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Final Report

An Actuator Disk Approach to Tidal Farm Simulation and Optimisation in OpenFOAM

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3rd Year Individual Project

I certify that all material in this thesis that is not my own work has been identified and that no material has been included for which a degree has previously been conferred on me.

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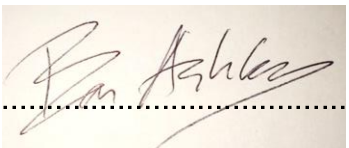

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Abstract

During this research, the modelling of a Horizontal Axis Tidal Turbine was undertaken through the use of an actuator disk model, of the type first used by Erik Svenning (Svenning, 2010), using the open source Computational Fluid Dynamics package OpenFOAM. This Volume Force Actuator Disk (VFAD) model was then updated and modified for use with the latest version of OpenFOAM and to allow for the modelling of multiple turbines. The model was also incorporated into transient and multiphase solver codes within OpenFOAM in order to facilitate use of the model for a wider range of applications.

The output of the model was validated using experimental data for turbine wake structure, showing a close fit and supporting the use of the model for investigating more complex flow problems relating to tidal turbines.

Once the model had been validated, investigation into array performance was undertaken using a control volume method to compute the performance of each turbine. The effects of lateral and downstream spacing on array performance are investigated and discussed with a view to increasing an array's power density.

It was found that a surrogate, statistical model can be used to approximate the VFAD model with a high level of certainty, paving the way for the use of genetic algorithms for the optimisation of turbine arrays.

Keywords:

Actuator disk modelling, OpenFOAM, Horizontal Axis Tidal Turbine, Renewable Energy Wake Interaction, Array Optimisation

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1. Introduction and background

Tidal energy holds great potential as a renewable energy source; both in the UK and globally. However, in order to harness this energy, significant research and development is still required. There are three main approaches to the production of electricity from the tides; tidal barrages, like the one at La Rance in France (Frau, 1993), tidal lagoons, such as the proposed design for Swansea Bay (Tidal Lagoon Swansea Bay, 2014), and tidal turbines, an example being the 1.2MW prototype design tested at Strangford Narrows in Northern Ireland (Marine Current Turbines, 2014). Each approach has its merits and weaknesses, for example, tidal barrages are capable of producing vast amounts of power, but have a large impact on wildlife and coastal habitats (Parliamentary Office of Science & Technology, 2013). As a result of the concerns regarding barrages, research has begun to favour tidal turbines, and arrays of such turbines, over other technologies as a viable source of renewable energy in future years, with the resource potential estimated to be 20% of the UK's current energy demand (Department of Energy & Climate Change, 2013).

As the technology behind such tidal turbines is still very much in its infancy, there remains much research to be carried out before large scale energy generation is achieved. To aid the continued development of the technology, many scenarios and designs may be investigated and optimised using Computational Fluid Dynamics (CFD) software, minimising the cost of the process by reducing the need for prototyping and testing, whilst speeding up the design process.

The main aim of this project was to achieve a computational model for the flow around a Horizontal Axis Tidal Turbine (HATT) which is computationally inexpensive, while still providing valid results. Once validated against cases from the literature, this model was used for the investigation of flow around arrays of HATTs, focusing on power extraction and array efficiency.

The modelling was carried out using OpenFOAM; an open-source, object-orientated, CFD code based upon the C++ programming language. The structure of the package allows for a large degree of adaptability in the set-up of simulations, enabling the production of a complex, bespoke and easily modifiable representation of a HATT.

The model itself is based on the 'Actuator Disk' representation of a horizontal axis turbine, which models the region swept by the turbine blades as a semi porous region through which the flow passes, with a pressure drop acting across the disk leading to the retardation of the flow in its wake. The Volume Force Actuator Disk (VFAD) model used builds upon this approach, as well as considering the radial distribution of forces from the turbine and swirl present in the turbine wake. This approach has been widely used in the modelling of such turbines, offering good results at a low computational expense.

An investigation into tidal farm layout was also undertaken, modelling the interaction of turbine wakes. Optimisation of tidal arrays was then explored both by hand, and a surrogate model derived through a statistics based Kriging process, with a view to optimising through the use of genetic algorithms.

2. Literature review

Tidal power has been identified as an important area of research for the realisation of the European Union's renewable energy targets, (European Renewable Energy Research Centres (EUREC) Agency, 2009), with CFD being a key tool in this area. Currently, HATTs are in the prototype stage, with individual turbine designs being tested and developed, such as the SeaGen 1.2MW turbine tested in Northern Ireland (Marine Current Turbines, 2014). It is expected that once these prototypes progress into commercially viable designs, they will be combined in arrays to form Tidal Farms (MacKay, 2008). Since the wake formed behind turbines can interfere with other members of the array (Myers & Bahaj, 2010), the layout of such farms is of crucial importance to ensure optimal operation. Optimisation of arrays may be carried out by hand, or through the use of optimisation algorithms, which have previously been used to optimise arrays of wind and tidal turbines (Bilbao & Alba, 2009), (Mosseti, et al., 1994).

2.1. Approaches to the Modelling of a HATT

There are a range of approaches to the modelling of horizontal axis turbines; from simple 'actuator disk' models, to more complex Blade Element Momentum (BEM) codes (Kulunk, 2011). Each of these approaches has its own merits and reasons for use, with actuator disk models being preferred for applications where a low computational cost is needed.

In order to model a horizontal axis turbine, an actuator disk model considers the region swept by the turbine blades, representing this as a porous region where forces are applied to the flow. Actuator disks have been used for modelling a wide range of applications in fluid mechanics, and the theory behind these models is mature (Horlock, 1978). The same theory that is applied to wind turbines (Kulunk, 2011) can also be used for tidal turbines, since the only major difference is in the fluid used, though cavitation and the presence of a free surface can affect the results for tidal turbines (Stallard, et al., 2011).

2.2. Using OpenFOAM to model a HATT

A tutorial for the modelling of a propeller outlines the setup of an actuator disk in OpenFOAM (Svenning, 2010). This model has an advantage over other approaches as it allows actuator disks to be defined within the mesh, and so does not limit the size of the domain allowing for the definition of multiple disk regions, meaning cases using multiple turbines may be run. Svenning’s model comes with the added benefit of representing the swirl in the turbine wake through the introduction of tangential forces into the flow, producing a more accurate wake structure than that produced by a more simplistic actuator disk model. The model also accounts for the loading distribution along the blades; modelling it according to the simplified Goldstein optimum (Goldstein, 1929), allowing the effects of non-linear blade loading to be modelled. Svenning validated his model using a case study carried out to model flow through a wind turbine in an enclosed tunnel (Mikkelson, 2003), and the model has since been used, successfully, to model the behaviour of a ‘Mexico Rotor’ wind turbine (Jeromin, et al., 2013).

It has been noted that the turbulent properties of tidal currents have been largely neglected in previous studies of tidal turbines (Blackmore, et al., 2014), and so solver classes that model turbulent flow, such as modified simpleFoam and pisoFoam solvers will be used for the modelling (The OpenFOAM Foundation, 2014).

2.3. Experimental Studies into the behaviour of HATTs

Previous studies into the wake recovery behaviour of tidal turbines (Myers & Bahaj, 2010), (Sun, 2008), have used mesh disk rotor simulators, metal disks with specially designed porosity values, to gather experimental data into the wake recovery behind HATTs. Although these experiments neglect the swirl present in real world wake structures, the wake recovery results may still be used for comparison as the swirl component in wakes normally dissipates a short distance downstream from the turbine (Myers & Bahaj, 2010).

2.4. Performance and Optimisation of HATTs using CFD

The performance of tidal turbines, simulated using CFD, has been analysed using a control volume approach around turbine locations (Gebreslassie, et al., 2015). The paper demonstrates how the fluxes through the region, combined with the pressure drop across the disk, can be used to compute the thrust acting upon the turbine and power extracted from the flow.

The layout of tidal farms may be designed through a number of approaches, with the use of optimisation algorithms representing a more sophisticated approach than, simpler, hand optimisation. For example, simulated annealing has been used for the optimisation of wind turbine placement for the maximisation of wind farm profit (Bilbao & Alba, 2009), and genetic algorithms have been used for the optimisation of large wind farms (Mosseti, et al., 1994). In some cases, where simulations are computationaly expensive, it is necessary to produce a surrogate model to be used with the genetic algorithms (Lophaven, et al., 2002).

Surrogate models for computer experiments can be generated through a Kriging process (Bohling, 2005), (Lophaven, et al., 2002), using a statistical approach to predict the outcome for a given input using sampled data from the original computer model (Jones, 2001). In order to better represent the vector space of possible inputs for the model, Latin Hypercube sampling may be used to gather a suitable data range with a minimum sample size (Lophaven, et al., 2002). Both Kriging and genetic algorithm optimisation may be carried out using the Matlab computer environment (Lophaven, et al., 2002), (MathWorks, 2015).

