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Programme Area: Marine

Project: PerAWAT

Title: GH Device Scale Modelling Report

Abstract:

This deliverable sets out the project's approach to device scale modelling of tidal devices. The report provides a clear definition of the requirements and methodologies being used for the modelling, along with the subsequent methods for integrating device scale models into the final array tool. Calculation of uncertainties in the final combined energy yield prediction model is also reviewed. Limitations and constraints such as blockages and free-surface interactions are discussed and options for dealing with them explored. Following on from this deliverable, numerical and experimental modelling were undertaken.

Context:

The Performance Assessment of Wave and Tidal Array Systems (PerAWaT) project, launched in October 2009 with £8m of ETI investment. The project delivered validated, commercial software tools capable of significantly reducing the levels of uncertainty associated with predicting the energy yield of major wave and tidal stream energy arrays. It also produced information that will help reduce commercial risk of future large scale wave and tidal array developments.

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ETI Marine Programme Project
PerAWaT MA1003
WG3WP4 D3 GH DEVICE SCALE MODELLING REPORT

Client **Energy Technologies Institute**

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CONTENTS

EXECUTIVE SUMMARY

This document outlines the issues associated with device scale modelling within an energy yield analysis. The aim of device scale modelling in the context of an energy yield assessment is to both evaluate the power production of an individual device; and to predict the change in local flow field conditions due to the energy extraction process.

A summary is provided of the standard guidelines for performance assessment of tidal energy devices that have been written in recent years. This is followed by a review of existing methods for modelling the power production of a tidal turbine and its impact on the local flow field .

The GH device scale modelling approach is described and explained. The GH device scale modelling approach incorporates many different aspects; evaluation of a representative incident flow speed onto the device, use of a turbine model which parameterises both power production and thrust as a function of flow state, use of a blockage model to correct for changes to power and thrust due to local blockage effects and uses a near wake mode to initiate far field wake modelling.

This report provides an overview if the approach adopted by GH TidalFarmer for energy yield assessment and a discussion on how the device scale models are implemented within the software. The uncertainties associated with the individual parts of the device scale model are reviewed and the developments for the GH device scale modelling approach planned under PerAWaT are summarised. The next step for the device scale modelling is the comparison with experimental and numerical validation data.

SUMMARY OF NOTATION

Turbine characteristics

C_p	Power coefficient (-)
C_T	Thrust coefficient (-)
C_{pb}	Boundless Power coefficient (-)
C_{Tb}	Boundless Thrust coefficient (-)
Λ	Tip speed ratio (-)
C_L	Hydrofoil lift coefficient (-)
C_D	Hydrofoil drag coefficient (-)
Fr	Froude number (-)

T	Axial thrust on rotor (N)
P	Rotor power (W)
L	Lift force (N)
D	Drag force (W)
A	Rotor area (m^2)
c	Chord length (m)
z	Water depth (m)
U	Incident velocity (m/s)
W	Resultant velocity (m/s)
Ω	Rotational speed (rad/s)
α	Angle of attack (rad)

Constants

ρ	Density (kg/m^3)

Abbreviations

1-d	one dimension (typically in the x-direction)
2-d	two dimensions
3-d	three dimensions

AEP	Annual energy production
BEM	Blade element momentum
CFD	Computational fluid dynamics
EMEC	European Marine Energy Centre
FDC	Fundamental Device Concepts
MRDF	Marine Renewables Deployment Fund
NS	Navier-Stokes
RANS	Reynolds averaged Navier-Stokes

A general glossary on tidal energy terms was provided as part of WG0 D2 – “Glossary of PerAWaT terms”. This is a working document which will be revised as the project progresses.

1 INTRODUCTION

1.1 Scope of this document

This document constitutes the third deliverable (D3) of working group 3, work package 4 (WG3WP4) of the PerAWaT (Performance Assessment of Wave and Tidal Arrays) project funded by the Energy Technologies Institute (ETI). Garrad Hassan (GH) is the sole contributor to this work package. This document describes the theory behind and the method of implementation of the device scale modelling of a tidal turbine for the purpose of energy yield analysis.

1.2 Purpose of this document

The purpose of WG3WP4 is to develop, validate and document an engineering tool that allows a rapid assessment of the energy yield potential of a tidal turbine array on non-specialist hardware. The specific objective of WG3 WP4 D3 is to both document and provide a technical justification for the approach to device scale modelling adopted within the suite of models that make up the engineering tool ‘GH TidalFarmer’.

1.3 Specific tasks associated with WG3 WP4 D3

WG3WP4 D3 comprises the following aspects:

- A detailed description of the representation of a tidal turbine for energy yield purposes.
- A description of device scale models and method of integration.
- A description of the implementation of device scale models in the GH Tidal Farmer code.

1.4 WG3 WP4 D3 acceptance criteria

The acceptance criteria as stated in Schedule 5 of the PerAWaT technology contract are as follows:

D3: Overall device scale modelling report includes:
- A clear definition of resulting overall device scale modelling methodologies, model integration and the associated uncertainties of the final combined model.
- Analysis covers both blockage and near wake models.

2 BACKGROUND AND THEORY

The purpose of the GH TidalFarmer design tool is to provide the tidal stream energy industry with a comprehensive and definitive detailed assessment of the potential energy capture of tidal arrays. The aim of the GH TidalFarmer software is to allow the user to design a tidal farm to achieve maximum energy production within the geometric and environmental constraints of the site. In order to obtain a prediction of energy yield of the farm under consideration, GH TidalFarmer requires, as an input, some form of description of the tidal energy device to be placed within the farm, hence the need for a device scale model.

This section introduces the key measures for characterising the performance of a tidal energy device, and presents the description required by GH TidalFarmer. The factors which affect the performance of a device when operating in an array that must be considered when undertaking an energy yield analysis are also discussed.

2.1 Characterisation of a tidal energy device

There are numerous devices currently under commercial development for the extraction of energy from tidal streams. Many of these devices use a different technology basis for capturing the energy available in the tidal stream e.g. horizontal axis rotors versus oscillating hydrofoils. As discussed in the tidal sub-project specification document WG0D2, the horizontal axis axial flow turbine is the leading technology, and as such was selected as the tidal energy device concept to be considered for the purposes of PerAWaT. The horizontal axis rotor is also the accepted technology in the wind energy industry.

The power coefficient, C_P, for a rotor is defined as the power produced by the rotor P divided by the total power available in a flow of mean upstream speed U and an area A equivalent to that swept out by the rotor,

$$C_P = \frac{P}{\frac{1}{2}\rho A U^3}$$

where ρ is defined as the density of the fluid. Both Betz (1920) and Lanchester (1915) derived the maximum power coefficient of a rotor in unbounded flow to be 16/27 (more commonly known as the “Betz limit” or “Lanchester-Betz limit"). Similarly, the thrust coefficient, C_T, is defined based on the axial thrust, T, made dimensionless by the upstream flow speed and rotor area,

$$C_T = \frac{T}{\frac{1}{2}\rho A U^2}$$

The blades on a horizontal axis rotor comprise a series of sections with hydrofoil profiles. Consideration of the forces acting on an individual rotor blade element provides a clear explanation of the fundamental principles upon which horizontal axis rotors operate and the forces which they experience. All horizontal axis rotors utilise the lift force, L, created by a hydrofoil moving relative to the fluid to generate motion and hence power. Figure 2.1 shows the resultant two forces (drive and thrust) that are created when a hydrofoil cuts through a moving flow. The drive force acts in the plane of the rotor and produces a torque which in turn leads to rotation and hence the generation of useful energy (power). The resultant force in line with the flow direction is a thrust force which must be reacted by the structure. The power produced and thrust experienced by a tidal energy device are two of the key measures which are used to characterise the performance a device.

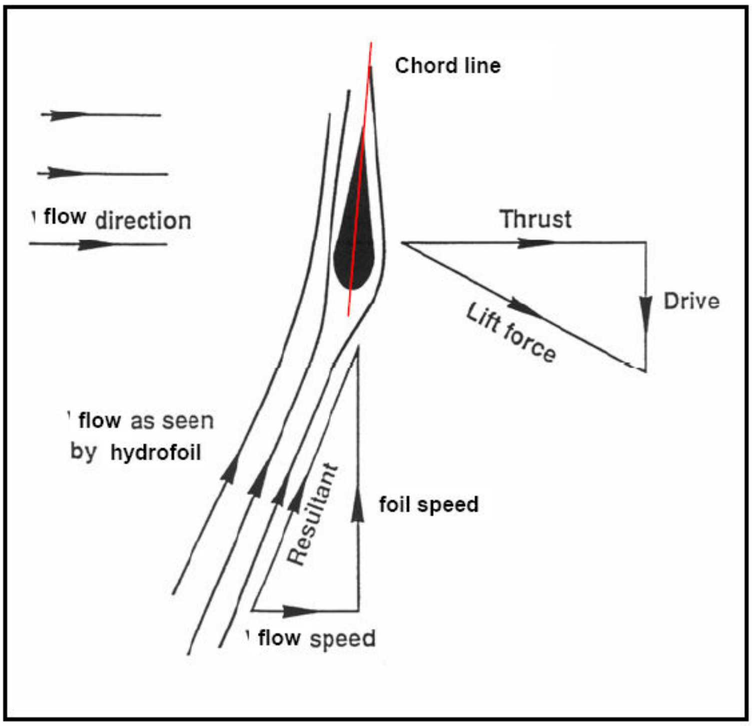

Figure 2-1 Flow over a hydrofoil

The angle between the resultant flow direction (as seen by hydrofoil) and the chord line (the red line in Figure 2.1) is known as the angle of attack. The amount of lift generated by the hydrofoil is a function of both the angle of attack and the profile of the hydrofoil. Below a certain angle of attack (the stall angle) there is a linear relationship between lift and angle of attack and above this point the lift starts to drop off. The hydrofoil will also experience a drag force, *D*, opposing the motion which is relatively constant at small angles of attack but increases markedly with angle of attack as the stall angle is approached and exceeded. The drag force acts to reduce the drive force (and hence power) and increase the thrust force. The lift and drag are also dependent on the Reynolds number that it operates at (see 104330BT01_v2.0 for a detailed discussion on this). Figure 2.2 is a schematic demonstrating the dependency of lift and drag coefficients on the angle of attack, where the lift coefficient (per unit length) is defined as

$$C_L = \frac{L}{\frac{1}{2}\rho c W^2}$$

where W is the resultant flow speed and c is the chord length of the hydrofoil. Similarly the drag coefficient (per unit length) is defined as

$$C_D = \frac{D}{\frac{1}{2}\rho c W^2}$$

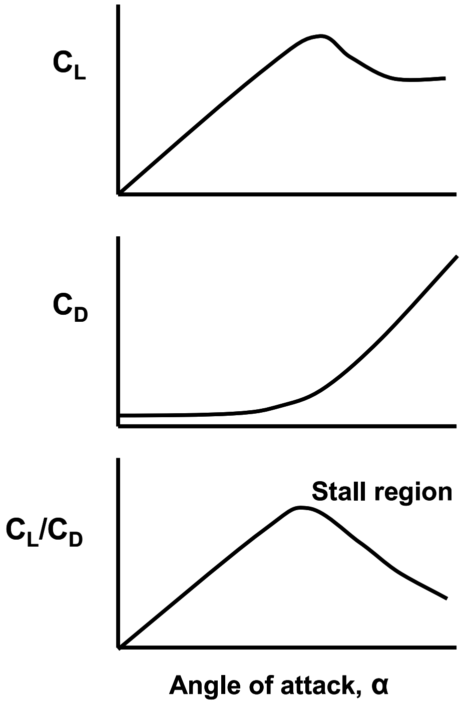

Figure 2-2 Schematic demonstrating the variation of lift and drag with angle of attack

The tip speed ratio, Λ, which is defined as the ratio of the rotor tip speed (ΩR) to the incident flow speed (U),

$$\Lambda = \frac{\Omega R}{U}$$

is the most commonly used dimensionless parameter for characterising the rotor operating state because together with the twist, it determines the relative flow angle incident on the varying sections of the blade. An optimal rotor design will operate with the hydrofoils at or near the maximum ratio of C_l/C_D in order to maximise the energy production for a chosen tip speed ratio.

