
Case	Details	Spec	Time
GGI	160k cells, 30 revolutions	16 cores	5 days
IBF	1 turbine, 148k cells	12 cores	17 hrs
IBF	7 turbines, 1M cells	12 cores	44 hrs

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

Array optimisation carried out using surrogate modelling and GA.





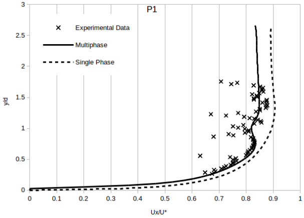


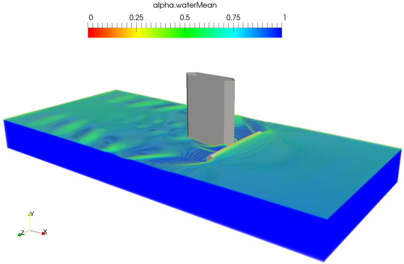
Bridge Scour project : Motivation

Figure : Rothern Bridge, Devon

- Debris blockages at bridges can change the flow behaviour thus increasing scour and hydraulic loading on the structure.
- Masonry arch bridges are the most commonly used bridge type in the UK.
  - Form 40% of UK bridge stock, many of which are heritage structures.
  - Have short span and low clearance increasing the chance of debris accumulation.
  - Past decade failures (e.g. in Cumbria flood of 2009).
- A pressing need to update UK safety codes to account for the effect of debris blockages on scour.

- Validated VOF modelling of flow around bridge pier
- Developed scour model using mesh (bed) motion
- Developing scour + deposition model using kinetic theory





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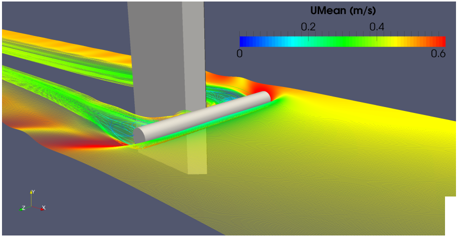

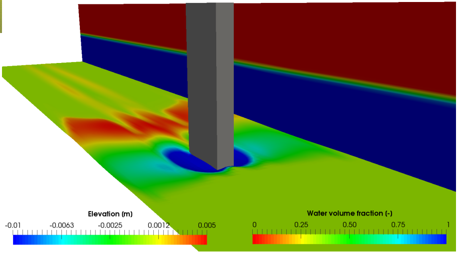

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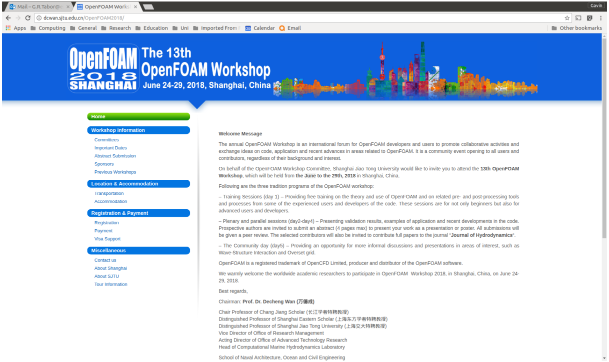
OpenFOAM Workshop 2018 – Shanghai, June 24-29th – http://dcwan.sjtu.edu.cn/OpenFOAM2018/



Thank you for listening

Any questions?

Papers

"Experimental and numerical investigation of interactions between above and below ground drainage systems", S. Djordjevic, A.J. Saul, G.R. Tabor, J.Blanksby, I. Galambos, N. Sabtu, G. Sailor. *Water Science and Technology* **67(3)** pp. 535 – 542 (2012).

"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).

"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).

"Comparison of multiple surrogates for 3D CFD model in tidal farm optimisation, W. Moore", H. Mala-Jetmarova, M. Gebreslassie, G. Tabor, M. Belmont, D.Savic, *Procedia Engineering* **154** pp. 1132 1139 (2016).

"The impact of tidal energy extraction is estuaries: analysis of the influence of channel geometry". M. Garcia-Oliva , S. Djordjevic, G. R. Tabor,*Renewable Energy Journal* **101** pp.514 – 525 (2017)