3. Methodology and Theory

3.1. Theoretical Background

3.1.1. Characteristics of Horizontal Axis Tidal Turbines (HATTs)

Through the understanding of the flow characteristics of HATTs, models for their behaviour can be derived. Since a turbine obstructs the flow, the flow velocity decreases as water approaches the turbine, decreasing rapidly as it passes though the turbine region before slowly recovering in the wake. Across the turbine region a pressure drop is formed, as energy is extracted from the flow (Horlock, 1978). The radial wake profile is dependent upon how the forces exerted by the blades are distributed radially (Svenning, 2010), and the downstream wake may be considered to be predominantly longitudinal in structure, though some swirl is present due to the rotational motion of the turbine blades (Myers & Bahaj, 2010).

Any model used to describe the flow around HATTs, and their far wake structures, must therefore replicate these behaviours, with the velocity gradient through turbines, and pressure drop across turbines being of particular importance.

3.1.2. An Introduction to the use of OpenFOAM in this work

OpenFOAM is a highly flexible CFD software package, and can be used for a wide range of applications to solve continuum mechanics problems. It consists of solver classes, which are written to model specific flow problems, and can be copied and modified by the user for scenarios not covered by the prewritten solvers. This adaptability means that OpenFOAM is well suited to pursuing higher level modelling, and is favoured over commercial codes for many research applications. The results of simulations may then be visualised, and analysed using the open source visualisation package ParaView, which may be accessed from OpenFOAM using the command 'paraFoam' (The OpenFOAM Foundation, 2014).

Since this research involved the setup of a complex, bespoke model for the investigation of the wake properties of tidal farms, OpenFOAM was selected for its flexibility and program structure.

3.1.2.1. Turbulence Modelling

The CFD simulations run throughout this work have used two types of turbulence modelling to approximate the turbulent behaviour present.

The first approach, used by both the simpleFoam and pisoFoam variants of the actuator disk solver, uses Reynolds Averaged Navier-Stokes (RANS) turbulance modelling in the form of the k-epsilon model. This turbulance model considers the turbulent kinetic energy, k, and the rate of viscous dissipation, epsilon, and is the most widely used and validated turbulence model available (Versteeg & Malalasekra, 2009). Like all RANS based turbulence models, the k-epsilon model mainly concerns itself with the mean effects of turbulance upon the flow.

When modelling HATTs, the behaviour of larger eddies within the wake is of interest, and for this reason Large Eddy Simulation (LES) was undertaken using the pisoFoam based solver. The ability to use LES was one of the prime motivations for the derivation of a pisoFoam based solver, and though it is more computationaly expensive that RANS modeling, it is often prefered when modelling turbine wake structure (Gebreslassie, 2012).

3.1.2.2. Solver Algorithms

simpleFoam – a steady state solver application, which used the SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) algorithm to solve for incompressible turbulent flow. This solver has the advantage of being computationally inexpensive, however, it can only be used for single phase cases using RANS based turbulence models. In addition, since it is a steady state solver, it cannot be used to investigate transient behaviour (The OpenFOAM Foundation, 2014).

pisoFoam – a transient solver for incompressible flows, allowing for the modelling of developing flows. It uses the PISO (Pressure Implicit with Splitting of Operators) algorithm and is commonly used for both RANS and LES turbulence modelling of single phase flows (The OpenFOAM Foundation, 2014).

interFoam – allows for the modelling of two phase systems, capturing the behaviour at the interface by calculating the volume of each fluid present. It can model using both RANS and LES approaches, using the PIMPLE algorithm; a variant on PISO (The OpenFOAM Foundation, 2014).

3.1.3. Modelling of HATTs

There are multiple approaches to the use of computational fluid dynamics for the modelling of a horizontal axis tidal turbine. Each technique makes a different trade-off between model resolution and computational expense. The main approaches are summarised below.

Perhaps the most obvious approach to the modelling a tidal turbine is the construction of a true to life 3D representation of the turbine, complete with full blade geometry. However, the computational expense of such a model prevents it from being a realistic approach to the modelling of such systems. For this reason, a number of more simplistic representations of turbines are used for modelling the different flow characteristics associated with these systems.

A simple actuator disk model offers good representation of the flow around turbines for a low computational cost. However, in their basic form, actuator disk models do not consider the effects of blade motion, considering only the pressure change across the disk. As a result of this, effects such as swirl and tip losses are not included.

Blade element theory provides a means for including the effects of blade geometry in the model of a horizontal axis turbine. The theory discretises the blade into N sections, and finds the overall behaviour of the blade by integrating along the blade. This approach is used in the Blade Element Momentum (BEM) model that is widely used for modelling the performance of differing turbine designs.

As the focus of this research was to gain an in depth understanding of the wake characteristics of HATTs, an actuator disk approach was the most suitable model. However, a basic actuator disk neglects the swirl present in turbine wakes, and so a more complex volume force actuator disk model was used (Svenning, 2010).

3.1.4. An outline of Actuator Disk Theory

An actuator disk is defined as a region in a flow domain across which there is a sudden change in flow properties. When applied to turbines, there is a pressure drop across the disk region where the momentum of the flow is reduced, represented in Figure 3-1 (Kulunk, 2011). From this, the basic principles of fluid dynamics may be applied in order to find the pressure drop across the disk, axial thrust and power. From this, the power coefficient (C_P), thrust coefficient (C_T), and tip speed ratio can all be derived for the disk, and an axial induction factor can be introduced in order to simplify the relationships involved. The derivation of these parameters is undertaken in the following pages (Kulunk, 2011).

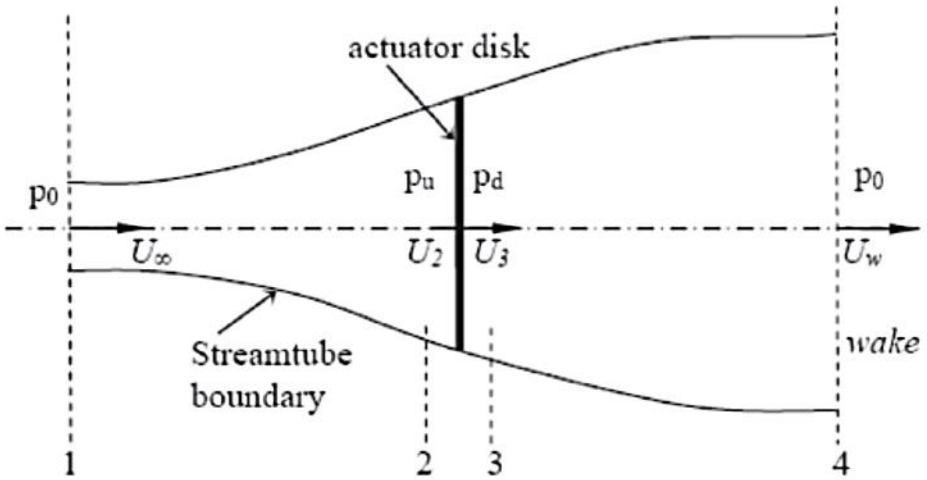

Figure 3-1: control volume used for actuator disk representation of flow through a turbine

Considering the continuity equation across the streamtube, the following expression is derived when the mass flow rate of fluid is considered at the input, disk and wake:

$$\rho A_{\infty} U_{\infty} = \rho A U_d = \rho A_w U_w$$

If it is assumed that flow through the disk is uniform, the mass flow rate may be written as:

$$\dot{m} = \rho A U_d$$

3.1.4.1. Axial Thrust, Pressure Drop and Power

When the conservation of linear momentum is considered for the flow, thrust is found to be:

$$T = \dot{m}(U_\infty - U_w)$$

If the Bernoulli equation is applied to the flow for each side of the disk, the results can be used to produce the following expression for the pressure drop across the disk:

$$\Delta p = \frac{1}{2}\rho\left({U_\infty}^2 - {U_w}^2\right)$$

Since thrust is the product of the pressure drop and the area of the disk, the following expression for thrust can be found:

$$T = \frac{1}{2}A\rho\left({U_\infty}^2 - {U_w}^2\right)$$

Through manipulation of the previous equations, the flow speed through the actuator disk can be found to be:

$$U_d = \frac{U_\infty + U_W}{2}$$

The power developed by the disk is given by:

$$P = TU_d$$

$$P = \frac{1}{2}A\rho\left({U_\infty}^2 - {U_w}^2\right).U_d$$

3.1.4.2. Power Coefficient (C_P), Thrust Coefficient (C_T), and Tip Speed Ratio (λ)

The three principle performance parameters for a HATT are:

$$Power\ Coefficient, C_P = \frac{2P}{\rho {U_\infty}^3 \pi R^2} \qquad Thrust\ Coefficient, C_T = \frac{2T}{\rho {U_\infty}^2 \pi R^2}$$

$$Tip\ Speed\ Ratio, \lambda = \frac{R\omega}{U_\infty}$$

3.1.4.3. Induction Factor (a)

In order to simplify the relationships describing the actuator disk model of a HATT, the axial induction factor is introduced. It is defined as:

$$a = \frac{U_\infty - U_d}{U_\infty}$$

Using this definition, it allows expressions to be derived for the following turbine parameters:

$U_d = U_\infty(1-a)$ $\qquad$ $U_W = U_\infty(1-2a)$ $\qquad$ $P = 2\rho A a {U_\infty}^3(1-a)^2$

$T = 2Aa\rho(1-a){U_\infty}^2$ $\qquad$ $C_P = 4a(1-a)^2$ $\qquad$ $C_T = 4a(1-a)$

3.1.5. The Volume Force Actuator Disk Model

In order to accurately model the wake structure of a HATT, a more sophisticated actuator disk representation was used. The pressure drop across the disk is achieved through the introduction of forces applied to all particles across the disk region, a volume force approach, giving the model its name. The basic characteristics of the model are the same as for the standard actuator disk representation, though it was realised through the use a volume force rather than a prescribed pressure jump. As well as acting axially to impede the flow, a component of this volume force acts tangentially, in order to introduce swirl to the wake structure, thus better representing the real world wake structure formed by such turbines (Svenning, 2010).