Plots of power and thrust coefficient against tip speed ratio are commonly known as "performance" or "characteristic" curves. Figure 2.3 shows these performance curves for a generic rotor geometry, as discussed in detail in 104330BT01_v2.0. These are dimensionless plots which provide information on the performance of the device for a given flow condition and operating status. The exact shape of the performance curves are dependent upon the choice and orientation of hydrofoils adopted in the design and the Reynolds number range that they are operating in.

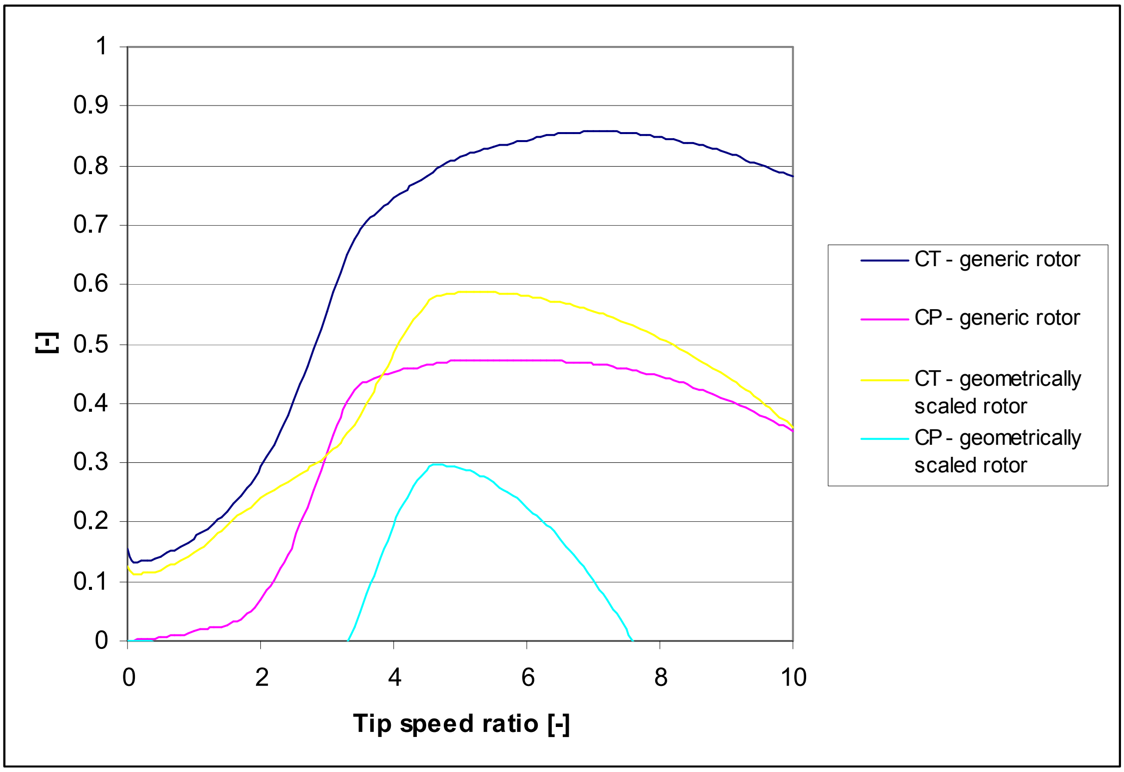

Figure 2-3 Power and thrust coefficient for the generic rotor. Reproduced from 104330BT01_v2.0

Not all tidal energy devices operate using a lifting mechanism depicted in figure 2.1 for energy production. For example, some utilise impulse or reaction mechanisms, in which the force leading to rotation arises due to a change in momentum of the fluid (e.g. flow diversion) rather than a lift force experience by the blade. The approach for evaluating the performance may be different in these cases, however a set of curves relating the power and thrust to the operating point of the device are also the usual method employed to characterise such devices.

The axial thrust, which can also be determined by the momentum deficit in the wake compared to the influx momentum, is one of the key parameter for characterising the flow conditions in the wake. Application of a one-dimensional momentum balance of flow past an actuator disc, is a commonly used method for evaluating the thrust and maximum (inviscid) power output. Momentum theory was presented in full in WG3WP4D2 and when coupled with blade element theory provides the industry standard method for design of wind turbines and prediction of their performance curves. Many standard texts have been written, such as Burton *et al.* (2001), which provide a thorough description of the blade element momentum theory, and the reader is referred to such a text for a complete account of these theories.

Dimensional power and thrust curves are useful for assessing the behaviour of a device at a specified site. Combined with a prediction of the resource behaviour at the site, a dimensional power curve enables a prediction of energy yield. The thrust curve is required in the resource analysis as it provides a measure of the rotors impact on the resource itself. Figure 2.4 shows a power curve which constitutes a plot of steady power produced against flow speed and steady thrust curve which similarly constitutes a plot of rotor thrust against flow speed.

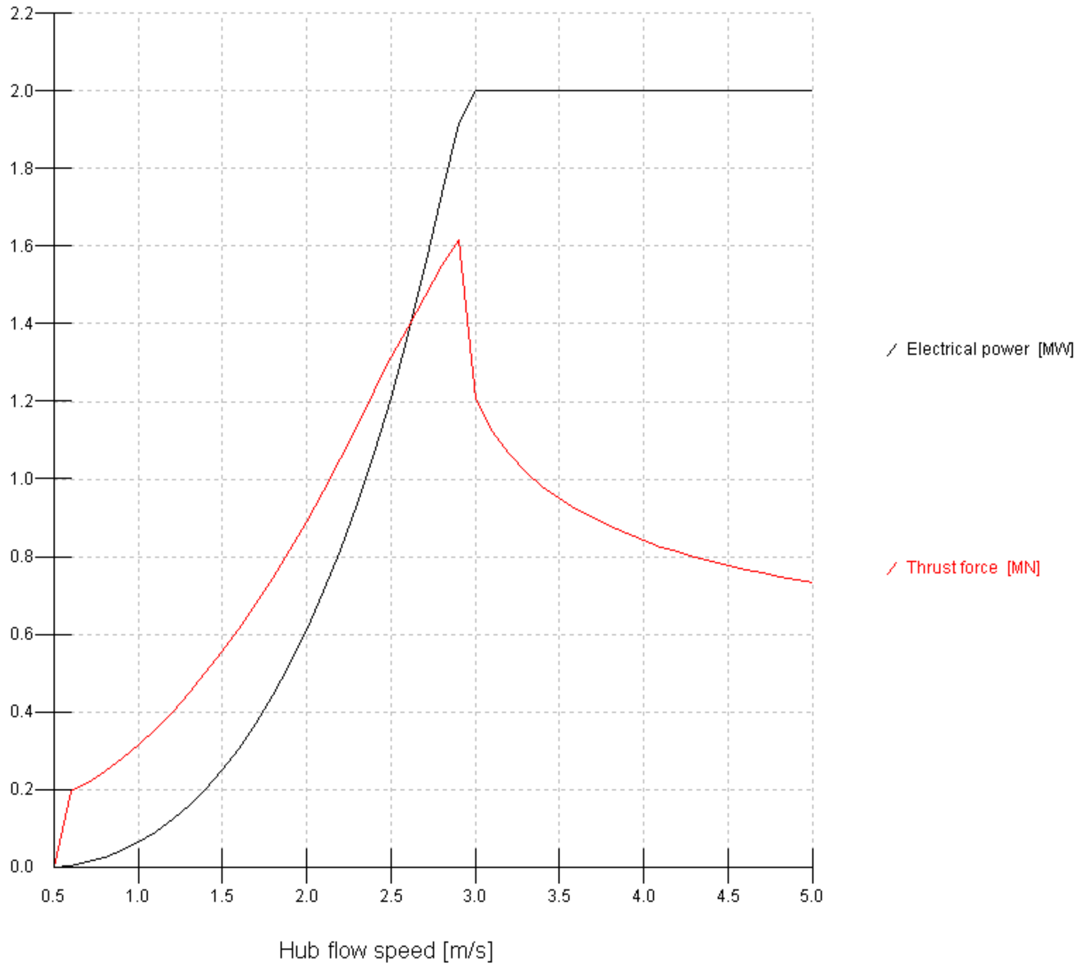

Figure 2-4 Power and thrust curves for a generic pitch regulated rotor

2.2 Factors affecting the performance of a tidal energy device (or shape of the power and thrust curves)

The operating philosophy (or control strategy) applied to a tidal energy device will determine the point on the characteristic curves at which the device is operating at for any given flow condition and hence the shape of the power and thrust curves. The power rating of a tidal energy device corresponds to the maximum power that it is designed to generate. Broadly speaking, the different operating philosophies can be categorised by the type of action that is taken when the flow speed increases above that at which the turbine is designed to produce its rated power. These different categories include:

- Variable pitch regulation
- Stall regulation (fixed pitch)
- Over-speed regulation (fixed pitch)
- Rated at peak flow speed

Figure 2.5 illustrates the key differences between the categories in terms of the flow over the hydrofoils. If the rotor blades have the ability to pitch, as in the case of variable pitch regulation, the rotor geometry will change when the blades are pitched (leading to a different performance curve each corresponding to a different geometry). Above rated flow speed the blades will be pitched to decrease their angle of attack, and hence shed power, to maintain a constant power. In the case of a fixed pitch rotor which has a stall regulation philosophy, as the flow speed increases, so does the angle of attack and hence the flow condition over hydrofoils move into the stall region, shedding power. The opposite is true of over-speed regulation philosophies, where the control system is designed to increase the speed of the turbine with increasing flow speed in order to shed power. The fourth category corresponds to the case where the rotor only achieves its maximum power rated at maximum flow speed.

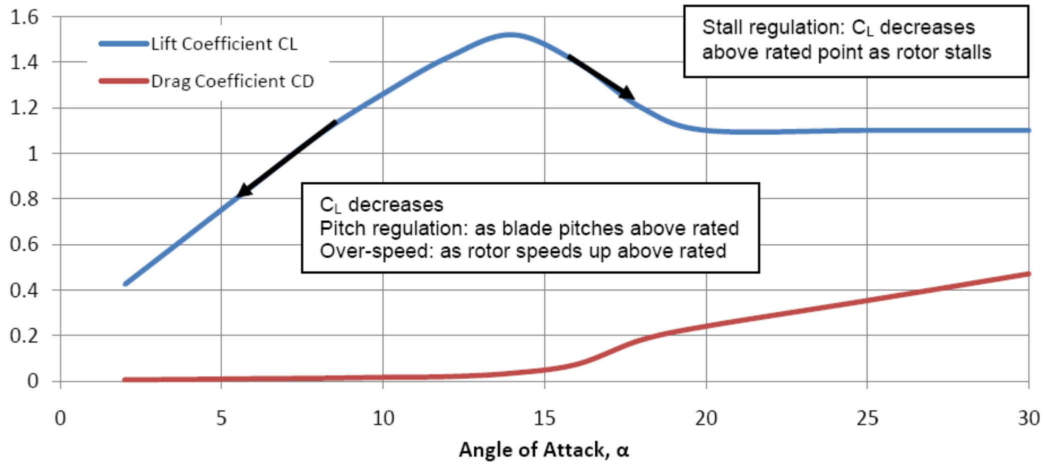

Figure 2-5 Operating philosophies for tidal turbines. Reproduced from Franks (2010).

