The PerAWaT project: Performance Assessment of Wave and Tidal Array Systems

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Abstract

The Energy Technologies Institute (ETI) is a UK based company formed from global industrial companies and the UK government. The ETI invests in projects to help create affordable, reliable, clean energy for heat, power and transport. The ETI core objective of accelerating the development and commercial deployment of energy technologies that reduce greenhouse gas emissions and help to achieve energy and climate change goals will be addressed by the primary objective of the PerAWaT project which is: To establish and validate numerical models to predict the hydrodynamic performance of wave & tidal energy converters operating in arrays. The deployment of large scale arrays of wave and tidal energy conversion devices will only occur when project developers have sufficient confidence in the return on their investment. This requires proven prototypes and validated methods for the prediction of resource and energy capture. This paper provides an overview of the PerAWaT project which will build on existing knowledge to accelerate the development of sophisticated tools that will become essential as the wave and tidal energy industries mature.

Keywords: Wave energy converter, Tidal energy converter, Array Performance, Energy capture

1. Project description

Marine energy technologies are at an early stage of development. One obstacle to their large scale deployment that can be foreseen is the lack of a robust understanding of the resource and how the devices will interact both with one another and with the resource and what effect these interactions will have on the energy captured and therefore the revenue stream that project developers might expect.

By establishing and validating numerical models that quantify these effects the PerAWaT project aims to reduce the level of uncertainty currently present in estimates of energy capture and therefore increase the confidence that project developers can have in the return on their investment.

1.1 Approach and project structure

The approach to the development, verification and validation of the numerical models is shown schematically in Figure 1.

Appropriate methodologies for use with the numerical models will be developed leading to the design of specific algorithms and engineering models. These will be verified against each other and also more complex methods e.g. CFD calculations.

Scale model test data will be collected within the project and access to full scale data from outside the project will be sought to facilitate validation.

The intention is to begin development of numerical tools in the first two years whilst in parallel collecting data for validation. The last two years of the project will then focus on verification and validation such that validated Beta versions of the tools will be available at the end of the project.

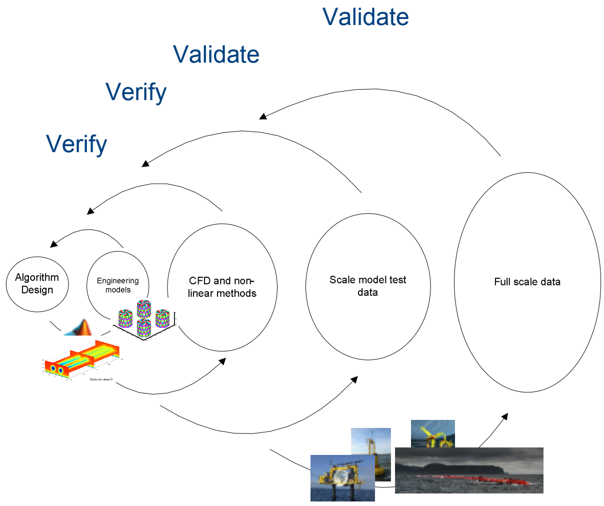

Figure 1 Approach to tool development, verification and validation

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The project has two parallel work streams: one for wave and one for tidal energy conversion systems. Each work stream is split into two work groups: numerical modeling and physical testing. The overall project team structure is presented in Figure 2.

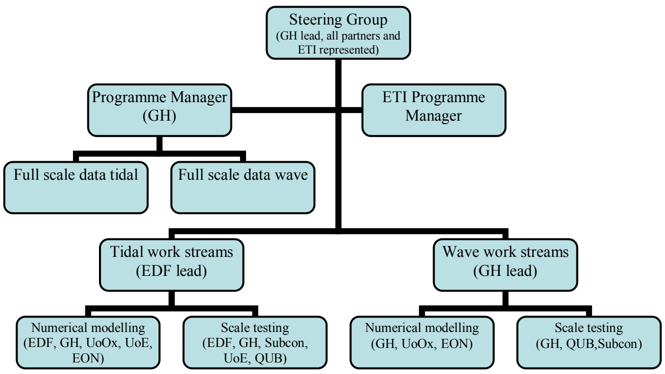


Figure 2 Project team structure

2. The wave work stream

Four of the project partners will be actively involved in the wave work stream.

GL Garrad Hassan (GH) will manage the wave work stream, develop engineering models that can be run on a PC, oversee the physical testing of arrays of devices at model scale and validate the models once the output from the physical testing and more complex methods become available.

