OpenFOAM at Exeter

Dr Gavin Tabor

CEMPS, University of Exeter

Presentation: Overview

1. What is OpenFOAM?
2. Exeter Overview
3. Optimisation
4. Tidal Turbines

Presentation: Overview

1 What is OpenFOAM?

2 Exeter Overview

3 Optimisation

4 Tidal Turbines

What is OpenFOAM?

OpenFOAM is an Open Source CCM (predominantly CFD) code :

- Written in C++
- Based on FVM on arbitrary unstructured (polyhedral cell) meshes
- Originally developed by Henry Weller and others at IC (1990 – 2000) as FOAM (Field Operation And Manipulation)
- Released 2004 under Gnu GPL by OpenCFD Ltd
- Now one of several independent versions and developments (-dev, pyFoam)
- Extensive user community :
  - UKRI User meeting: U.Leeds 13th, 14th April 2015
  - 10th OpenFOAM Workshop: U.Michigan 29 June - 2nd July 2015
- Academic and commercial usage.

UNIVERSITY OF EXETER

Advantages :

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

OpenFOAM comes with extensive pre-written solvers – can still be used as a "black box" CFD tool.

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.

UNIVERSITY OF EXETER

Strictly, OpenFOAM is not a CFD code – it is a C++ library of classes for writing CFD codes.

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

- Class mechanism – define new "types" for CFD
- Operator Overloading – provides standard mathematical syntax
- Inheritance, polymorphism etc – encodes relationships between conceptual entities in code
- Interface vs implementation : segregation of effort.

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

At the highest level, provides a framework for significant development projects

Example : Burgers equation

1d Burgers equation :

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} = \nu\frac{\partial^2 u}{\partial x^2}$$

3d version (conservative form) :

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

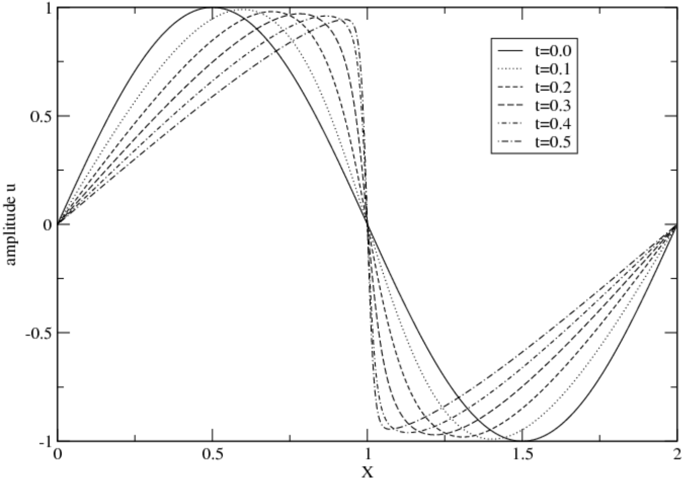
Implemented in OpenFOAM as :

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

UEqn.solve();
```

Enclose in loop and iterate :

```
while (runTime.loop())
{
    Info << "Time␣=␣" << runTime.timeName() << nl << endl;

    #include "CourantNo.H"

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

    UEqn.solve();

    U.correctBoundaryConditions();

    phi = (fvc::interpolate(U) & mesh.Sf());

    runTime.write();