In order the produce a power (or indeed thrust) curve for a specified site it is also necessary to have information on the incident flow conditions. A simplified model of the tidal cycle will provide information on the mean variation of incident flow field at a specified site; however this is not representative of the instantaneous flow field. Factors which influence the instantaneous incident flow velocity include:

- The boundary layer due to the sea bed. This leads to a shear profile being incident on the rotor capture area, causing the mean flow incident on the rotor tip when it is closest to the sea-surface to be greater than when the rotor tip is closest to the seabed.
- The presence of ambient turbulence in the water column will lead to fluctuations about the mean velocity that is incident on a tidal energy device, for example on a horizontal axis rotor a large variation in incident velocity due to a passing turbulent gust may cause a rotor to fluctuate in and out of a stall operating point.
- Passing surface waves will also lead to fluctuations about the mean velocity and can lead to a constant offset from the mean if drift effects are occurring as discussed by Hedges (1987).
- The presence of the bounding surfaces such as the sea surface and sea bed lead to a constraint on the streamtube expansion (blockage effects).

Turbines which are situated within arrays will be subject to inter-array effects, which will also affect the incident flow velocity

- Configuration of turbines in rows is likely to lead to some turbines being situated within the wake of another turbine. This will lead to a reduced incident velocity as well as a modified ambient turbulent intensity.
- Local blockage due to the presence of a neighbouring turbines leads to further constraints on streamtube expansion.

Blockage effects also act to increase thrust loads and potentially increase power compared to the equivalent unblocked upstream flow conditions. The reader is referred to WG3WP4D1 for a more in-depth discussion on the phenomenon of blockage.

Other factors which will affect the shape of the power curve, in particular, include:

- The mechanical losses that occur in drive train

- The electrical losses that occur in the transmission system, the generator and any other parts of the system before the point of electrical power output will affect the shape of the thrust and power curves.
- The exact implementation of the power take-off system, which may lead to non-linear changes dependent on the nature of the incident flow conditions.

Various different established modelling methodologies exist for horizontal axis rotor that are capable of producing steady power and thrust curves, and a summary of these is provided in Section 4. However in order to capture all of the non-linear relationships which exist due to complexities inherent in both the turbine configuration and onset flow conditions, a dynamic curve is required. A dynamic power curve is one which is a constructed from many observations of a unsteady system. An example of a dynamic power curve is given in Figure 2.6. This plot was produced by running (or taking) multiple simulations (or measurements), covering the full range of flow speeds likely to be incident on the rotor during its operation, and taking the mean power and flow speed for each operational condition. This approach ensures that any unsteady effects which do not average out are captured in the power and thrust curves.

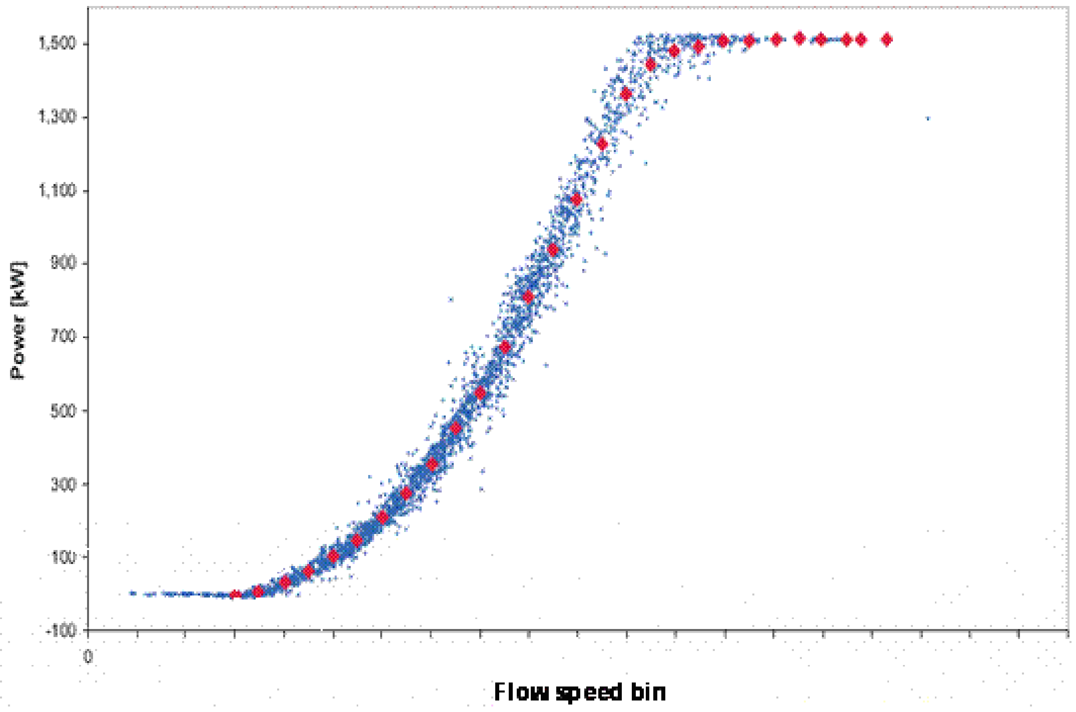

Figure 2-6 Construction of a dynamic power curve

McCann et al (2008) show that the dynamic power curve incorporates the effect of the dynamic controller, which, due to the constantly changing flow speed is unable to match the 'ideal' steady state characteristic. Dynamic power curves tend to have a rounded knee around the point of rated power, as shown by Figure 2.7, which is a comparison of a steady and dynamic power curve produced from simulations. As this is an area where significant energy production occurs the difference in the steady and dynamic power curves can lead to large differences in the predicted annual energy yield. The use of a dynamic power curve ensures that the dependency of power on the range of incident flow conditions, control strategy and rotor design are fully captured.

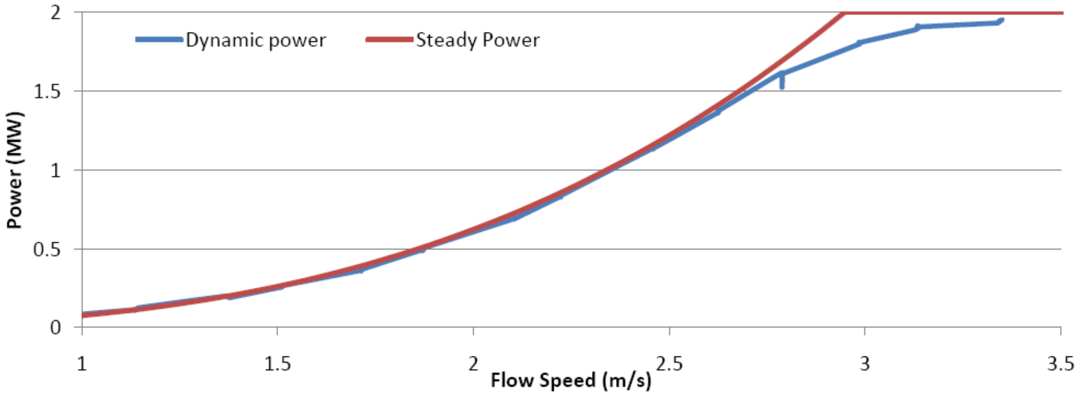

Figure 2-7 Steady and dynamic power curve for a pitch regulated rotor. Reproduced from Franks (2010).

3 STANDARD GUIDELINES FOR THE PERFORMANCE ASSESSMENT

There are several different fundamental device concept (FDC) categories that can be identified from the full range of devices currently being developed (see WG0D2 for more detail on the various categories); however even within the FDC categories, the method of power regulation, and hence key device characteristics, are likely to vary. In order that the performance of the different tidal energy devices can be assessed using a consistent and relevant set of criteria, various guidelines have been drawn up in recent years which attempt to provide clear methodologies for the assessment procedure and protocols for ensuring data quality. The normative reference for these documents is the international standard IEC 61400-12-1 (2005), on power performance measurements of electricity producing wind turbines.

The tidal turbine industry has not yet reached the stage of commercial maturity demanding of a finalised international standard, although one is currently under development and should become available by 2013. In the absence of an international standard, an initial protocol document (University of Edinburgh, 2007) was commissioned by the DTI in advance of the selection process for the Marine Renewables Deployment Fund (MRDF). More recently, EMEC (2009a) were commissioned by BERR to produce a guideline on the same subject as part of their marine renewable energy guide series. An assessment of the levels of uncertainty in each part of the assessment process and rigorous documentation detailing the conditions under which the power curve was measured is a suggested requirement in all of the aforementioned guidelines.

The current industry standard tools for predicting the energy yield of arrays in the wind energy industry (such as GH WindFarmer) also require a description of the device to be placed within the array under consideration. A typical input description of the device takes the form of a measured power curve, as in Figure 2.4. Such curves, which are warranted by the turbine manufacturer, have usually been measured according to the international standards, such as IEC 61400-12-1 (2005).

In order to calculate the expected annual energy production (AEP) for a single device an assessment of the resource at the proposed site is required. There is a separate set of guidelines for assessing the resource e.g. EMEC (2009b). The guidelines require that the resource assessment is conducted by using a minimum period acoustic Doppler measurement campaign and a robust harmonic analysis procedure. A frequency distribution of velocity at the site over the duration of one year is an output from the resource assessment. This is combined with the power curve to calculate the AEP.

4 REVIEW OF EXISTING APPROACHES TO DEVICE SCALE MODELLING

This section describes methods for evaluating the power output of a device and the resulting impact the device has on the surrounding flow field. A comprehensive review of the established modelling methodologies for modelling blockage and near wake effects on tidal turbines was provided in WG3WP4D1 and WG3WP4D2, however a brief overview of the existing modelling methods is provided here in relation to power production and impact on the local flow field.

4.1 Modelling methodologies

Actuator disc theory is based on the assumption that an ideal fluid and can be used to correlate the power and thrust of a turbine to the incident upstream flow speed, provided a description of the rotor performance is provided (C_P and C_T). This 1-d analysis provides a limited prediction of the change in local flow conditions and so corrections to account for blockage are also limited.

Blade element momentum theory can be used to evaluate the unsteady power output and corresponding rotor forces for a given time varying input flow field. However, it does not solve the flow domain and thus can not be used to directly predict the changes in performance due to bounding surface and /or other rotors.

3-d Potential flow methods idealise the fluid to allow analytical solutions of the flow field around a body (such as a turbine) to be found. Vortex methods can also be used to both evaluate the performance of rotors operating in a boundless flow (force, torque and power are determined by the Kutta-Joukowski law and local circulations) and evaluate the impact on the device on the local flow field.

CFD numerically solves either simplified or the full Navier-Stokes (NS) equations. Solving the non-linear Partial Differential Equations (PDE's) allows greater complexity to be introduced into the incident flow field and interaction with the rotor. Thus CFD can be used to produce power production and rotor forces as well as solving the local flow field domain.

The advantages and disadvantages of all above approaches are summarised in the Table 1.