The distribution of this volume force across the disk area is non-uniform, following the Goldstein optimum (Goldstein, 1929) in order to better fit the actual force distribution along turbine blades. The model is set up so that the thrust and torque of the turbine is met, whilst maintaining specified the force distribution.

The Goldstein optimum gives the following distribution for the axial forces (Svenning, 2010):

$$F_{axial} = A_x r^* \sqrt{1 - r^*}$$

And the tangential volume forces have the following distribution:

$$F_{tangential} = A_\theta \frac{r^* \sqrt{1 - r^*}}{r^*(1 - r_h') + r_h'}$$

Where: $r^* = \frac{r' - r_h'}{1 - r_h'}$ $r' = \frac{r}{R_P}$ $r_h' = \frac{R_H}{R_P}$

$R_H = Interior\ radius\ of\ actuator\ disk$ $R_P = Exterior\ radius\ of\ actuator\ disk$

A_x and A_θ are constants which ensure that the total distributed forces match the prescribed thrust and torque for the disk. They are defined as:

$$A_x = \frac{105}{8}\frac{T}{\pi\Delta(R_P - R_H)(3R_H + 4R_P)} \qquad A_\theta = \frac{105}{8}\frac{Q}{\pi\Delta R_P(R_P - R_H)(3R_P + 4R_H)}$$

By setting up the turbine model in this manner, it is hoped that the model will provide a better representation of a real world turbine than the basic actuator disk approach.

3.1.6. Optimisation and Pareto Efficiency

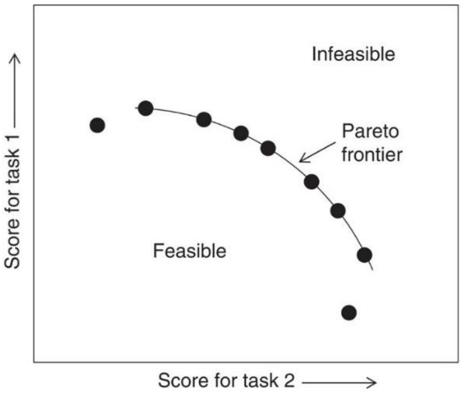

Figure 3-2: illustration of Pareto optimality

An array of turbines may be optimised according to a number of parameters, according to the quantities that need to be maximised. For example, an array may be optimised for power per area, power per cost, turbine efficiency, or other design points depending on the project priorities.

If an array is optimised for cost and power, area can be used as an indicator of the overall cost for the optimisation process; since for a set number of turbines the cost is constant, with the price of cabling being the difference between array layouts.

For a dataset, optimal solutions form a Pareto optimality curve (Encyclopedia Britannica, 2014), this curve is made up of points where an improvement to one parameter requires a loss to the other, and so optimal solutions may be chosen from this curve depending on design priorities. An example of a Pareto curve may be seen in Figure 3-2 (Kleeson, et al., 2014).

3.1.7. Use of a Surrogate Model for Genetic Algorithm Optimisation

3.1.7.1. Genetic Algorithms

Genetic algorithms work by mimicking the process of evolution; starting with a random population of solutions, desirable characteristics in this random population are identified with reference to the original problem, and passed on to a child population. This process runs through multiple iterations, with a set of optimal solutions generated over time (Whitley, 1994).

In addition to the children of the best solutions from the parent generation, mutations are included in each generation to ensure that any beneficial characteristics not included in the optimal parent solutions is not lost to the child population (Whitley, 1994).

Since their development in 1975, genetic algorithms have been widely used for a range of applications, with genetic algorithm functionality included in the Matlab computer environment, through a number of built in or open-source toolboxes, depending on the optimisation problem required (MathWorks, 2015), (Pohlheim, 2006).

3.1.7.2. Surrogate Model

Running a genetic algorithm to optimise a CFD model directly is unfeasible, due to the high computational cost, and time required to run the volume of scenarios generated by the genetic algorithm. In order to get around this issue, a statistical, surrogate model was used to approximate the CFD model (Lophaven, et al., 2002). This surrogate model allows a GA to run through many combinations of parameters in a short space of time, leading to an optimal solution which may then be confirmed using the original CFD model.

3.2. Methodology

3.2.1. Model Set-up and development

Since the original volume force model was produced on a now outdated version of OpenFOAM (Svenning, 2010), before the model could be used or further developed the code needed to be updated. This was done by analysing the differences in code structure between the old and new simpleFoam solver, and replicating these modifications within the solver class provided by Svenning to enable the solver to be compiled in the latest version of the software.

Once the model was working successfully, further modifications were needed to allow for the consideration of multiple turbines, since, in its original configuration, the code could not process multiple disks. Since this required significant structural changes to the solver architecture, the modifications were carried out by Dr Gavin Tabor, through the introduction of a separate dictionary containing a list of the turbines with their properties. This dictionary was then read and a constructor used to add the turbines to the mesh. These changes are explained in more detail in the following code analysis.

3.2.2. Code Analysis

This section briefly explains the contents of each of the main files making up the modified simpleFoam based VFAD solver class, with key passages of code used in the modification of the solver described and the contents of the turbine properties dictionary detailed.

The files of interest within the solver structure include: actuatorDiskExplicitForce.C, actuatorDiskExplicitForce.H, actuatorDiskExplicitForceSimpleFoam.C, createFields.H, and UEqn (velocity equation).

3.2.2.1. actuatorDiskExplicitForce.C

The actuatorDiskExplicitForce.C class file contains the information needed to construct an actuator disk object, and is read by the solver class in order to create an implementation within the model, adding volume forces to the mesh from specified thrusts, torques and disk geometries. The main modification made to this class from Svenning's original implementation (Svenning, 2010) was to use a constructor script to create an actuator disk

```
actuatorDiskExplicitForce::actuatorDiskExplicitForce
(
    const dictionary& turbineProperties
)
  :
  //  turbineProperties_(turbineProperties.subDict("actuatorDisk")),
  turbineProperties_(turbineProperties),
  mPointStartCenterLine(turbineProperties_.lookup("startPoint")),
  mPointEndCenterLine(turbineProperties_.lookup("endPoint")),
  mExtRadius(readScalar(turbineProperties_.lookup("exteriorRadius"))),
  mIntRadius(readScalar(turbineProperties_.lookup("interiorRadius"))),
  mThrust(readScalar(turbineProperties_.lookup("thrust"))),
  mTorque(readScalar(turbineProperties_.lookup("torque"))),
  mRho(readScalar(turbineProperties_.lookup("density")))
{

            if(debug >= 2) {
                Info << "Actuator disk values loaded from fvSolution:\n";
                Info << "mIntRadius: " << mIntRadius << "\n";
                Info << "mExtRadius: " << mExtRadius << "\n";
                Info << "mThrust: " << mThrust << "\n";
                Info << "mTorque: " << mTorque << "\n";
                Info << "mRho: " << mRho << "\n";
                Info << "mPointStartCenterLine: " << mPointStartCenterLine << "\n";
                Info << "mPointEndCenterLine: " << mPointEndCenterLine << "\n";
            }

}
```

Figure 3-3: constructor script used to create actuator disks within the mesh, taken from the actuatorDiskExplicitForce class file object. This reads the turbineProperties dictionary, using parameters such as “startPoint”, “endPoint” etc. in order to construct a new actuatorDiskExplicitForce type object. This links in with the turbineProperties dictionary, which used a ‘ptr list’ format to allow for multiple turbines to be parsed by the constructor class. The code for this is shown in Figure 3-3.

3.2.2.2. actuatorDiskExplicitForce.H

This file declares the actuator disk class, working with actuatorDiskExplicitForce.C to allow for the creation of disks within a mesh from a turbineProperties dictionary and a solver class such as actuatorDiskExplicitForceSimpleFoam.C.

3.2.2.3. actuatorDiskExplicitForceSimpleFoam.C

This file is the modified version of the simpleFoam solver class file; with the volume force included and code to read a turbine properties dictionary and create actuator disk objects using the actuatorDiskExplicitForce.C and actuatorDiskExplicitForce.H files.