    Info<< "ExecutionTime␣=␣" << runTime.elapsedCpuTime() << "␣s"
        << "␣␣ClockTime␣=␣" << runTime.elapsedClockTime() << "␣s"
        << nl << endl;
}
```

Test case : 1-d sine wave



Presentation: Overview

1 What is OpenFOAM?

2 Exeter Overview

3 Optimisation

4 Tidal Turbines

UNIVERSITY OF EXETER

Research group

Current composition: 4 PhD students; 1 visiting student; 1 PDRA :

- Shenan Grossberg – Adjoint Optimisation applied to vortex separators
- Ed Shorthouse – Development of surrogate models for built environment
- Miriam Garcia – Flood risk for esturine tidal turbines
- Ben Jankauskas – Hydrodynamic vortex separators as reaction vessels
- Pedro Lopes (U.Coimbra, Portugal) – Air entrainment at stepped spillways.
- Dr Mulualem Gebreslassie – Modelling and optimisation of tidal turbine arrays

Resources; computer lab (5 Linux workstations) – 32 core parallel machine 'Callisto' – access to 1920 core University machine 'Zen' – MRI, micro-CT scanner, 3d printing facilities (CALM)

1:Biofluids/IBM

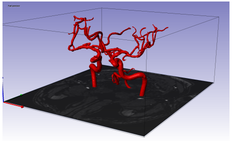
Image Based Meshing – process of converting 3d scans (micro-CT, MRI etc) into computational meshes for CCM. Worked closely with Simpleware Ltd developing CFD output for ScanIP code.

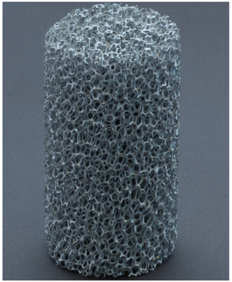
Applications include :

- Blood flow – heart valves, stents
- Air flow in trachaea

but also

- Porous media – packed beds, foams
- Reverse engineering



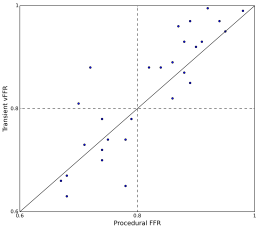


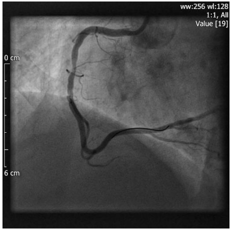
UNIVERSITY OF EXETER

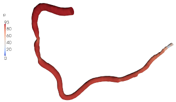
Example – FFR

Fractional Flow Reserve – measure of blockage of artery in CHD. $FFR < 0.75$ considered serious. Usually measured using invasive measurements (dangerous!)

Interest in computational FFR – could be as reliable as standard techniques.



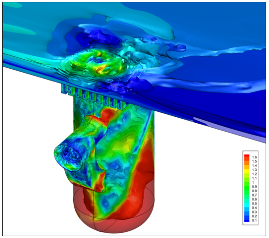


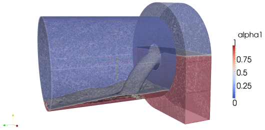


2:SUDS

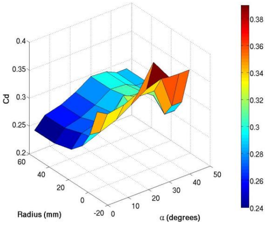
Sustainable Urban Drainage. Significant research at Exeter (CWS). My research includes :

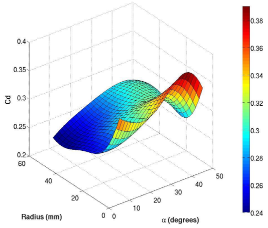
- Collaborative research with Hydro International – PhD project on VFC simulation (Dr Dan Jarman) – ongoing STREAM PhD projects on Adjoint Optimisation and on reaction vessels
- EPSRC project – FRMRC-II – on road runoff into sewers
- Visiting PhD student Pedro Lopes – Air entrainment at stepped spillways
- New EPSRC project starting on flood scour around bridges





3:Optimisation





Significant Exeter involvement in optimisation through Genetic Algorithms + allied techniques (evolutionary algorithms, machine learning).

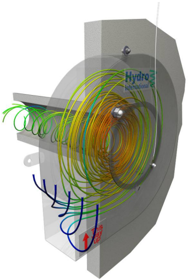
Investigating application to CFD. Significant challenges (cost of evaluating cost function *very* high) – new EPSRC project

Direct application to optimisation of turbulence models, meshing

Development of *surrogate models* through kriging, Neural Networks etc.

Also Adjoint methods...