Table 1 Comparison of device scale modelling methods

Existing model	Advantage	Disadvantage
Actuator disc theory	Simple proven method.	Rotor characteristics (C_P and C_T) must be pre-defined. Provides no information on the flow acceleration outside of the streamtube.
Blade element momentum (BEM) theory	Relatively simple model. Proven method to predict rotor performance. Can be coupled to models which simulate the incident flow field. Can be easily coupled to the equations of motion for the whole turbine system, leading to a model which can incorporate non-linear power take-off and dynamic effects (e.g. GH Tidal Bladed).	Does not predict the impact on the flow field outside of the streamtube.
3-d Potential flow methods	Proven method in the wind industry. Models predict the rotor performance and the impact on the local flow field.	Not insignificant computational effort. Require corrections for the prediction of viscous effects. No standard model capable of incorporating non-linear power take-off dynamics utilises this hydrodynamic modelling approach.
Computational Fluid Dynamics (RANS)	Solves the whole fluid domain. Incorporates detailed 3-d flow effects.	Very sensitive to set-up (selection of most appropriate turbulence model etc.). Models require device specific calibration. Prohibitively computationally expensive when looking to evaluate a dynamic power curve. A lack of reliable turbulence models is also a factor preventing their use for full design purposes. No standard model capable of incorporating non-linear power take-off utilises this hydrodynamic modelling approach.

Only the last two modelling methods listed in the table above are capable of predicting change to the local flow field due to the presence of a device (alternative approaches to modelling the local flow field were reviewed in WG3WP4D1 and WG3WP4D2). The latter three modelling methods listed above are all capable of producing simulated mean power and thrust outputs for a given flow field simulation. However, as discussed in Section 2.2, in order to capture all of the non-linear relationships which exist due to complexities inherent in both the turbine configuration and onset flow conditions dynamic curves are required.

Figure 2.7 presented a dynamic power curve, which is the mean power output from multiple time domain simulations using GH Tidal Bladed in which the onset flow conditions covered range of flow speeds experienced by the rotor during its lifetime. The hydrodynamics in GH Tidal Bladed are computed using a BEM method. However despite these sophisticated methods employed to evaluate device performance, as discussed in Section 3, the complexities of fully representing a real device over all operating scenarios has led to many project developers and investors of wind farm projects to require turbine manufacturers to supply a measured power curve for the energy yield analysis. Typically the power curve is evaluated and or checked by an independent third party to provide even more confidence in the power performance characterisation. The regulatory documents referenced in Section 3 suggest that a power curve is produced from measurements of both the resource (current speed) and power output at the test site for a period sufficiently long to establish a statistically stable dataset. As discussed in Section 2.2, this approach ensures that any unsteady effects which do not average out are captured in the power curve.

It is more difficult to obtain an accurate measure of the thrust on a full scale device than its power production, since an elaborate deployment of strain gauges would be required. A thrust curve is required for the resource analysis to simulate the impact of the device on resource. In the wind industry, a certified tool such as GH Bladed is usually deemed sufficient for generating the dynamic thrust curve.

4.2 Application to ducted and open-centre rotors

Within the PerAWaT project three fundamental rotor configurations have been selected for analysis:

- Three bladed horizontal axis axial flow turbine (three bladed turbine)
- Ducted horizontal axis axial flow turbine (ducted turbine)
- Open-centre horizontal axis axial flow turbine (open-centre turbine)

The parametric descriptions provided in Section 2 are directly applicable to all three concepts. However, alternative modelling methods to evaluate the power and thrust curves might be device specific. For example the OpenHydro blade design is significantly different to Clean Current's because the OpenHydro design is a reaction turbine, whereas Clean Current utilise a lifting mechanism. Both are open-centre devices, but it is the blade design which governs the modelling method.

The differences in terms of near wake modelling are discussed in WG3WP4D2.

4.3 Definition of incident flow field

As discussed in Section 2.2, the velocity profile of the current incident on a tidal energy device at any given time is dependent on various different parameters, which include:

- the natural shear layer that is present in a tidal column
- unsteady effects such as waves and turbulence

- local blockage effects due to both constraining surfaces (e.g. the seabed and sea surface) and any neighbouring turbines within close proximity within an array
- the position of the device relative to any upstream interferences, such as the wake of another device.

In order to produce a power or thrust curve it is necessary to evaluate a flow speed which is representative of the entire flow incident on the device and there are various different methods of doing this. Regardless of whether the incident flow field is to be measured or modelled, a single incident flow speed is required for the purpose of parameterisation.

The EMEC (2009a) guideline (which focuses on measured power curves) suggests that the measured flow speed velocity profile is binned by height and integrated according to the corresponding width of the height bin. This provides one flow speed which is representative of the incident velocity distribution.

For the case of a measured power and thrust curve, the state-of-the-art method of measuring the current incident on a device is with a bottom mounted acoustic Doppler device. Such devices used multiple acoustic beams to measure the components of velocity at varying heights. The beams have to be set at an angle to one another as they cannot interfere resulting in averaged (rather than instantaneous) measurements of flow speed at varying height, however it is possible to measure the velocity with sufficient resolution to measure the ambient turbulence intensity, as a means of characterising the incident flow field. Note that the flow speed decreases as it approaches the rotor and thus measurements must not be taken too close to the rotor, but sufficiently close to be correlated to the resulting power output.

For the cases where only simulated power and thrust curve are available, appropriate flow models must be adopted to simulate the relevant range of input conditions. The modelled input flow field can then be considered similar to a measured flow field and can be processed to yield a rotor averaged incident flow speed.

4.4 Time-domain simulation vs. “binning” the tidal cycle

The driving force behind tidal flows is due to differential gravitational forces which are periodic in nature. Harmonic analysis for the prediction of tidal elevation and currents is a well established science, as described by Boon (2007) It assumes that tidal motion can be represented by the sum of a series of simple harmonic terms (tidal constituents) with each term being represented by an oscillation at a known frequency of astronomical origin. This phenomenon enables the prediction of tidal flow speed variations in to the future.

The ability to model future tidal flows using harmonic prediction can be utilised to evaluate the future energy yield of a proposed project with a known operational duration. However, this approach will not take into account all the additional effects such as metrological forcing or unsteady phenomena which affect the incident flow conditions.

The behaviour of long term wind and wave fields are not predictable in the same way as for tidal cycles and in order to model a representative range of wind, wave, turbulence and current conditions a full time-domain simulation with excessive computation requirement would be necessary. The method of bins is a data reduction procedure that groups test data for a certain parameter into subsets typified by an independent underlying variable or variables. Such a “binning” method reduces a full simulation of the complete tidal cycle to a number of flow states simulations. The method is widely adopted in the wind industry, where there are many different incident flow directions and velocity distributions possible and the and the method is recommended in IEC-61400-12-1 (2005).

The EMEC (2009a) guideline suggests the measurements of power are grouped by flow speed bin increments of 0.1m/s. Ideally a corresponding measured power curve is constructed from the mean value of power per flow speed bin. Figure 2.6 provides an example of the mean values of power evaluated from the raw measured power data.

For each defined "flow state" a parametric model which adequately describes the power output for a given flow state (i.e. a dynamic power curve) is used to represent the device performance, thus reducing the need for any unsteady flow modelling. This allows the tidal cycle to be represented as a number of discrete flow states. For each flow state the local operating conditions for each device location is found and coupled with input device characteristics to evaluate a mean power output. An energy calculation then combines mean power at each flow state with occurrence distribution of that flow state, resulting in the expected energy yield. The total array energy extraction is a sum of all the individual devices and can be described by the equation below:

$$\text{Total array energy yield} = \sum_{Nk}\sum_{Nj}\sum_{Ni} P^{i}_{jk}.O_{jk}$$

Where:

- P is the mean power output and O is the percentage of occurrence;
- i is the turbine index which provides a reference number of the turbine in the array, and Ni is the total number of turbines in the array;
- j is the flow speed index related to the speed bin (e.g. 1.9-2.1m/s) under consideration, and Nj is the total number of flow speeds in the long term flow speed distribution for each flow direction; and,
- k is the index for flow direction, with Nk being the total number of flow speed directions. A typical tidal stream site has only two directions, but a complex site may have more and this is particularly important for the analysis of non-yawing devices.

The Figure 4.1 below illustrates the variability in the flow speed occurrence when different data sets and predictions are used. A key aspect of the GH TidalFarmer approach is to better quantify the uncertainties associated with device scale modelling (see Section 7).

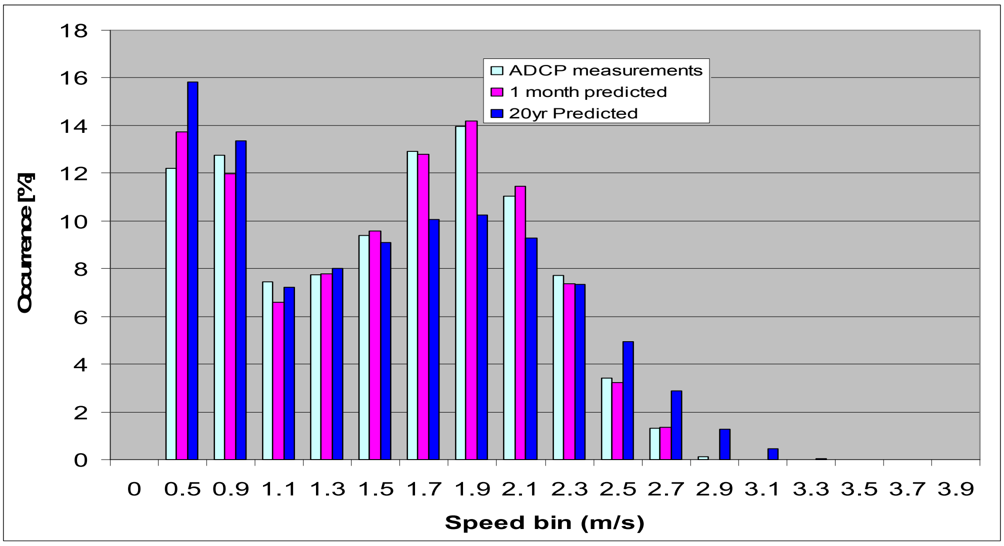

Figure 4-1 Example of flow speed distributions

5 GH APPROACH TO DEVICE SCALE MODELLING

The GH approach to energy yield prediction is to use the method of bins as described in Section 4.4. The impact of adopting this approach means that the device scale modelling is simplified to a quasi-steady analysis.

The aim of device scale modelling in the context of an energy yield assessment is to:

- evaluate the power production of an individual device; and
- predict the change in local flow field conditions due to the energy extraction process

Section 5.1 defines the GH Turbine model which is adopted to characterise a tidal energy device and Section 5.2 outlines how the GH Turbine model is integrated with the other device scale models.

5.1 GH Turbine model

5.1.1 Parametric description

As outlined in the Sections 2&3 above the standard method to describe a tidal energy device is in the form of a power curve and thrust curve. The issues of unsteady effects can be addressed with the use of dynamic curves. Where power and thrust are simplified to:

$$\mathrm{P}(U(x,y,z,t),Cp,\eta) \Rightarrow \mathrm{P}(U_{j,k})$$

$$\mathrm{T}(U(x,y,z,t),Cp) \Rightarrow \mathrm{T}(U_{j,k})$$

Where,

- P is the mean power output, T is the rotor thrust and *U* is the flow speed incident on the rotor.
- *j* is the flow speed index and *k* is the index for flow direction.,

As described in Section 4 the preference of project developers in the wind industry is to use measured power and thrust curve to characterise a device. The intention of GH TidalFarmer is to similarly use a supplied power and thrust curve as presented in Section 2.1, which has been measured/certified by independent 3rd parties. Before the international standard for power prediction of tidal turbines becomes available, a combination of the existing guidelines (EMEC (2009a) and those written by University of Edinburgh (2007) for the MRPF) will be used for the generation of the power curve. Documentation detailing both the device configuration and metocean conditions during the measurement period will be requested to accompany any measured power curve. The intention is that any local effects which impact on the site specific measurement of power and thrust are removed, leaving the boundless turbine characteristics.