The disk objects are created using a PTR list script, shown in Figure 3-4.

```
//Read actuator disk geometry
//actuatorDisk.ReadGeometry(mesh);

IOdictionary turbineProperties
(
    IOobject
    (
        "turbineProperties",
        runTime.constant(),
        mesh,
        IOobject::MUST_READ_IF_MODIFIED,
        IOobject::NO_WRITE
    )
);

PtrList<dictionary> diskDicts(turbineProperties.lookup("turbines"));

PtrList<actuatorDiskExplicitForce> turbineForces;
turbineForces.setSize(diskDicts.size());

forAll(diskDicts, i)
{
    turbineForces.set
    (
        i,
        new actuatorDiskExplicitForce(diskDicts[i])
    );
}
```

Figure 3-4: PTR list function which creates and initialises disks based upon turbine properties dictionary

3.2.2.4. createFields.H

The createFields.H file describes the quantities relevant to the solver, such as velocity and pressure, and in the VFAD model, a volume force quantity is also added to this, to allow for the volume forces to be written to file, and thus visualised in ParaView (Svenning, 2010).

3.2.2.5. UEqn

The UEqn file contains the velocity equation to be solved throughout the simulation, and differs from the original solver through the addition of the volume force quantity, which means that throughout the mesh the effect of the volume force on the flow velocity is simulated.

3.2.2.6. Turbine Properties dictionary

In the original model produced by Svenning (2010), the turbine properties are listed in the fvSolution file within a case, which details the algorithms, solvers and tolerances to be used by a case (The OpenFOAM Foundation, 2014). It was decided that the solver would be more user friendly, and easier to modify, if the properties of each disk were detailed in a separate dictionary. With this in mind, a turbineProperties dictionary containing a list of disks and their properties was created. The dictionary contains a list of actuator disk objects, with the following quantities provided:

- startPoint – the coordinates of the beginning of the disk region in the mesh.
- endPoint – the coordinates of the end of the disk region within the mesh.
- thrust – total thrust imparted upon the flow by the volume forces associated with the disk.
- torque – total torque introduced by the volume forces in the disk region.
- density – density of the fluid that the disk forces are operating upon.
- interiorRadius – interior radius of the disk region, taken from the centrepoint.
- exteriorRadius – exterior radius of the disk region, taken from the centrepoint.

Each disk object is read, and the values for each of the above quantities used to create an instance of an actuator disk object.

3.2.3. Writing Transient and Multi-Phase VFAD solvers

In its original form, the VFAD model is based upon the simpleFoam solver, which considers steady state, single phase turbulent problems. To allow for cases where the transient behaviour is being investigated, or where the behaviour of the air-water free surface is of interest, solvers designed to work in these scenarios had the VFAD code programmed into them, to boost the versatility of this turbine model.

3.2.3.1. Programming of actuatorDiskExplicitForcePisoFoam

In order to construct a VFAD model that could be used for transient and LES simulations, the volume force code, and disk constructor code needed to be introduced to the standard pisoFoam solver. The basic steps in the programming of this new solver class were:

- Copy the pisoFoam solver from the program files into the user directory, and add in the actuatorDiskExplicitForce.C class file, and the actuatorDiskExplicitForce.H header file.
- Update the make/options and make/files to include the added class, and relevant dictionaries for the VFAD solver.
- Add the actuator disk constructor code to the pisoFoam.C class file.
- Introduce the volume force term to the velocity equation in the pisoFoam.C class file.
- Add the volume force to the createFields.H file.

Once this programming was complete, and the solver compiled successfully, the solver was run for a simple case to test its functionality.

3.2.3.2. Programming of actuatorDiskExplicitForceInterFoam

The approach taken to the programming of a multiphase version of the VFAD solver was equivalent to that taken for the derivation of the pisoFoam solver. The main difference between the two approaches was that since interFoam is a solver for compressible flows, the structure of the velocity equation is different; interFoam solves this equation for ‘density x velocity’ and so ‘volume force x density’ was introduced to the equation instead of simply ‘volume force’. This ensured that the solver was using consistent dimensions.

As interFoam is a solver for multi-phase problems, the setup of a test case for this type of problem required far more work than for the other two solvers, when using a case adapted from

Dr Gebreslassie's work (Gebreslassie, 2012), the solver ran for several iterations before becoming unstable. This suggests that the solver is functioning correctly, and that with a correctly set up case, the solver would produce useful results. Due to the time constraints of this project, it was decided to prioritise other areas of the research at this stage.

3.2.4. Using Control Volumes to investigate performance

For a control volume around a turbine location, the fluxes across the volume, and through each face may be used to compute the thrust force acting upon the turbine blades. By applying the conservation of linear momentum across the region, the thrust, T, may be defined as (Gebreslassie, et al., 2015):

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

The first term considers the pressure drop across the turbine, with the three other terms considering the linear momentum fluxes in the x, y and z directions.

Once the thrust force upon the turbine has been found, the power extracted from the flow by each turbine can be calculated using the following equation.

$$P = T.\overline{U}_t$$

Where $\overline{U}_t$ is the averaged velocity through the disk region. Through the use of a control volume around each turbine in an array, the effects of other members of an array upon the performance of an individual turbine may be investigated

Under the guidance of Dr Mulualem Gebreslassie, cell zones within the mesh were set up to represent the faces and regions needed to define the control volume for each turbine. These regions were defined using the topoSet utility available in the standard version of OpenFOAM, which enables regions to be identified and cell sets created, ready for further manipulation. Once the cell zones were created, a script was used within the control dictionary of the simulation to compute the values at each iteration of: inlet velocity, velocity through the disk, inlet pressure, outlet pressure, and fluxes in and out of the region in the y and z directions. This script made use of the swak4Foam (SWiss Army Knife for Foam) toolbox, available online (Gschaider, 2014). This data was then logged, and once the model had converged, the values were used to compute the thrust, and subsequently, the power of the turbine.

3.2.5. Creation of a Surrogate Model

A surrogate model was produced through a Kriging process (Lophaven, et al., 2002) which uses a dataset of known results from a computational model to approximate the results for untested inputs, using linear regression or other correlation models (Bohling, 2005). In order to provide a comprehensive description of models behaviour, Latin hypercube sampling was used to fully represent the vector space occupied by all possible combinations of parameters (Lophaven, et al., 2002). By varying all input parameters simultaneously, it samples the data in a more efficient manner, reducing the number of cases to be run in the original CFD model.

4. Computational Investigation

4.1. Validation of VFAD model

4.1.1. Tunnel Blockage Case

To ensure the correct set up of the model in the current version of OpenFOAM, the model was tested against the original validation case (Svenning, 2010), to ensure functionality had been preserved in the modification process. This involved a comparison between results shown for a wind turbine model in an enclosed tunnel (Mikkelson, 2003) and results for an OpenFOAM case set up to replicate this with the VFAD model.

4.1.2. Mesh Disk Rotor Simulator

In order to ensure the model provided a suitable description of the flow around tidal turbines, validation was sought against experimental work carried out on mesh rotor disk simulators (Myers & Bahaj, 2010). This work made use of porous mesh disks to produce wake structures resembling those of tidal turbines in order to study wake recovery under varied flow conditions.

4.2. Testing the modified pisoFoam solver

The modified pisoFoam solver was tested using a case provided by Dr Mulualem Gebreslassie for both RANS and LES turbulence modelling. This case required some modification to work with the VFAD model since they had been originally designed for use with a Momentum

Reversal Lift model for a vertical axis turbine (Gebreslassie, 2012). This case was used to assess the model performance for a large, computationally expensive case.

4.3. Testing the control volume approach for multiple turbines

In order to test the control volume approach an array was built and tested as each turbine was added, to ensure the control volumes were working as required. This culminated in an eight turbine array being tested successfully, providing a framework for the optimisation studies.

4.4. Set up of Optimisation Study

4.4.1. Set up of three row domain

Table 4-1

Inside Radius (m)	0.02
Outside Radius (m)	0.15
Thrust (N)	30.00
Torque (N.m)	0.50

In order to investigate the optimal lateral and downstream spacing for turbines laid out in three rows, a suitable domain needed to be constructed using the blockMesh meshing tool in OpenFOAM. The domain was set up to compare the performance of turbines with the parameters arbitrarily set as shown in Table 4-1, and had dimensions L = 6m, W = 4m, H = 2m.