Queen's University Belfast (QUB) will be looking at regional scale modelling considering the effect of large arrays of devices on the wider wave field.

The University of Oxford (UoOx) will be developing more computationally intensive non-liner hydrodynamic models to verify the engineering models developed by GH and help to identify the limit of their applicability.

E.ON will provide an end user perspective that will inform and guide the development of the engineering models. E.ON will also act as a Beta tester.

The cross-comparisons between the outputs of numerical and experimental work groups will contribute to PerAWaT's main objective, which is the reduction of the uncertainty associated with the numerical predictions and increase the confidence in the developed software, ensuring its usefulness to the key players in the marine renewables sector.

Two scales have been identified 'Array scale' that will focus on the interaction of the devices operating in close proximity within an array and 'Farm scale' that will focus on the effect that a large array will have on the regional wave field and vice versa.

The contribution of the partners (GH, UoOx and QUB) to the wave energy numerical modelling component of the PerAWaT project is outlined in Figure 3.

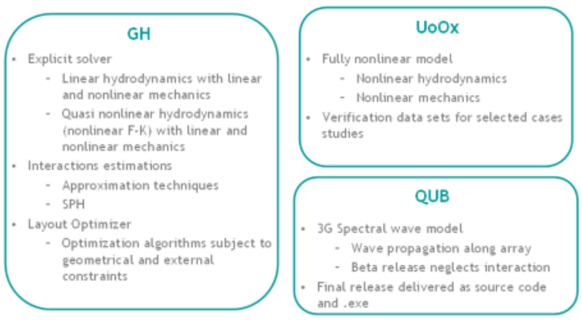
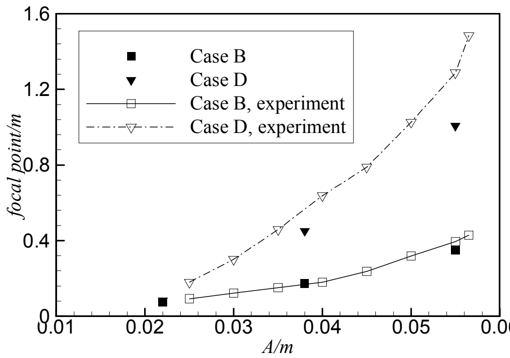


Figure 3 Contributions made by participants to wave energy numerical modelling

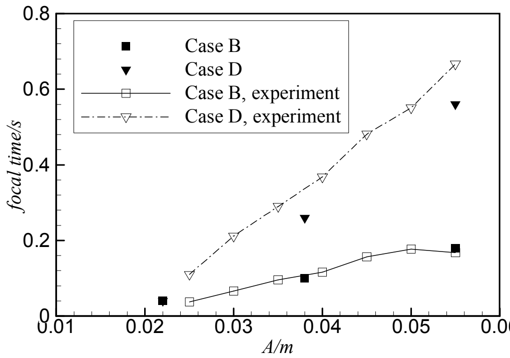
2.1 Array scale

As Figure 3 illustrates, GH will further develop [1] a methodology based on linear and partly (quasi) nonlinear hydrodynamics while UoOx will focus on a fully nonlinear hydrodynamic model. In both approaches linear and nonlinear descriptions of the mechanically applied forces, due to the PTO and mooring system, will be implemented depending on the version of the solver (frequency or time domain, respectively). GH will make use of commercial software (WAMIT) to calculate geometry dependent hydrodynamic properties for WECs operating in isolation and also for WECs installed in an array.

The purpose of the nonlinear modelling work is to investigate the implications of nonlinear wave-structure interactions and nonlinear control on the performance of arrays of WECs. A major focus of the work will be on the "array" effect. This is associated with the phenomenon of near-trapping, in which very large localised wave elevations may be predicted by linear theory, due to quasi-resonant standing wave effects. The aim is to characterise the effect of nonlinearities on this phenomenon and their influence on the behaviour of WECs. The results from the model will be validated by comparison with experiments undertaken in the PerAWaT programme. Comparison with results from the GH modelling procedure will then make it possible to estimate the conditions under which nonlinear effects can modify predictions of average power.