However because the tidal energy industry is only in the early stages of development, there are less than a handful of (full-scale) devices installed from which a measurement of power output has actually be obtained. Within the duration of the PerAWaT project, an occasion may arise where an energy yield calculation is attempted for an array of device for which a measured power curve is unavailable. For the purposes of PerAWaT, a dynamic power curve will be constructed from time-domain simulations using GH Tidal Bladed. Although complex CFD models could also be used to establish rotor power and thrust curves they do not typically incorporate the complex non-linear drive train and control system behaviour and losses which impact on the conversion of rotor power to electrical power.

Similarly for a ducted or open-centre device it is the intention that representative power and thrust curves are supplied by the device manufacturer. For the purpose of the PerAWaT project GH is engaging with device developers to access such data. However, if such data are not forthcoming, then GH would employ in-house models to develop power and thrust curves for generic open-centre and/or ducted devices.

5.1.2 Evaluation of the incident velocity

GH TidalFarmer utilises an inter-array flow model to determine the incident flow speeds at each device location within a tidal farm. Changes in flow velocity arise from two sources: local bathymetry changes; and changes due to the extraction of energy by surrounding/upstream devices.

The focus of the rationalised flow field modelling report (WG3WP4D4) and the inter-array flow field report (WG3WP4D6) will be to discuss the development of a spatial flow field for use in the energy yield analysis. The intention here is to highlight the requirements for the array scale flow modelling needed to feed the device scale modelling. Because the relationship between flow speed and power output is typically cubic in the below rated flow speed region there is a need to ensure that the prediction of the incident flow speed is accurate to avoid the magnification of errors when calculating power output.

As discussed in Section 2.2 there are time varying fluctuations in the incident flow as well as spatial variations. The parametric description which correlates device power output and incident flow speed needs to be account for both of these effects. The assumption is that the time varying effects average out, however, variations in flow speed over the rotor swept area will impact on the mean power and thrust experienced by the rotor. As such it is important to predict velocity variations over the rotor swept area. Modelling the flow shear profile will be important because the rotor may take up a significant proportion of the water column and hence experience a non-linear variation in flow speed between the top and bottom of the rotor.

Another consideration of the spatial flow field modelling is the grid resolution. A horizontal grid resolution no more than the rotor radius is considered necessary to avoid excessive interpolation.

5.2 Turbine model integration

The GH turbine model utilises an evaluated incident flow speed and power curve to calculate the mean power output for each turbine at each flow state. This model does not predict the change in power output due to blockage effects and thus a subsequent calculation is required to evaluate any change in device performance due to blockage. The turbine model also does not make any prediction of the impact of the energy extraction process on the local flow field. The GH Blockage model is use to predict changes in device performance and any changes to the local flow due to blockage. The GH near wake model is used predict the shape of the initial velocity deficit just behind the device (subsequent wake modelling will be addressed in WG3WP4D5).

6 INTEGRATION AND IMPLEMENTATION DEVICE SCALE MODELS WITHIN GH TIDALFARMER

This section describes how GH device scale modelling is incorporated into the GH TidalFarmer software tool.

6.1 Description of GH TidalFarmer

The purpose of the GH TidalFarmer design tool is to provide the industry with a comprehensive and definitive tool that can optimise energy capture of tidal stream turbine arrays. To assess and optimise the energy capture of an array at a specific site four distinct steps are required:

1. Site specific tidal flow field prediction
2. Array influenced flow field prediction
3. Energy calculation for the life time of the project
4. Energy optimisation by altering array layout

To assess the energy capture capability of a specific site the tool shall be required to evaluate the flow field within and around the array and incorporate the effect turbines have on each other and on the flow.

6.2 An overview of the GH TidalFarmer approach

The overall concept of the GH TidalFarmer modelling method is to reduce the extremely complex interactions between tidal turbines and the surrounding flow field into a series of distinct physical processes which can be simplified and modelled.

The underlying analysis simplifies the physical processes under investigation via the selection of an appropriate scale. The three appropriate scales of interest here are: Coastal basin, Array and Device scale.

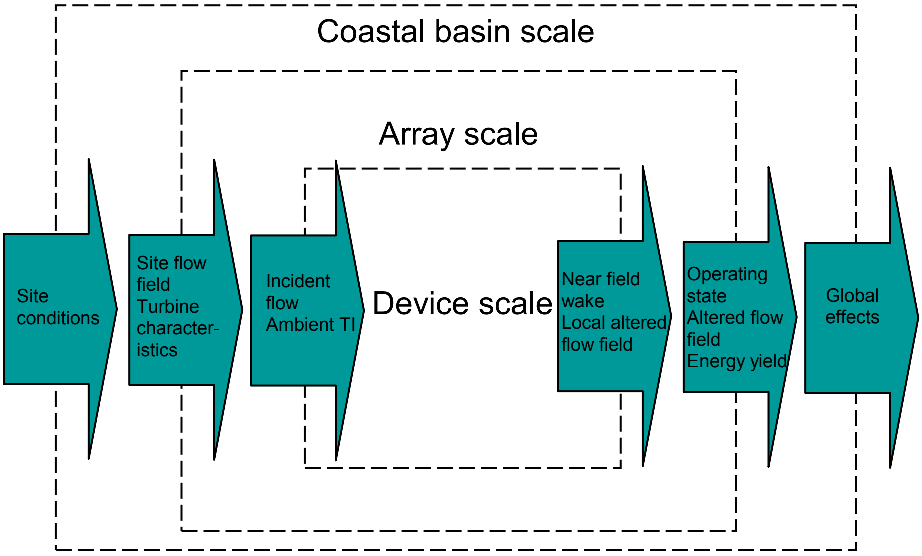

Figure 6-1: Hierarchy of modelling domains and scales

One of the aims of the PerAWaT project is to provide validation data to support the use of appropriate parametric descriptions of the energy extraction process. The methods used to provide this data involve both numerical and experimental modelling. The numerical modelling approach begins with the detailed modelling of a device in order to develop/validate the device scale representation for use in the array scale modelling. The array scale modelling then utilises a parametric description of individual devices operating in an array which then provides a further parameterisation for use in the coastal basin modelling in order to determine how arrays of devices might impact on the global flow field. The experimental work packages support the validation of the numerical models at each model scale. In addition they provide the ability to supply more numerous investigations into inter-array effects. This multi-scale and multi-method approach is required to yield greater understanding and to better define the limitations of rationalised models.

To develop an appropriate design tool, rationalised modelling methods based on physical understanding of the Navier-Stokes (NS) equations that provide robust estimates with known uncertainties are preferred to more complex (and computationally intensive) numerical methods (generally referred to as Computational Fluid Dynamics (CFD) models i.e. numerical solvers of the 3-d NS equation). The tool GH TidalFarmer uses a collection of models to undertake an energy resource analysis and layout optimisation of a proposed tidal stream farm. The present form of the code undertakes the inter-array flow modelling and energy prediction calculation and optimisation. It does not contain a flow solver for the basin scale tidal flow modelling and it currently uses inputs from existing shallow water numerical solvers to provide the required 2-d flow field. Code developments under PerAWaT will develop the interface with shallow water flow solvers to provide an integrated link (allowing for multiple existing codes to be used) and then undertake the required analysis to convert these typically time-domain models in to spatial flow fields for each flow state. The flow field modelling requirements and approaches for GH TidalFarmer will be discussed in more detail in WG3WP4D4.

The current approach which loosely couples the flow field solver and the inter-array modelling such that perturbation caused by the devices within the array on the global flow field is not fed back into the global flow field model. This approach requires that the order of magnitude of the perturbations is small compared to the driving head. Figure 6.2 provides some results of simplified, but realistic, scenarios using the blockage correction developed by Whelan (2009). The model presented by Whelan is a 1-d analytical solution for an infinite array. The figure presents the percentage reduction in downstream free surface elevation as a function of blockage ratio for a representative Froude number ($Fr = 0.123$), where

$$Fr = \frac{U}{\sqrt{gz}}$$

is the Froude number based on the upstream depth z (e.g. if $U = 2.5$m/s, $z = 42$m). The results also model the turbines to be operating at peak C_P. Assuming a rotor diameter of 18m, a water depth of 42m and a lateral spacing of 2D yields a blockage ratio of 17%. The model predicts an increase in power of 30% at this blockage ratio, however as shown in Figure 6.2 the downstream elevation is predicted to decrease by only 0.3% (NB. the percentage decrease in elevation is also analogous to the percentage reduction in downstream flow speed). Thus this initial analysis predicts that the downstream impact of an infinite row of turbines at a lateral spacing of two rotor diameters to be small and hence confirms that the assumption made by GH TidalFarmer (i.e. that the order of magnitude of flow perturbation is small compared to the driving head) is reasonable.

The previous example does not address the possibility of upstream flow diversion away from the array and in situations where, for example an array is situated between an island and the main land, the upstream effect of the array should be considered. Although the current code can predict the extent of the upstream increase in dynamic pressure, it cannot predict the effect of an array on the basin scale flow. Although detailed analysis of the effect of an array on the global flow field will be required when arrays sizes are very large, the starting point for the Beta 1 tool is to undertake an energy yield analysis upon an array where it has been shown that the array, operating at rated power, will not divert the flow and hence reduce energy yield potential of the array. Without specialised computing power this type of analysis can only be done at the basin scale using a parametric description of an array. Typically modelling at the basin scale will be done at grid resolution much coarser than that required to sufficiently evaluate the incident flow on to individual devices (especially if the model is limited to 2-d). It is a central aspect of the Tidal Farmer code to evaluate the incident flow on to each device in order to undertake power predictions and wake modelling. The coupling between flow speed and power output is typically cubic for pre-rated operation and hence there is a need to ensure that the prediction of the incident flow speeds are sufficiently accurate to avoid potentially large errors.

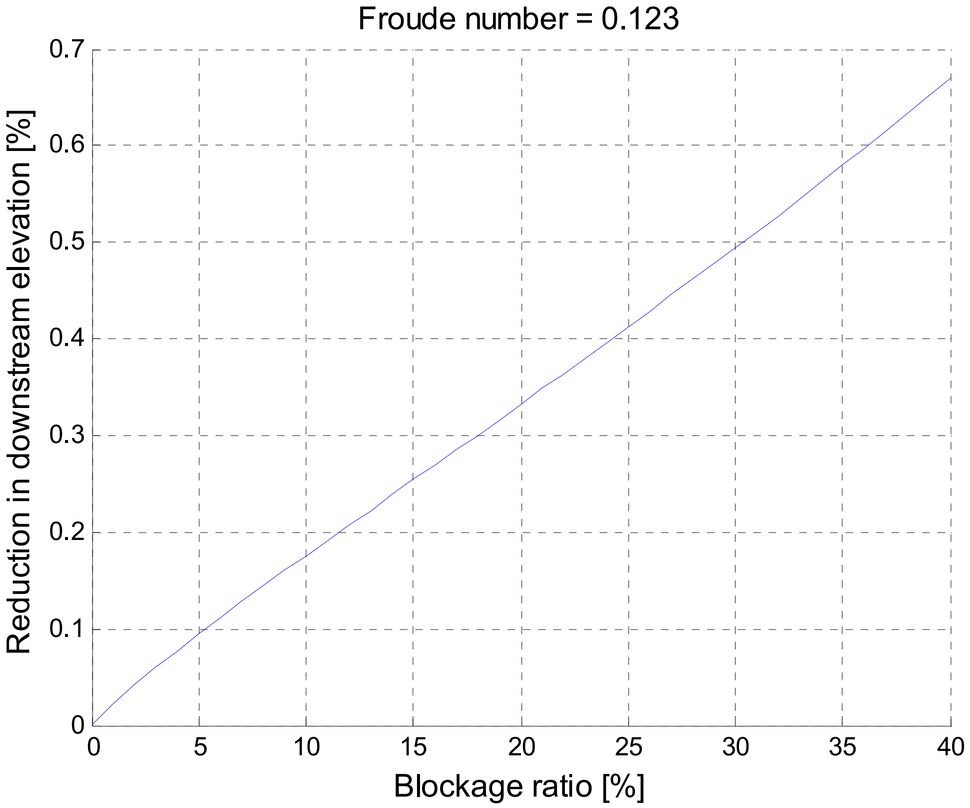

Figure 6-2 Example the global effect on idealised array layouts

The present conceptual layout of GH TidalFarmer is outlined in Figure 6.3. In the context of the four key aspects of an energy yield and optimisation tool, GH Tidal Farmer undertakes analysis at each step:

1. **Site specific tidal flow field prediction**

As stated above the current code does not include a shallow water flow solver and thus requires the input from an existing solver. To provide a reasonable model of the spatial flow field across a site the model needs to incorporate a basin scale domain. Modelling a large domain in 3-d is computationally prohibitive and so typically 2-d models are used. There are numerous models set-up for the sites like the Pentland Firth. And usually these models are tuned to fit the available site data. Assimilation methods can be employed to iterate the flow solver to fit all of the available site data, but typically the models produce 2-d flow fields which are in a mean sense correct. GH has developed code which post processes flow solver results coupled with all available site data to correct the flow field and also extrapolate it in the depth domain (if the input data is not from a 3-d model).