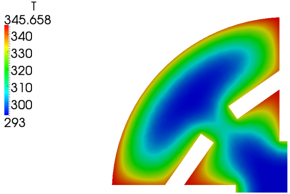
4:Industrial Applications



Involved in numerous projects with industrial partners (funded by companies, Innovate UK, KTP, EPSRC). Examples :

Hydro International – SME (120 employees) in SUDS – currently funding 2× STREAM PhD positions

Tidal Turbine project – novel cross-flow turbine design for shallow water applications (large farms)



HiETA – 3d printed heat exchangers – starting projects (Innovate UK, KTP)

Presentation: Overview

1. What is OpenFOAM?
2. Exeter Overview
3. Optimisation
4. Tidal Turbines

GA Optimisation of Turbulence Models

PhD project (Bjoern Fabritius) to investigate optimisation of turbulence models.

Rationale :

- Turbulence models complex, typically include several parameters (standard $k - \epsilon$ contains 5)
- Attempts made to provide justification for values; more often just parameter-fit to data.
- Parameters often taken to be universal constants – are they?
- Fine tuning accepted for certain canonical flows (eg. circular impinging jet)

Aim of project was to use modern optimisation techniques to explore parameter space and look for optimal values

What are GA's?

Genetic Algorithms – attempt to use Natural Selection techniques to "evolve" an optimal solution to a complex problem.

Methodology :

1. Develop coding for parameters of project (a genome)
2. Create a population of individuals with varying genomes
3. Evaluate fitness of individuals (run CFD code)
4. Eliminate "un-fit" individuals from gene pool
5. Create new population from retained individuals by
    - Exchanging genetic info (sex)
    - Random mutation
6. Repeat until convergence

Application to turbulence modelling

GA's can explore parameter space and evolve optimal solutions to complex multi-parameter problems.

Created optimisation toolkit in PyFoam with OpenFOAM running CFD simulations.

Aim to explore parameter space for particular turbulence models + demonstrate optimisation process for complex physical model. Questions to answer;

- Are the standard parameters optimal for particular canonical flow problems (eg. BFS)?
- What are the tradeoffs between parameters for different flow problems (multi-objective optimisation)
- Could we create a complete new model from scratch?

Transport equations for k and ε

$$\frac{\partial(\rho k)}{\partial t} + \mathrm{div}(\rho k u) = \mathrm{div}\left[\frac{\mu_t}{\sigma_k}\mathrm{grad}\, k\right] + 2\mu_t S_{ij} \cdot S_{ij} - \rho\varepsilon$$

$$\frac{\partial(\rho\varepsilon)}{\partial t} + \mathrm{div}(\rho\varepsilon u) = \mathrm{div}\left[\frac{\mu_t}{\sigma_\varepsilon}\mathrm{grad}\, \varepsilon\right] + C_1\frac{\varepsilon}{k}2\mu_t S_{ij} \cdot S_{ij} - C_2\rho\frac{\varepsilon^2}{k}$$

$$\mu_t = \rho C_\mu k^2/\varepsilon$$

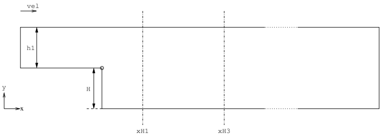
C_1, C_2 most significant parameters

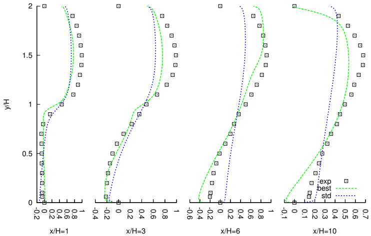
Have also investigated $k-\omega$, Spalart-Allmaras models

Pitz-Daily Optimisation: $k - \epsilon$