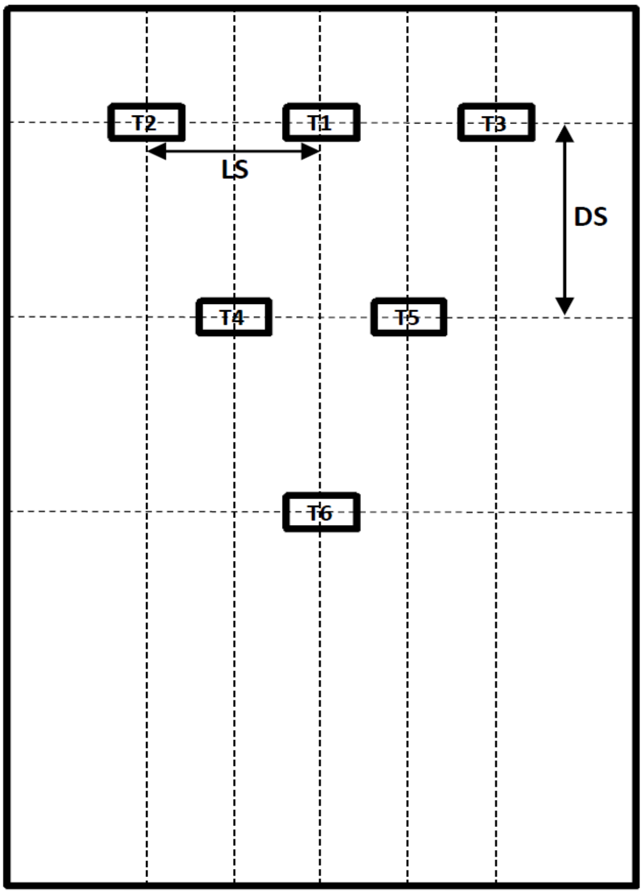

Figure 4-1: layout of turbines used for optimisation study

The design of the mesh was governed by the desire to strike a balance between the total number of elements and ensuring a suitably fine mesh around the turbines. To do this the mesh was split into two blocks, and upper block and a lower block, joined along the plane on which the centres of each turbine lay. The mesh was then graded for each block, meaning that the mesh was finest in the horizontal region where the turbines were situated, and finer far above and below the turbines.

The turbine layout used for the optimisation study is shown in Figure 4-1 showing the lateral spacing (LS), and downstream spacing (DS), and the layout of the three rows. This layout should allow the influence of upstream turbines on a third row to be investigated, since turbines positioned laterally to these turbines would only have a small influence upon the performance of the six turbines considered.

4.5. Derivation of a Surrogate Model

Matlab, an object orientated software environment widely used throughout a range of engineering disciplines, was used to generate a Latin hypercube with five parameters being varied, leading to fifty cases to be run using CFD. Each of the parameters; row 1 power, row 2 power, row 3 power, lateral spacing, and downstream spacing, was explored across a range of feasible values:

- For each row thrust was varied between 15N and 45N and torque between 0.25Nm and 0.75Nm to scale the power extracted by each row.
- Lateral spacing was varied between 0.7m and 1.3m.
- Downstream spacing was varied between 1.4m and 2.6m.

Once these cases were run, and the data processed, the parameters and output were inputted as matrices into the Kriging script included in the open-source DACE (Design and Analysis of Computer Experiments) toolbox in Matlab (Lophaven, et al., 2002). This created a surrogate model that could be used to feed a genetic algorithm script, with various toolboxes available for running genetic algorithms (MathWorks, 2015), (Pohlheim, 2006). In order to assess the validity of the surrogate model, it was tested against four randomly generated cases run using the VFAD computer model.

5. Presentation of Results

5.1. Validation Results

5.1.1. Tunnel Blockage

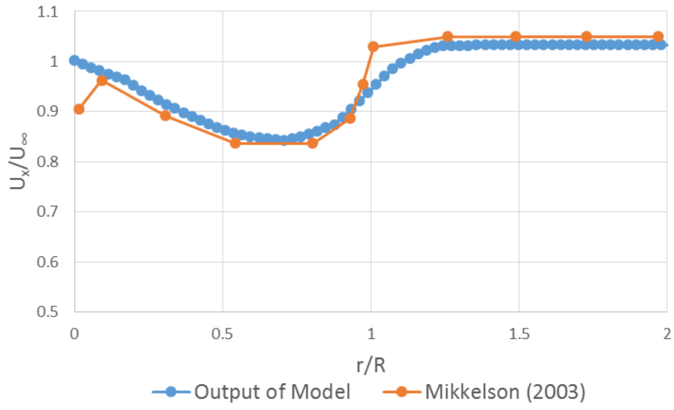

Figure 5-1: radial velocity profile far downstream from disk, R being the disk radius

Figure 5-1 shows the agreement between the VFAD model and the model used by Mikkelson (Mikkelson, 2003).

The difference between the curves can be explained by the different force distributions used by the two models (Svenning, 2010). This conforms to Svenning's findings, thus validating the upgrade of the model into the latest version of OpenFOAM.

5.1.2. Mesh Disk Rotor Simulator

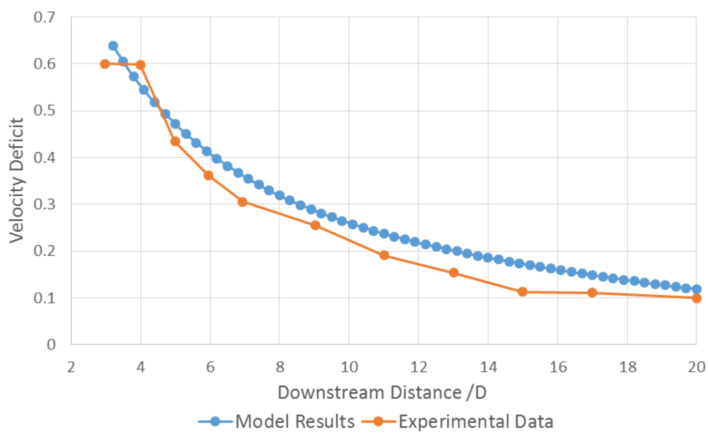

Figure 5-2: velocity deficit versus downstream distance, in terms of turbine diameter D

The curve depicted in Figure 5-2 shows the correlation between the model output and the experimental results of an actuator disk study for a thrust coefficient of 0.86 (Myers & Bahaj, 2010).

The overall correlation is strong, with the model providing a slight overestimate for velocity deficit when compared to the data. Since the data was conducted for mesh rotor disks, physical versions of the simple actuator disk model, the difference between the model and the experimental data may not mean that the model is inaccurate, as it is being compared against an experimental approximation to a HATT. The strong correlation shown suggests that the model is providing a suitable approximation of a tidal turbine; and, as such, the model may be used to explore more complex behaviours relating to HATTs where physical experiments are impractical.

5.2. Performance of transient VFAD solver

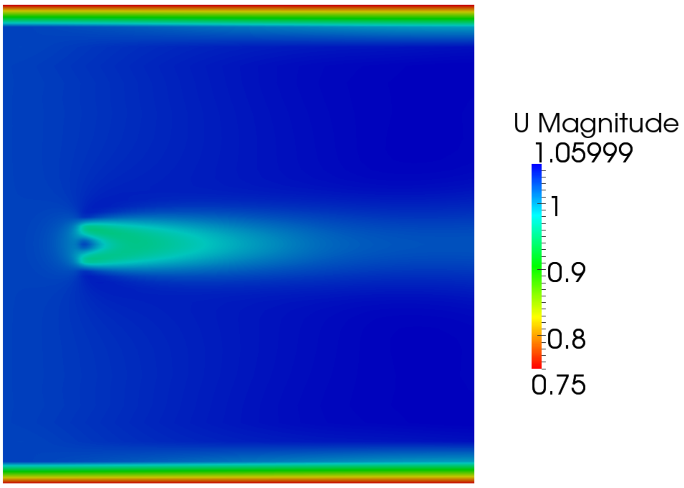

Figure 5-3: plan view of velocity contours through domain

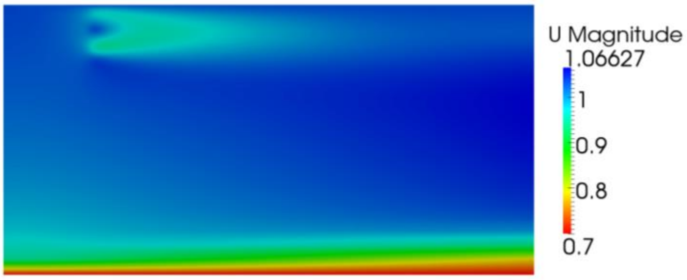

Figure 5-4: side view of velocity contours through domain

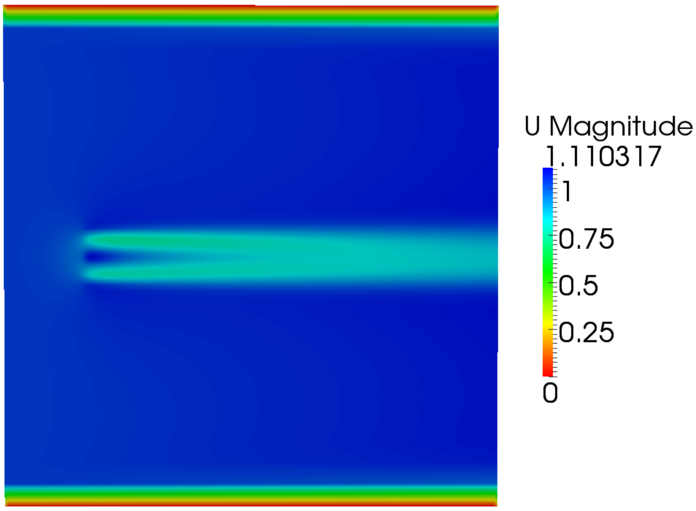

Figure 5-5: plan view of velocity contours when using LES

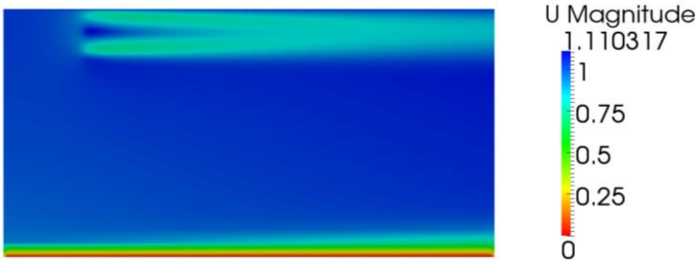

Figure 5-6: side view of velocity contours using LES

5.2.1. RANS Modelling

When set up using the modified test case, the transient, pisoFoam based solver produced the velocity contours shown in Figure 5-3 and Figure 5-4. This showed the transient solver to be functioning as expected, since the results matched the predictions for this case.