GH Tides is the name given to the code that has been developed to post-process ADCP site data and produce a long term prediction of the flow at reference locations across the site.

Coupling the long term distribution of flow speed occurrence with the spatial flow maps provides the required description of the specific tidal flow conditions at the site of interest.

2. Array influenced flow field prediction

The array influenced flow field prediction incorporates changes to the local operating conditions of the flow field incident on a device. Changes to the flow field include:

- changes in the local flow field due to blockage;
- changes in the flow field due to the wake of upstream devices; and,
- changes in the ambient turbulence intensity due to upstream devices.

Device scale modelling is central to the evaluating the array influenced flow field. Both the local blockage modelling and the initiation of the wake modelling are evaluated as part of device scale modelling.

3. Energy calculation for the life time of the project

The energy yield calculation uses the mean power prediction for each device at each flow state coupled with a long term distribution of flow speeds (at a reference location) to calculate a mean annual energy yield representative of the project lifetime.

In analysing the array energy yield production several energy calculations are performed to allow assessment of the efficiency of the proposed array layout design and to thus aid layout optimisation. These are:

A. Basic model: All devices experience the same flow regime as at the reference location, at the hub height, without any allowance for losses. .

B. All turbines with the bathymetry induced local speed changes.

C. All turbines experiencing the same flow regime as at the reference location, at the reference height, including calculation of wake losses.

D. All turbines with the bathymetry induced local speed changes, calculation of wake losses, and local blockage effects modelled.

To indicate the performance of the array layout the following efficiencies are evaluated:

- Spatial efficiency = Calculation B / Calculation A
- Wake efficiency = Calculation C / Calculation B
- Blockage efficiency = Calculation D / Calculation C
- Array efficiency = Calculation D / Calculation B

The program calculates the net energy output, array and bathymetry efficiency for each individual turbine and the tidal farm as a whole. To calculate the net energy production of each tidal turbine calculation C or D is required. Calculations A and B are used to estimate the wake and bathymetry effects experienced by each turbine.

4. Energy optimisation by altering array layout

The present GH optimiser is based on a hill-climbing algorithm. This approach is also applicable to tidal turbine array layouts.

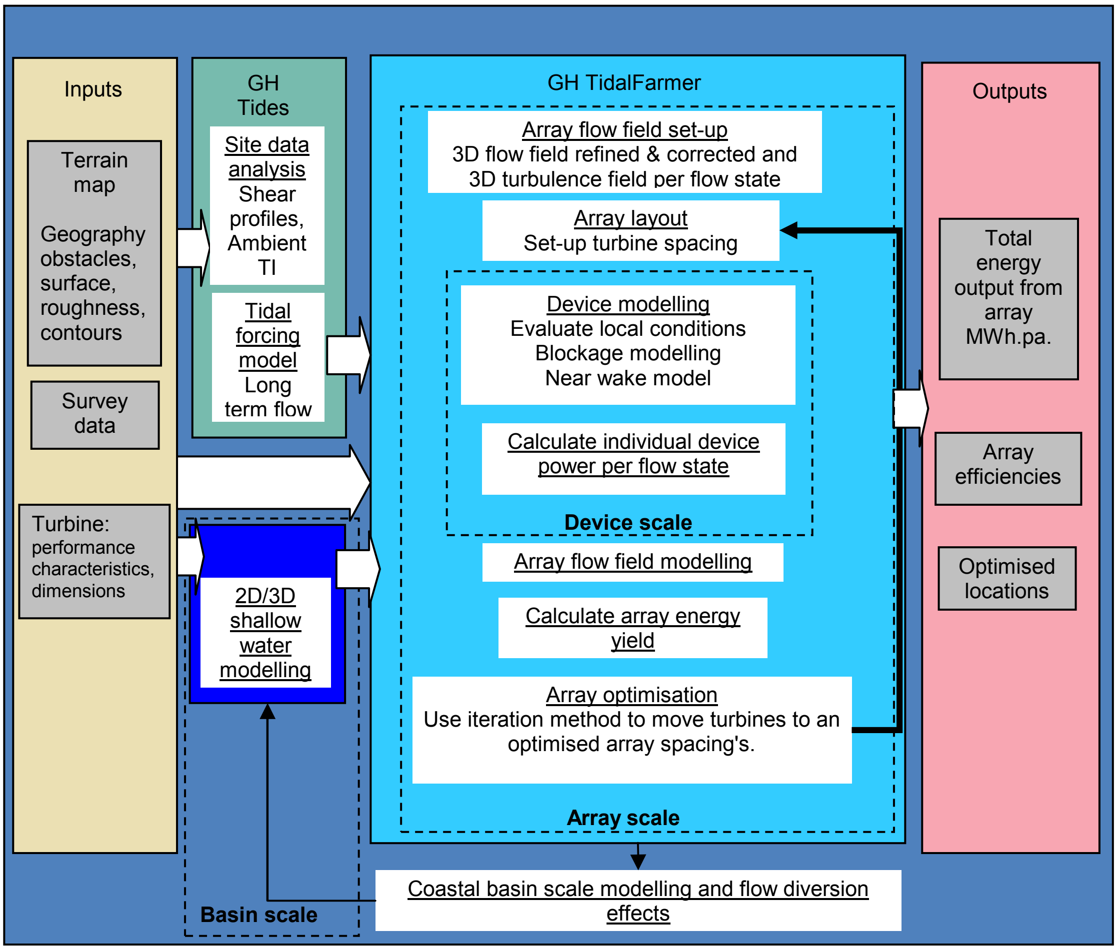

Figure 6-3: Overview of GH TidalFarmer software architecture and device scale models

Device scale modelling is at the heart of the GH Tidal Farmer code because it yields the prediction of power output for each flow state analysed. As discussed in Section 4.4, the method of binning allows each distinct flow state to be analysed separately hence removing the need for an unsteady time domain analysis. Device scale modelling incorporates several mathematical models that collectively allow a mean power prediction for each device during each flow state. The Figure 6.3 shows how the GH device scale modelling sits within the GH TIdalFarmer code. Figure 6.4 shows the different aspects of the GH device scale models.

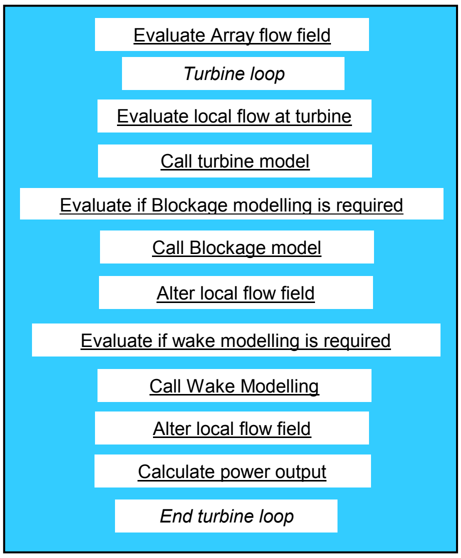

Figure 6-4: Overview of GH Device scale modelling

6.3 Device scaling modelling inputs

As stated previously the purpose of the GH device scale modelling is to:

- evaluate the power production of an individual device; and
- predict the change in local flow field conditions due to the energy extraction process

As described in Section 5 the GH approach is to employ dynamic power and thrust curves (and preferably a measured power curve) coupled with the local operating conditions at each device location.

The inputs to the GH TidalFarmer tool consist of:

- Turbine characterises including a power curve (and the corresponding ambient turbulence level), and thrust curve. In addition the rotor diameter and hub height dimensions are also required.
- Site flow field maps (typically a 2-d flow field will be provided).
- A long term flow state occurrence distribution at specified location(s)
- Site bathymetry
- A description of the roughness variations across the site
- A definition of any site constraints.

Within the TidalFarmer code the following inputs are evaluated:

- A local 3-d flow field per flow state
- A local 3-d ambient turbulence intensity field per flow state
- The local depth and the proximity to extrusive slopes etc.
- The boundless rotor performance characteristics Cp and Ct are derives from the measured power and thrust curve.
- The proximity of the sea-bed and free surface to the rotor
- The proximity of near field objects, such as adjacent turbines and channel walls
- The required accuracy for the calculation (i.e. set the grid size and modelling method) based on the iteration point in the optimisation loop.

6.4 Device scale modelling procedures

The main steps within the device scale modelling code include:

For each turbine

- Evaluate the incident flow field normal to rotor
- Calculate the root-mean-cubed incident flow speed over the rotor swept area
- Calculate the incident ambient turbulence intensity over the rotor swept area
- Evaluate the operating Cp and Ct
- Calculate the mean power output for the given incident flow speed

For each turbine group

- Call blockage performance modelling (GH Blockage modelling)
    - Evaluation of the local blockage effects, including local depth and any near by channel walls and position of surrounding local turbines
    - Set up model
    - Calculate changes in performance (altered Cp and Ct)
- Call blockage flow field modelling (GH Blockage modelling)
    - Use blockage performance model set-up using altered Cp and Ct
    - Calculate changes to local flow field

For each turbine requiring wake modelling

- Call wake set-up model (GH Near Wake modelling)
    - Calculate the centreline deficit
    - Evaluate available surrounding momentum
    - Correct for surrounding momentum
    - Evaluate the wake width
    - Evaluate the velocity deficit Gaussian profile

Further details on both the Blockage and near wake modelling can be found in the WG3WP4D1 and WG3WP4D2.

The resulting output from the device scale modelling is the mean power output for each turbine for each flow state, as well as any alterations for the inter-array flow field.

Figure 6.5 illustrates the device scale modelling process.