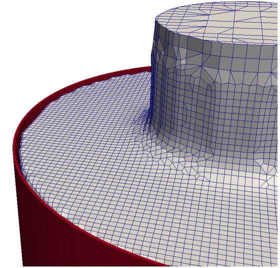
- 50 individuals, 30 generations
- tournament selection, single point crossover
- k-ε model, Re=64,000
- simpleFoam on 10 cores, runtime approx. 2.5h

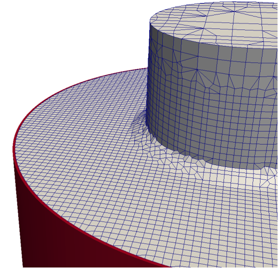
	C_1	C_2
Standard	1.44	1.92
Best Indiv.	1.91	1.86
$\Delta/\%$	32.6	-3.1





Meshing

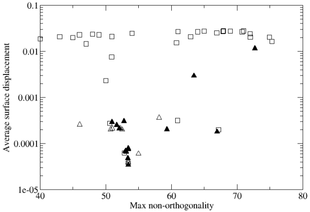


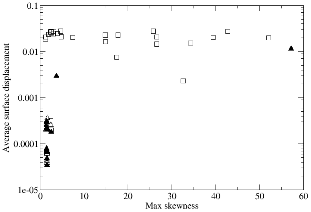


Meshing critical step in CFD process – demanding and time-consuming

Tools such as `snappyHexMesh` robust – but setting parameters is tricky

Solution : treat as multi-parameter, multi-objective optimisation process





Presentation: Overview

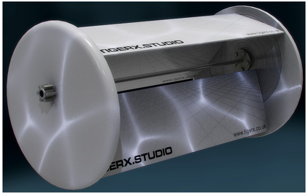
1. What is OpenFOAM?
2. Exeter Overview
3. Optimisation
4. Tidal Turbines

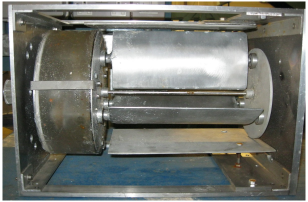
Tidal Turbines

Novel design for tidal turbine based on cycloidal turbine

involving complex rotating airfoil blades

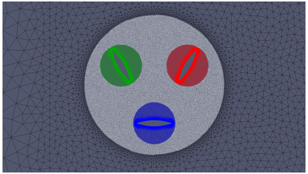
- Blades act in drag mode on one side; rotate (0.5Ω) to develop lift on other side
- Unit operates as cross-flow turbine
- Energy extracted through volume – high efficiency (measured efficiency of $\sim 50\%$)
- High blockage factor; suitable for near-surface (eg. esturine) sites.
- Likely deployment in very large arrays

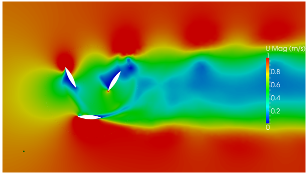


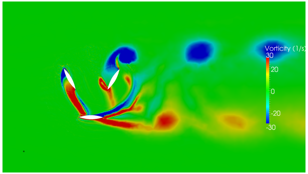


UNIVERSITY OF EXETER

Blade motion



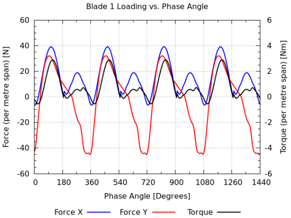


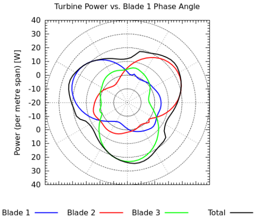


Very complex blade motion – GGI using 5 nested frames

Mesh generated with Pointwise – 2d simulations

- Swept turbine diameter = 0.14m
- $k-\omega$-SST model wall resolved ($y^+ \sim 1-2$)
- 100,000 cells; gradual mesh inflation
- Provides force and torque loadings

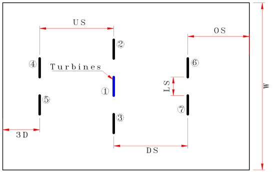




UNIVERSITY OF EXETER

Turbine modelling – simplified

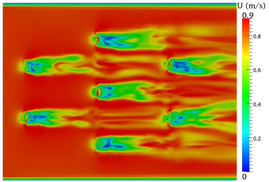
Full simulation very expensive to run – need something cheaper



Immersed body force method :

- Blades represented by stationary body forces

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



- Plus 'vortex ring' body forces
- Compromise between accuracy and efficiency
- Capable of representing large scale vortexes – 3d LES

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*. Capable of exploring complex N-d parameter space and reliably identifying optimum (Pareto front).

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

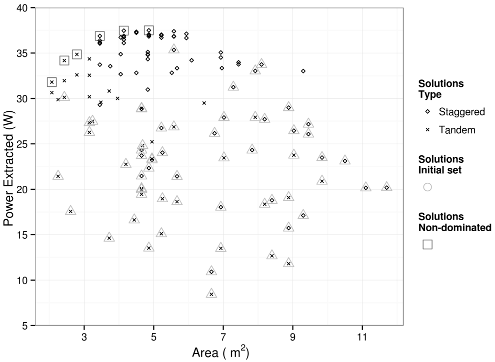
Current task to develop *surrogate model* – run 10's of simulations and use *Kriging* to mine results and create correlation.

UNIVERSITY OF EXETER

Optimisation

Preliminary 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



Over to Hrv . . .

Current funding

"Optimal Design of Very Large Tidal Stream Farms for Shallow Estuarine Applications" (EPSRC) £1,126,664 M.R.Belmont, G.Tabor, I.Bryden, T.Bruce, D.Savic, S.Djordjevic