5.2.2. LES Modelling

In order to make a better comparison between the computational cost of the VFAD model and the MRL model developed at the university, the domain was adapted to run LES. The velocity contours produced from the simulation are shown in Figure 5-5 and Figure 5-6. The LES model shows an extended wake region when compared to the RANS version, which may be caused by the consideration of larger eddies, which take longer to dissipate.

5.3. *Results of Modelling for Multiple Turbines*

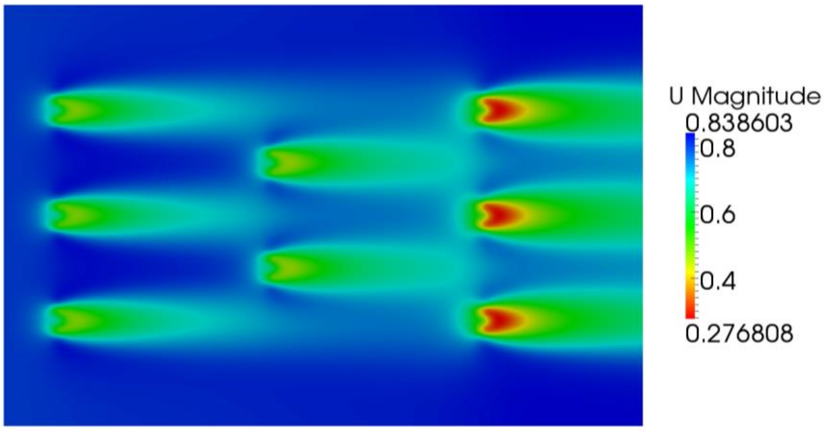

Figure 5-7: Plan view of velocity magnitude through the eight turbine domain

The model was set up to simulate the behaviour of an array of eight turbines. The performance of each member of the array was then calculated to find the effects of other turbines.

The velocity through this domain is shown in Figure 5-7, with Figure 5-8 and Figure 5-9 showing the velocity and pressure profiles along the domain. This case formed the foundation for the six turbine array for array optimisation.

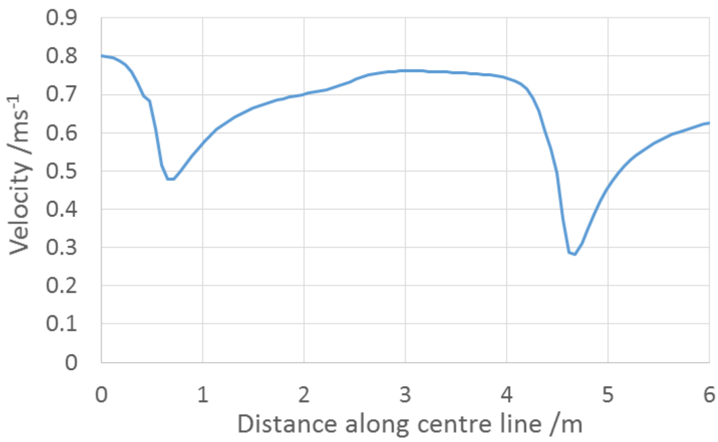

Figure 5-8: Velocity profile through turbines 1 and 7

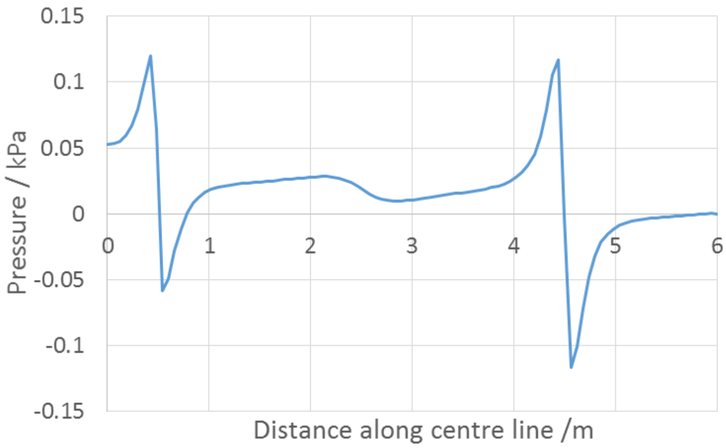

Figure 5-9: Pressure variation through turbines 1 and 7

The velocity, shown in Figure 5-8, conforms to the expected behaviour. With two large drops in velocity occurring where the flow encounters the turbines, with a larger drop for the second turbine.

As with the velocity profile, the pressure curve in Figure 5-9 is as expected, with the two pressure drops corresponding to central turbines in the first and final rows. The larger of these pressure drops occurs for the downstream turbine. The small drop between these two pressure drops occurs when the flow passes between the two turbines in the second row.

5.4. Array Optimisation Study

5.4.1. Varying Lateral Spacing (LS) of Turbines

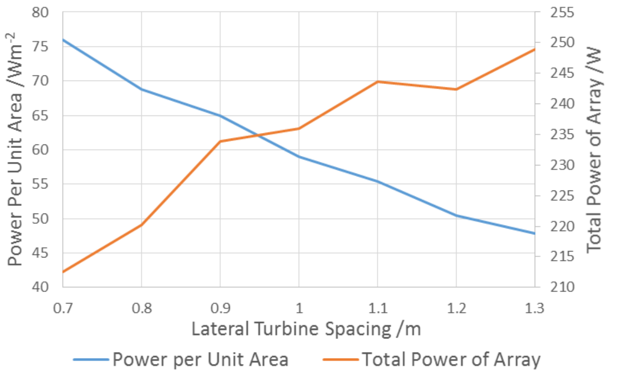

Figure 5-10: array power and power density, against lateral spacing

Figure 5-10 illustrates how varying the lateral turbine spacing affects the total power produced by the array, as well as the power produced per unit area. Since an optimal array produces as much power as possible for a minimum cost, a compromise between the total power produced, and array area, needs to be found. For arrays with large LS, the power produced per turbine is higher since the turbines in the 2nd and 3rd rows recieve more power, however power per area is reduced.

5.4.2. Varying Downstream Spacing (DS) of Turbines

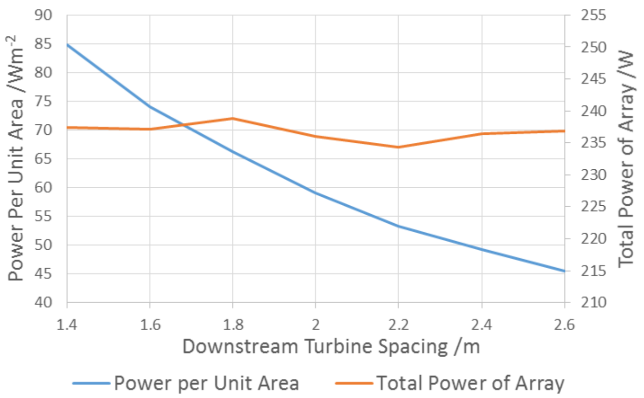

Figure 5-11: array power and power density, against downstream spacing

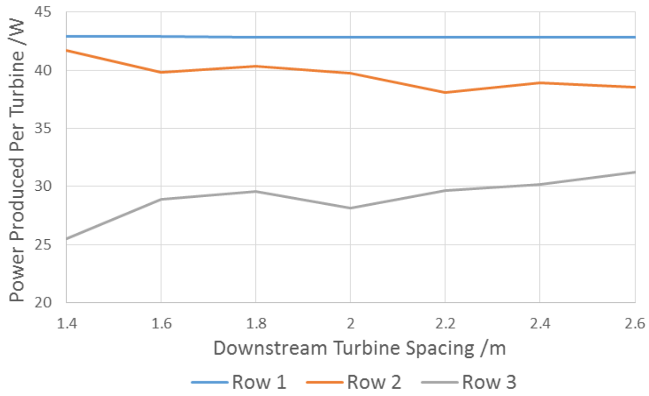

Figure 5-12: comparison of performance for turbines in each row of array when downstream spacing is varied

Figure 5-11 shows how the power per unit area and total power produced by the array varied with DS. The total array power changes little with DS, though the power produced by turbines in each row varies more, and this variation is masked in the total power curve. This is illustrated in Figure 5-12. Whilst having a small DS increases the power density of the array, the power loss of the third row is such that the advantage is limited.