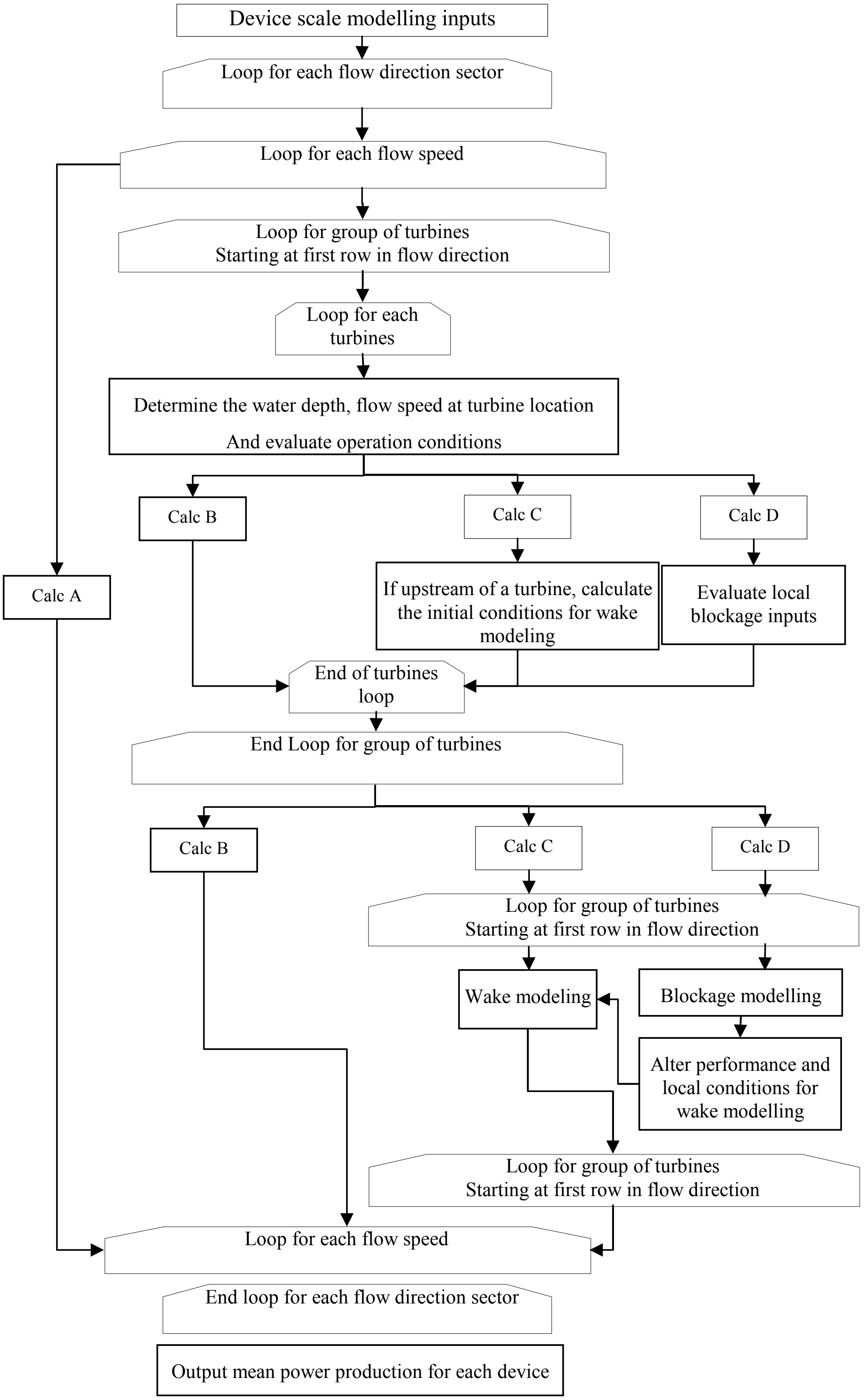

Figure 6-5 Flow diagram of the GH Device scale modelling

6.5 Implementation

The GH TidalFarmer Base Module shown in Figure 6.6 represents the code architecture which will be developed under the PerAWaT project, i.e. the “Beta 1” and “Beta 2” deliverables.

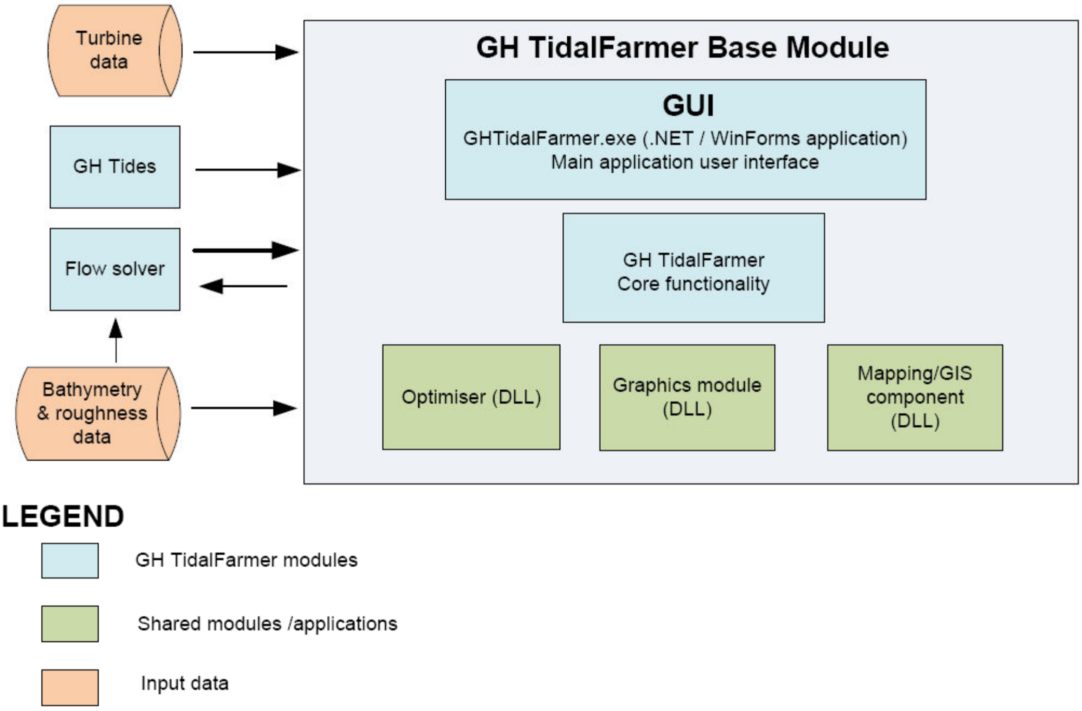

Figure 6-6 Summary of the GH TidalFarmer envisaged structure

The GH TidalFarmer software tool will consist of a single executable file (including a user interface) with which the user will interact, as well as a number of calculation modules which will be implemented as dynamic-link libraries (DLLs). Tidal calculations will be controlled and coordinated by a top-level “core functionality” module. The GH device scale modelling forms a significant part of the core functionality module, because it is at the centre of the main energy yield calculation within GH TidalFarmer.

Choosing the most appropriate programming language depends on the method of investigation and how the results will be analysed. Currently the code is written as a Matlab script, which allows for easy interrogation and analysis.

The user interface is likely to be written in a .NET language such as C#, while the modules which do the actual calculations will either remain in Matlab or migrate to another language, such as Fortran or C++. For the Beta releases a generic basic user interface will be provided to allow the user to input key data and query the calculation outputs.

The diagram below illustrates the present structure of the device scale modelling aspect of the GH TidalFarmer code. Tables 6.1 and 6.2 provide a functional description of the GH device scale modelling.

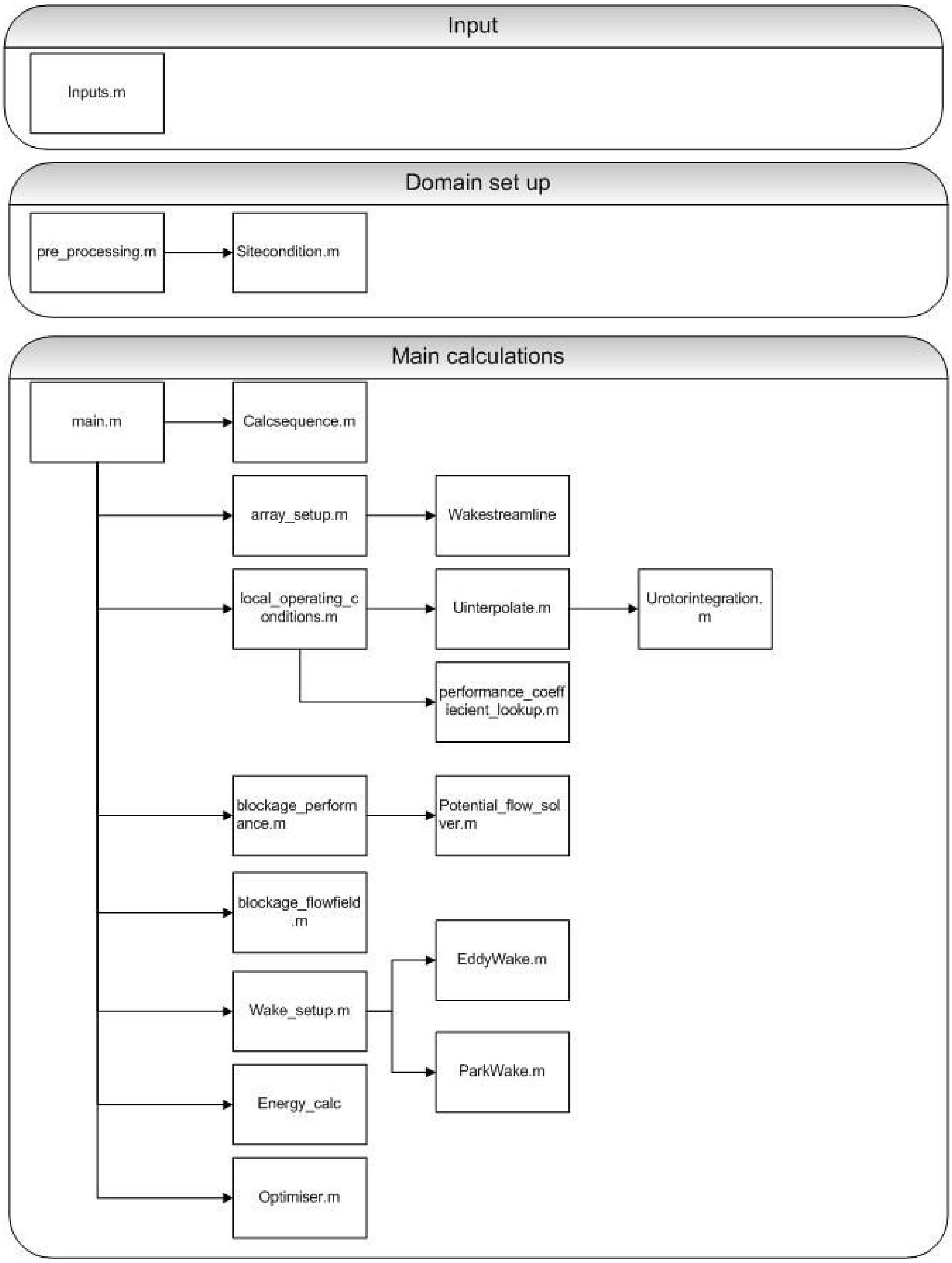

Figure 6-7 Current GH TidalFarmer (MATLAB) code

Table 6.1 Summary functional description

Model	Inputs	Outputs	Method used
Turbine model	Power and thrust curve	Power output for each flow state (speed and direction). Cp and Ct per device per flow state.	Look up table
Blockage model	Incident 3-d flow field Boundless turbine characteristics (Cp_b, Ct_b) Turbine locations	Altered turbine performance characteristics (Cp, Ct)	Blockage performance model
		Altered 3-d flow field around turbine.	Blockage flow field model
Near wake model	Turbine Ct Incident rotor averaged flow speed Ambient turbulence intensity	3-d wake velocity deficit profile	Near wake model

Table 6.2 Detailed functional description of the device scale modelling

Matlab file reference	Task	Input	Output	Method
	device modelling			
local_operating_conditions.m	Evaluate local conditions	3-d flow (u & v), & TI field, device hh, device dia.	flow field in area of device	Indexing of 3D flow field
	Find local devices	domain range and device positions	index of nearest devices	Logical indexing to find nearest devices
Uinterpolate.m	Interpolate flow field on to rotor plane	flow field in area of device	flow field in rotor plane TI field in rotor plane	Interpolates flow field and TI field on to rotor plane
Urotorintegration.m	Evaluate U, and surrounding momentum	flow & TI field on rotor plane, rotor area	incident flow speed (U), equivalent surrounding momentum (Urms)	Area integration of incident flow field (and surrounding flow field)
local_operating_conditions.m	Calculate power and Cp&Ct	incident flow speed	power and Cp&Ct	Look up device characteristics against incident flow speed.
	Blockage performance modelling			
blockage_performance.m	Select local device groups for blockage modelling	device locations, Flow direction,	Selected device group (device locations)	Proximity algorithm.
(Calcsequence.m)	Evaluate group sequence	Criteria for proximity (radial distance apart)		
blockage_performance.m	For device group:	Selected device group (device locations)	For each selected device:	Lookup algorithm
	Get local device conditions		device locations	
	Evaluate effective distances to boundaries		Local geography:	
			Water depth, distance to channel walls, hub height.	
			Operating condition:	
			Uo, Cpb, Ctb.	
	Set up devices in potential model	For each selected device:	Model set-up	Using equations 4.1 to 4.3 (WG3WP4D1) to set model parameters.
		device locations		
		Local geography:		
		Water depth, distance to channel walls, hub height.		
		Operating condition:		
		Uo, Cpb, Ctb.		