"Additive Manufacture for Automotive Fuel Cell Systems (AMAFS)" (Innovate UK) £97,000 G.Tabor, HiETA

"The use of hydrodynamic vortex separators as reaction vessels for resource recovery from wastewater" STREAM PhD £15,000 G. Tabor (P.I.), D. Jarman (Hydro International)

"The optimisation of wastewater treatment systems using adjoint solutions for CFD-based simulations" STREAM Eng.D £48,000 G. Tabor (P.I.), D. Jarman (Hydro International)

Just starting :

"Data-Driven Surrogate-Assisted Evolutionary Fluid Dynamic Optimisation" (EPSRC) £687,882 R.M.Everson, G.Tabor, J.Fieldsend

"Risk Assessment of Masonry Bridges unde Flood Conditions: Hydrodynamic Effects of Debris Blockage and Scour" (EPSRC) £634,734 S. Djordjevic, P.Kripakaran, S. Arthur, G.Tabor

"A CCP on Wave/Structure Interaction: CCP-WSI" (EPSRC) £591,087 D.Greaves, D,Graham, L.QUian, C.Mingham, D.Causon, J.Zang S.Yan, Q.Ma, A.Kyte, C.Greenough, G.Tabor

"To develop capability in Computational Fluid Dynamic (CFD) techniques to enable the innovative exploitation of Additive Manufacture technology and grow market share" KTP (2 yrs) £138,580 G. Tabor M.Baker, M.Adams (HiETA Ltd)

"To develop and embed capability in thermal modelling of cooling and refrigeration techniques, in order to optimise manufacture of ready to eat food products" KTP (2 yrs) £138,580 G. Tabor, M.Baker, R.Bain (Ginsters)

UNIVERSITY OF EXETER

Selected Papers

"Improving the quality of finite volume meshes through genetic optimisation" B. Fabritius, G. Tabor. Submitted to : *Engineering with Computers*

"Computational Fractional Flow Reserve From Coronary Computed Tomographic Angiography: Comparison of diagnostic accuracy of a new simplified computational model to existing techniques." D. Tranter, B.Clayton, G.R.Tabor, P.G.Young, A.Shore, G. Morgan-Hughes, S. Iyengar, C.A.Roobottom. Submitted to : *Investigative Radiology*

"CFD of Vortex Flow Controls at high flow rates", D. Jarman, D.Butler and G. Tabor, to appear in *ICE.Proc: Engineering and Computational Mechanics* (2014)

"CFD characterization of flow regimes inside open cell foam substrates" A.della Torre, G.Montenegro, G.Tabor *Int.J.Heat and Fluid Flow* **50** pp.72 – 82 (2014)

"Computation Fluid Dynamics of Flow through Packed Beds: Monte-Carlo Simulation coupled with Image Based Meshing and Additive Layer Manufacturing." M.J.Baker, S.Daniels, P.G.Young and G.Tabor *Computers and Chemical Engineering* **67** pp. 159 – 165 (2014)

"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)

"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)

"Computational investigation of vortex flow controls at low flow rates", G.Queguigneur, D. Jarman, E.Paterson, G.Tabor, *ICE.Proc: Engineering and Computational Mechanics* **166 # 4** pp. 211–221 (2013)

"Experimental and numerical investigation of interactions between above and below ground drainage systems", S. Djordjevic, A.J.Saul, G. Tabor, J.R.Blanksby, I.Galambos, I. Sabtu, G.Sailor, *Water Science and Technology* **67#3** pp.535-542 (2013)