5.4.3. Latin Hypercube Sampling

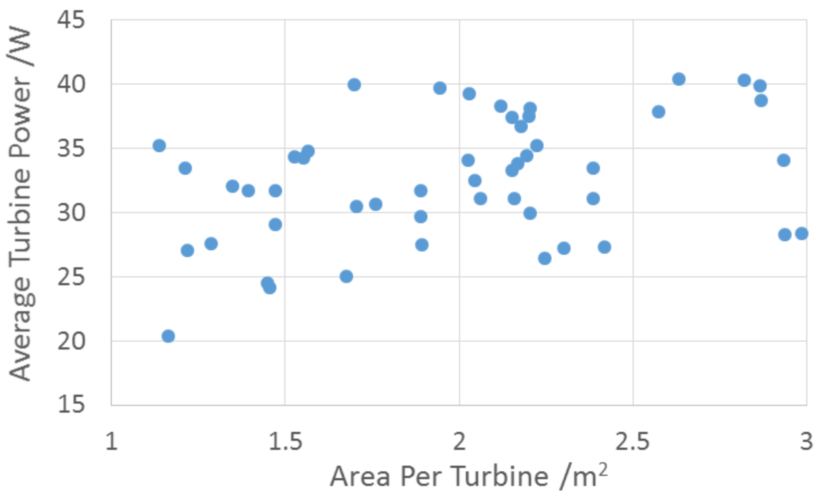

Figure 5-13: Average Turbine Power against Area for the Latin hypercube sample

Figure 5-13 shows the distribution of the results produced through the running of the Latin hypercube sample cases, with optimal solutions found at the top left of the distribution, where there is a high power density in the array.

Though the optimisation of this system, a Pareto front would be formed in this top left region, representing a family of optimal solutions representing various compromises between total power produced and array density.

5.5. Surrogate Model Performance

The results of testing the accuracy of the surrogate model are presented in Table 5-1. It shows that the kriging predictor provides a good model for the behaviour of the CFD results. Since optimal solutions found from the surrogate model would be tested using the VFAD model to ensure their validity, the agreement shown between the two is sufficient to support the use of this kriging model as a tool in the optimisation process.

Table 5-1: showing the performance of the surrogate model for 4 random test configurations

Case	Power Density of Array /Wm^{-2}		% error
	Output of VFAD Model	Kriging Approximation	
1	15.97	16.44	-2.905
2	13.01	12.70	2.412
3	9.922	10.02	-0.9356
4	13.30	13.20	0.7774

6. Discussion and conclusions

Throughout the course of this project, the Volume Force Actuator Disk model has been used and adapted to address a wide range of problems; with perhaps the most significant outcome of this work being the illustration of the models versatility and overall suitability for research into tidal energy.

The model validation has shown good agreement with cases in the literature, and the low computational cost has meant that studying the behaviour of arrays of turbines has been possible, with the potential to apply this approach to far larger arrays in the future.

The versatility of the model is enhanced by the high degree of customisability inherent to OpenFOAM, with the functionality of the original VFAD solver being relatively simple to implement in other solvers, such as the pisoFoam and interFoam VFAD solvers produced as a part of this work. This allows the model to be used for a wider range of flow scenarios, through modification of one of the many specialised solver classes that are included in OpenFOAM.

Through the analysis of turbine performance using the control volume approach, the model becomes a far more powerful research tool, and has allowed for the investigation of array performance.

An approach to the optimisation of arrays of turbines based upon this model has also been set out, through the use of Latin hypercube sampling and a surrogate model to enable the use of optimisation algorithms. Despite there not being time to optimise the surrogate model using genetic algorithms during this project, the performance of the surrogate model, and thus, the suitability of this approach has been shown.

6.1. Model Validity and Performance

The approaches taken to the validation, both by Svenning (2010), and by myself in this study, have shown good agreement between the model output and experimental data.

The computational cost of the model is low, with simulations completing in a few hours for arrays comprising of multiple turbines and meshes with around 1 million elements. This low computational load means that the model could be used for larger and more complex simulations in the future.

6.2. Transient Model using pisoFoam

In order to model transient behaviour using the VFAD model, and to allow for the use of Large Eddy Simulation, the model was programmed in to the pisoFoam solver included in OpenFOAM. This pisoFoam based solver was tested for both RANS and LES turbulence modelling, showing good results.

The new solver was then used throughout the array performance studies and multi turbine cases and showed good performance, modelling a wide range of scenarios whilst maintaining stability. By introducing the VFAD model to the pisoFoam solver, it created a more versatile modelling tool than the simpleFoam approach, which was constrained to steady state RANS modelling. This shows how the VFAD approach may be applied to a range of prewritten solvers in OpenFOAM in order to investigate scenarios using the most suitable tool.

6.3. Investigation of Array Performance

Through investigating the performance of an array under different turbine spacings, the feasibility of using the VFAD model for studying the properties of a turbine array was demonstrated. It was shown that the lateral spacing can have a huge effect on the turbines downstream, with small spacings leading to an increased blockage ratio and poor array performance. While the effect of varying the downstream spacing was less drastic overall, the variations in performance of each row in the array were significant, suggesting that having a large lateral spacing, and small downstream spacing can improve array efficiency.

6.4. Use of Surrogate Model and Optimisation

The surrogate model produced through Kriging produced a good fit for the output of the VFAD solver, meaning that any optimal value found using the surrogate model would likely correspond to an optimal output of the VFAD model. By validating the output of the surrogate model, the foundations are laid for the optimisation of arrays using this approach and the VFAD solver in the future.

6.5. Suggestions for Further Work

6.5.1. VFAD Model Development

Overall, the performance of the VFAD model for the modelling of a tidal turbine has been good, though the model could be made to show improvement for modelling a specific turbine design were the distribution of forces across the disk to be programmed to match an actual distribution instead of the idealised Goldstein optimum. A CFD approach may be used to analyse the distribution of forces along the blades, which then can be used to program the force distribution on the disk (Svenning, 2010).

The model has performed well when compared to cases in the literature; however, a more thorough investigation of model validity would be of use, comparing the data to that of a turbine based experiment and not one using a perforated disk.

It would also be of interest to adapt the model to introduce a mechanism to reproduce the vortices shed by blade tips; with rotational annular stream tube analysis, which has been used to model this effect in wind turbines, providing a potential method for this model enhancement (Kulunk, 2011).

6.5.2. Array Optimisation

Though this project did not progress to the generation of genetic algorithms, this is being pursued as a separate project over the summer. Through the set-up of a more general domain representing a section of a larger array, a surrogate model would allow for the optimisation of a larger array that considers both array area and total power produced, with genetic algorithms being used to generate a family of optimal solutions forming a Pareto curve. Depending on progress, this could lead to further research in this area.

This is a research topic with much potential, and the VFAD model is likely to provide a useful tool in the future, with this project opening up multiple applications for this approach in the future.

6.5.1. Application of Model to Multi-Phase Flow

The model was adapted to work using the interFoam solver, but there was insufficient time to develop a case to test the functionality. The air-water boundary can have many effects upon the wake structure behind tidal turbines (Stallard, et al., 2011), and the use of a multi-phase solver may be used to investigate these (Gebreslassie, 2012). It would be of use to develop some cases to test the functionality of the modified interFoam case programmed as part of this study.

7. Project management, sustainability and health and safety

7.1. Project Management

Since this project was research based, with the results and findings governing the direction taken at each stage, the scheduling throughout was not strict, and often the time required by a task was unknown. A Gantt chart, shown in Figure 7-1, was used throughout the computational work, to keep track of progress and plan the next stage of investigation. And the risks to project success were identified and mitigated against according to Table 7-1. Through this constant monitoring of progress, and identification of risks, the project was allowed to progress successfully and efficiently towards the stated goals.

Weekly meetings with my project supervisor, Dr Gavin Tabor, also served as a means to assess and discuss progress and immediate steps to be taken throughout the work. This was a key process in the shaping of the project, helping to guide and shape the research in order to achieve a set of meaningful outcomes.

The logbook kept throughout this project provided an important tool for self-management and the structuring of the research. During this work, there were often multiple areas being investigated, and the logbook provided a means to set down and clarify the goals and action points at each stage. It also allowed me to make note of ideas and queries throughout the week leading up to meetings, ensuring I did not forget or miss-remember key details.