Matlab file reference	Task	Input	Output	Method
	Set up domain (for required accuracy)	Point in optimisation loop.	Domain on which to solve the model defined	Matrix set-up algorithm
		Predefined settings.		
	Loop for each device in group			
	Evaluate flow field and altered conditions	Model set-up	Flow field solution	Solve equation 4.4 (WG3WP4D1) on model domain
			Calculated change in rotor performance	Use equation 4.5 (WG3WP4D1) to establish new rotor resistance
	Evaluate error from boundless conditions	Model set-up (no boundaries included)	Model Error	Solve simplified equation 4.4 (WG3WP4D1) .
		Operating condition:		Actuator disc theory
		Uo, Cpb, Ctb.		
	End loop for each device in group			
	Evaluate average error			
	Iterate until error within tolerance	Collective resistance error	Iteration requirement	Comparison algorithm
	Change operation point	Individual resistance error	Altered model inputs for next iteration.	Iteration algorithm
	Feed back bounded Cp, Ct		Altered rotor performance	
	Blockage flow field modelling			
blockage_flowfield.m	For device group:	Selected device group (device locations)	For each selected device:	Lookup algorithm
(Calcsequence.m)	Get local device conditions		device locations	
blockage_flowfield.m	Evaluate effective distances to boundaries		Local geography:	
			Water depth, distance to channel walls, hub height.	
			Operating condition:	
			Uo, Cpb, Ctb.	
	Set up devices in potential model	For each selected device:	Model set-up	Using equations 4.1 to 4.3 (WG3WP4D1) to set model parameters.
	(including wake representation)	device locations		
		Local geography:		
		Water depth, distance to channel walls, hub height.		
		Operating		

Matlab file reference	Task	Input	Output	Method
		condition:		
		Uo, Cp, Ct (i.e. blockage corrected values).		
	Set up domain (for required accuracy)	Predefined settings.	Domain on which to solve the model defined	Matrix set-up algorithm
	Evaluate normalised flow field in relevant places around device group	Model domain	Flow field solution	Solve equation 4.4 (WG3WP4D1) on model domain
		Model set-up		
	Alter flow field with normalised blockage model flow field due to local blockages	Blockage induced flow field	Combined flow field	Flow field combination algorithm
	Near wake modelling			
	Feed in Blockage model data	Corrected rotor Ct	Updated Ct value	Checking algorithm
Wake.m	Calculate the centreline deficit	Rotor Ct value	Centreline velocity deficit	Equation 6.17 (WG3WP4D2).
		Ambient Turbulence intensity value (dept averaged)		
wakestreamline.m	Evaluate available surrounding momentum	Surrounding flow field (corrected for blockage if available)	Equivalent free stream velocity.	Limiting expanding check algorithm
Wake.m		Proximity to boundaries and other device wakes		Area integration algorithm
	Correct for surrounding momentum	Equivalent free stream velocity.	Corrected centreline velocity deficit	Equation 6.18 (WG3WP4D2). if applicable.
	Evaluate the wake width	Corrected centreline deficit	Domain on which to set-up the near wake model defined	Matrix set-up algorithm
		Position in optimisation loop	Wake width evaluated	Equation 6.16 (WG3WP4D2).
	Evaluate the velocity deficit Gaussian profile	Corrected centreline deficit	Near wake form	Gaussian equations
		Model domain		
		Wake width		
		Elliptical wake widths (if available)		

7 UNCERTAINTIES ASSOCIATED WITH THE GH APPROACH TO DEVICE SCALE MODELLING

7.1 Uncertainties associated with device scale modelling

The energy production calculation of a tidal farm is always subject to uncertainties that should be accounted for by assessing the degree of accuracy of the associated models and methods. The two main areas of uncertainty relating to device scale modelling include:

- Measurement uncertainties
    - Instrument measuring error
    - Instrument set-up error
    - Signal post processing errors

- Modelling uncertainties
    - Simplifying governing equations
    - Numerical errors associated with solving the equations.

These uncertainties can be either calculated or estimated. Ideally the tidal farm development should aim to minimise the overall uncertainty. The specific uncertainties associated with different aspects of the device scale modelling are discussed below.

7.1.1 Uncertainties associated evaluating the power and thrust curves

Depending on the method by which the performance curves are derived the uncertainties vary. If the curves originate from measurements then the following uncertainties applies:

- Measurement uncertainties
    - Acoustic Doppler device uncertainties
        - Uncertainties due to the measurement setup
        - Inherent measurement error
        - Uncertainties associated with instrument data processing
        - Instrument motion
        - Translation uncertainty due to poor correlation in the flow
        - Removal of real vs. noise in signal processing (filtering errors)
    - Power measurement
        - Metering instrument error
        - Unknown losses between device and meter
    - Thrust measurement
        - Uncertainties due to the measurement setup
        - Inherent measurement error
        - Signal noise removal (filtering errors)
        - uncertainties due to the measurement setup
- Power and thrust curve adjustments
    - Unknown local effects
        - Speed changes between measurement at rotor plane
        - Unknown blockage effects (e.g. unknown tidal elevation)
    - Uncertainties associated with the theory to correct for blockage
- Look-up table
    - Uncertainties associated with bin widths

Errors in flow measures are in the order of 1-2.5%, and are typically much larger than power signal errors. Local effects need to be assessed based on the specific available technical information.

If the dynamic curves are predicted using numerical methods, then the uncertainties become:

- Model uncertainties
    - Incident flow models
        - Uncertainties due applicability of turbulence models
        - Uncertainties due applicability of shear profile models
        - Uncertainties associated with calculation resolution
    - Power and loading prediction models
        - Uncertainties associated with the theory limitation (e.g. 3-d effects)
        - Uncertainties associated with calculation resolution
- Look-up table
    - Uncertainties associated with bin widths

Different modelling methods will have different levels of uncertainty. The aim of PerAWaT (and ReDAPT) is to quantify these uncertainties

7.1.2 Uncertainties associated blockage modelling

The application of the blockage model introduces several modelling uncertainness

- Blockage model uncertainties
    - Theory
        - Uncertainties associated assuming a steady uniform flow
        - Uncertainties associated applying a correction as a perturbation
    - Calculation
        - Uncertainties associated solving the potential model
            - Bessel function integration limit
        - Uncertainties associated with calculation resolution

The blockage model is a first approximation model so the expected uncertainty will be >10%. However the expected increase in performance due to blockage is expected to be less than 5%, so the impact on the overall energy yield uncertainty will be small.

7.1.3 Uncertainties associated wake modelling

The use of a semi-empirical near wake model introduces several uncertainties:

- Near wake model uncertainties
    - Theory
        - Uncertainties associated assuming a steady uniform flow

    - Empirical data
        - Measurement uncertainties
            - Instrument set-up
            - Instrument error
            - Signal processing errors
    - Calculation
        - Uncertainties associated with parametric description using Ct and ambient turbulence intensity

- Uncertainties associated with the impact of local devices on the near wake form
- Uncertainties associated with the provided thrust characteristics
- Uncertainties associated with blockage model corrections
    - Thrust
    - Local flow field
- Uncertainties associated with calculation resolution

The calculation uncertainty can to an extend be managed and the resolution of the analysis altered to get a more accurate solution. The main area of uncertainties is whether the empirical relationship is representative of reality. Only full scale data will demonstrate this.

7.2 Planned developments under PerAWaT

The aim of the PerAWaT project in relation to device scale modelling is to develop and then assess the uncertainties associated with the GH device, blockage and near wake models.

As discussed in Section 4, the use of measured performance curves in the form of a power and thrust curve is preferred to numerical predictions of power output. Hence the access to full scale data is important to assess the assumption that for an energy yield analysis a tidal energy device can be characterised by a power and thrust curve. The ReDAPT project aims to provide sufficient detail to validate this assumption. In addition, there are a number of developers who plan to or are in the process of obtaining power curves certified by third parties. Reports from MCT, such as at recent public presentation held by the IMechE showing results from SeaGen (http://nearyou.imeche.org.uk/events/event.htm?eID=3292) and detailed by Fraenkel (2006) with respect to their previous SeaFlow deployment suggest a strong correlation between blade element momentum predictions and power measurements. DNV are currently certifying the SeaGen power curve and the hope is that this certified power curve will become publically available.

The experimental work packages within PerAWaT which will support the assessment of the device scale modelling include WG4WP1, WG4WP2 & WG4WP3. The device scale experiments (WG4WP1&3) will yield information about the near wake form in varying inflow conditions. It will also provide data on the impact of bounding surfaces. The inter-array experimental work package (WG4WP2) will provide information on lateral blockage effects on performance and on the local flow field.

The numerical programme within PerAWaT will further provide validation data to compare the rationalised device scale models against. CFD simulations will provide detailed descriptions of the near wake form for a range of representative inflow conditions.

In addition to the performance curve data, the ReDAPT project should also provide data regarding the upstream inflow conditions and the downstream wake structure. This data will provide further validation data for the GH device scale modelling approach.

8 SUMMARY

This report describes the GH device scale modelling method, including a discussion on the parametric description of a device for the purpose of both power output prediction and the impact the device has on the local flow field. The methodology of the GH device scale modelling approach has been detailed and an account of how the model will be incorporated in the Beta code provided.

The GH device scale modelling incorporates the following key aspects:

- Evaluation of a representative incident flow speed onto the device rotor (flow speed input from array scale modelling)
- Use of a turbine model which parameterise the power production as mean power output vs incident flow speed to evaluate the mean power output per device for each flow state.
- Use of a turbine model, which parameterise the energy extraction as the rotor thrust vs incident flow speed, to initiate wake modelling
- Use of a blockage model to correct for changes in power output and rotor thrust due to local blockage effects and also predict the changes to the local flow field.
- Use of a near wake model to initiate far field wake modelling

The next steps for this work package in relation to device scale modelling are:

- To analysis the experimental results provided from WG4WP1, WG4WP2 & WG4WP3;
- Compare the results to the existing model and adjust as required;
- Further compare the adjusted model with the numerical modelling results provided from WG3WP1& WG3WP5; and
- Analyse and report on the uncertainty associated with the model in WG3WP4 D11&12.
- Utilise full scale data when they become available.

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