Table 7-1: risk assessment table used to manage project risks

ID	Risk item	Effect	Cause	Likelihood	Severity	Importance	Action to minimise risk
1	Errors in code	This could cause the modelling of the turbine to take longer than anticipated	- lack of understanding when coding - Typing errors	5	8	40	- Proof read code to check for typing errors - Ensure that I understand the purpose of the code I use
2	Time Delays from other Deadlines	Other work for University modules may impact my ability to keep up with the desired progress for this project	- Lack of planning for workload	5	4	20	- Look up deadlines and plan work around busy times to ensure there is time for both this project and other work
3	Loss of work	Significant amount of wasted time as work has to be re done	- Not backing up work - IT issues	3	7	21	- Back up all work on an external hard-drive
4	Delays from lack of access to required information	Time delays from not being able to access any required information	- A need to access sensitive info	1	5	5	- If there is a need for such information, it will be identified early and access requested before in good time

Implement the Svenning Model in OpenFOAM	35 days	Wed 10/12/14	Tue 27/01/15
Validate the updated model	**14 days**	**Wed 28/01/15**	**Mon 16/02/15**
Validate against Svenning's test case	4 days	Wed 28/01/15	Sun 01/02/15
Validate against experimental data for Horizontal Axis Tidal Turbines	11 days	Mon 02/02/15	Mon 16/02/15
Modify model for use with multiple turbines	**11 days**	**Tue 17/02/15**	**Tue 03/03/15**
program in turbine properties dictionary	9 days	Tue 17/02/15	Fri 27/02/15
test modified solver	2 days	Mon 02/03/15	Tue 03/03/15
Produce transient and multi-phase solvers	**14 days**	**Wed 04/03/15**	**Mon 23/03/15**
Program pisoFoam based solver	5 days	Wed 04/03/15	Tue 10/03/15
Test pisoFoam based solver	2 days	Wed 11/03/15	Thu 12/03/15
Program interFoam based solver	5 days	Fri 13/03/15	Thu 19/03/15
Test interFoam based solver	2 days	Fri 20/03/15	Mon 23/03/15
Use control volumes to analyse turbine performance	**10 days**	**Tue 24/03/15**	**Mon 06/04/15**
Set up and run for a single turbine	4 days	Tue 24/03/15	Fri 27/03/15
Set up and run for a row of turbines	2 days	Mon 30/03/15	Tue 31/03/15
Set up and run for a 5 turbine array	2 days	Wed 01/04/15	Thu 02/04/15
Set up and run for an 8 turbine array	2 days	Fri 03/04/15	Mon 06/04/15
Optimisation Study	**15 days**	**Tue 07/04/15**	**Mon 27/04/15**
Set up 6 turbine array ready for optimisation study	2 days	Tue 07/04/15	Wed 08/04/15
Hand optimisation	**6 days**	**Thu 09/04/15**	**Thu 16/04/15**
Vary LS	3 days	Thu 09/04/15	Mon 13/04/15
Vary DS	3 days	Tue 14/04/15	Thu 16/04/15
Genetic Algorithm Optimisation	**7 days**	**Fri 17/04/15**	**Mon 27/04/15**
Set up and run Latin Hypercube cases	3 days	Fri 17/04/15	Tue 21/04/15
Use Matlab to produce a surrogate model through Kriging	2 days	Wed 22/04/15	Thu 23/04/15
Use Matlab to run a GA optimisation	2 days	Fri 24/04/15	Mon 27/04/15
Deadline for Practical Work	0 days	Mon 27/04/15	Mon 27/04/15

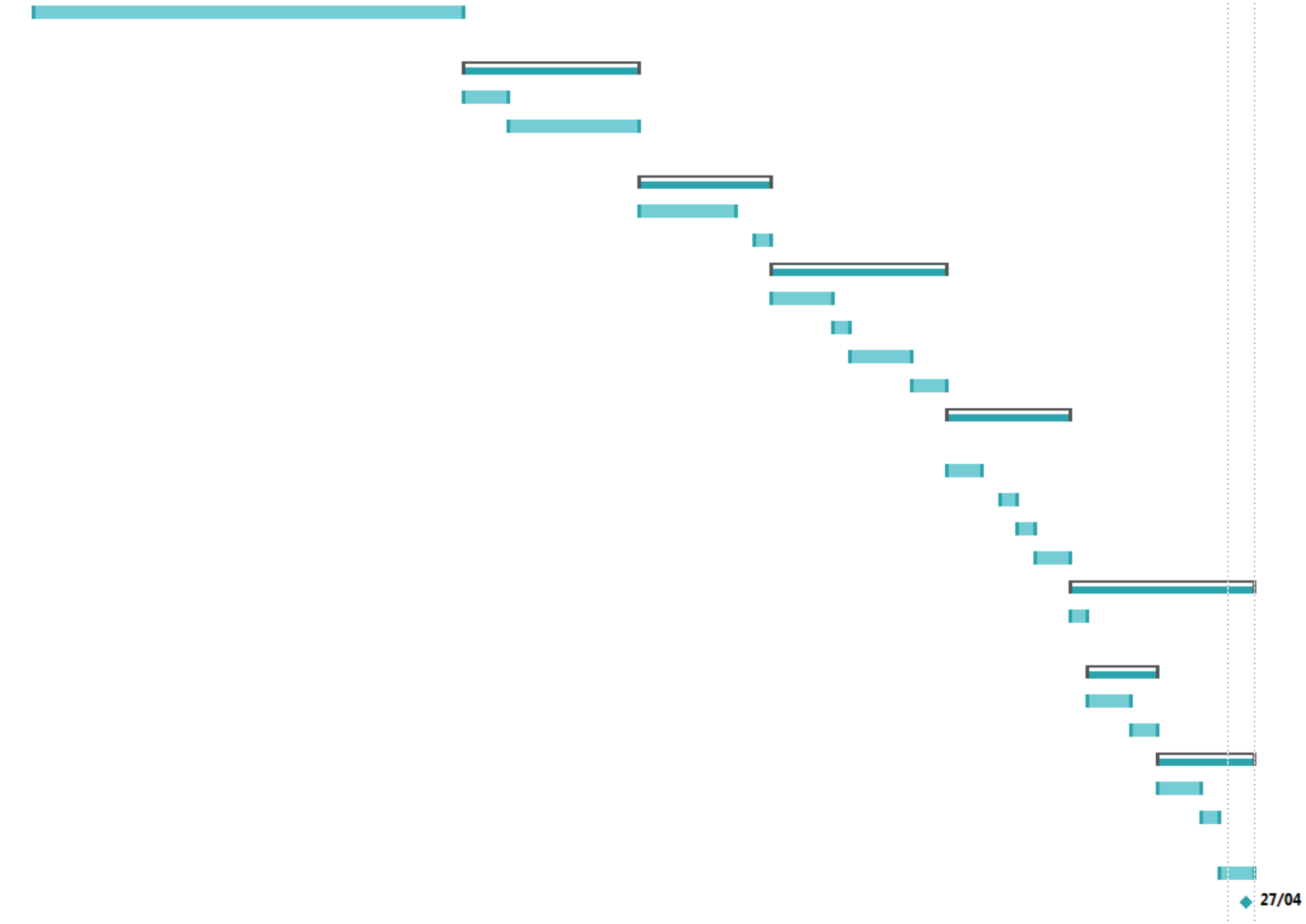

Figure 7-1: Gantt chart used throughout the computational work to keep track of progress and aid time management

7.2. Sustainability

Sustainability is the main motivation behind this research, and, as a continuation, the tidal power industry as a whole. In the drive to reduce fossil fuel dependency and carbon emissions in the UK, tidal energy has been touted as a major part of the solution (MacKay, 2008). The research carried out within this project seeks to contribute to the realisation of this potential. Through the production, validation, and then applied use of an accurate computer model, time, money and resources may be spared, enabling the continued development of efficient, economically viable, renewable power production from the world's tidal resources.

In addition, tidal power presents a low impact form of sustainable power when compared to other forms of renewable energy; such as onshore wind, solar farms, and hydroelectric installations. The implications to local people of such projects can lead to the refusal of permission, with the 'NIMBY' ('Not In My Back Yard') effect a common obstacle faced by those seeking to develop renewable energy projects (Van der Horst, 2007). Since the bulk of the infrastructure associated with tidal stream farms would lie below the surface, in areas where strong currents limit the use of the waters for other purposes, the direct impact upon local people would be minimal.

The UK is currently the global leader in marine renewables, with more capacity being tested in UK waters than in the rest of the world combined (renewable UK, 2015), and it has been estimated that if this is developed effectively, the UK could capture a 22% market share of an industry said to be worth £76 billion by 2050 (The Carbon Trust, 2011). With many of the UK's marine renewables resources situated in peripheral regions, such as South-West England and Northern Scotland, the further development of tidal technologies could bring economic growth, and large numbers of skilled jobs, to areas where there are currently few opportunities.

7.3. Health and Safety

Throughout this work, care has been taken to adhere to the Health and Safety guidelines for office work set out by the UK government (Health and Safety Executive, 2013). Despite there being no practical elements of the work, where the risks are more apparent, the project involved many hours working at computers, which brings its own risks, such as repetitive strain, aches, stiffness and eye discomfort (Health and Safety Executive, 2013).

To counter these risks, an effort was made to ensure that the computer screen was set to an appropriate height, the office chair was supportive and set to a suitable height, and that regular breaks were taken to alleviate the risks of fatigue in line with the official government guidelines for office work (Health and Safety Executive, 2013).

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