(a)



(b)

Fig. 4 OXPOT predictions compared with experiments on shift in focus point of a nonlinear wave group: (a) position of the focal point; (b) time of focusing (from [3])

The nonlinear model is based on a higher order boundary element code OXPOT developed at UoOx [2,3,4]. Results have been successfully compared with experiments concerning nonlinear wave kinematics, nonlinear diffraction by fixed cylinders and the nonlinear hydrodynamics of an oscillating cone. Figure 4 shows predictions of the shift in focus point of some wave groups investigated experimentally by Baldock et al. [5], plotted against wave crest amplitude. These shifts in space and time (as compared with predictions from linear theory) are a sensitive indicator of the global nonlinear interactions in an irregular wave.

The development of models using the two different approaches will allow cross-verification and also inform the extent to which a linear hydrodynamic model can be used in more extreme sea states and in particular survivability conditions. Comparisons between the two approaches and validation of the models against experimental data will utilise the variables listed in Table 1.

Monochromatic tests (regular waves)
• PTO force / torque spectrum per PTO mode • RAO (Response Amplitude Operator, i.e. non-dimensional body motions) • RCW (Relative Capture Width, i.e. ratio between the absorbed power and that contained in a wave front with the same width as the WEC)
Multi-chromatic tests (irregular waves)
• PTO force / torque per PTO mode • Instantaneous motion / velocity profiles • Instantaneously absorbed power • Average power absorption per sea state (function of control settings)

Table 1. Variables to be used in cross-verification of linear and nonlinear hydrodynamic models

Whilst the cross verification between different hydrodynamic models will enhance confidence in the numerical methods the collection of high quality physical scale model data collected under controlled conditions will be essential for validation. The PerAWaT project will commission tests using ~1/20th scale models in a large wave tank to capture the performance of devices operating in isolation and arrays.

The fundamental objectives of the 1/20th scale tests are the following:

- Provision of suitable experimental data for validation of numerical tools;
- Quantification of the wave loading and energy absorption of a farm of WECs;
- Definition of the limits of validity of the numerical models for performance and survivability scenarios.

2.2 Farm scale

The project will also provide a solution for large wave farms by including sub-grid elements in a third generation spectral wave model to describe wave energy converters acting in an array. This work, led by QUB will initially neglect the interactions between array elements (except for the change in the wave field due to the energy extraction) and assume all WECs behave as in isolation, and at a later stage benefit from the GH and UoOx work to derive a potentially more accurate parametric representation of the WECs (calibrated sub-grid elements).

Physical testing at ~1/50th scale at the QUB facility in Portaferry will be used to:

- Assess of the influence of a variant incident wave field on the power capture of a large wave farm.

3. The tidal work stream

Six partners are involved in the tidal work stream.

EDF will manage this work stream, perform CFD analysis at device and basin scale and also undertake scale model tests of single rotors.

GH will develop engineering models that will run on a PC, oversee physical testing and verify and validate their models against more complex methods and physical test data.

UoOx will undertake detailed CFD of tidal devices and basin scale modelling of energy extraction.

The University of Edinburgh (UoE) will undertake detailed CFD at device scale and undertake physical testing at 1/10th scale in the open sea.

The University of Manchester (UoM) will undertake physical testing at model scale of arrays of tidal energy conversion devices

E.ON will collaborate with the work at UoOx and also provide an end user perspective and act as a Beta tester.

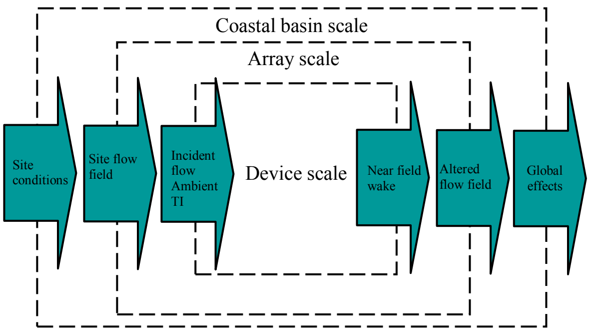


Figure 4 Interaction between different scales

The model development and physical tests will be performed at three scales: 'Device', 'Array' and 'Coastal'. This 'nested' approach to the project and the interactions between the different scales are shown schematically in Figure 3.

The device scale models will focus on development of the wake behind a single device, and how this is affected by turbulence (wave and sea bed generated), and blockage. The array scale models will take parameterised models of the individual wakes and determine how they affect the interaction of devices within an array. This will then lead to a 'global' parameterisation of the effect that an array of devices will have on the coastal or regional flow fields.

3.1 Device scale

The interaction that an individual tidal stream turbine has with the incident velocity profile is shown schematically in Figure 4.

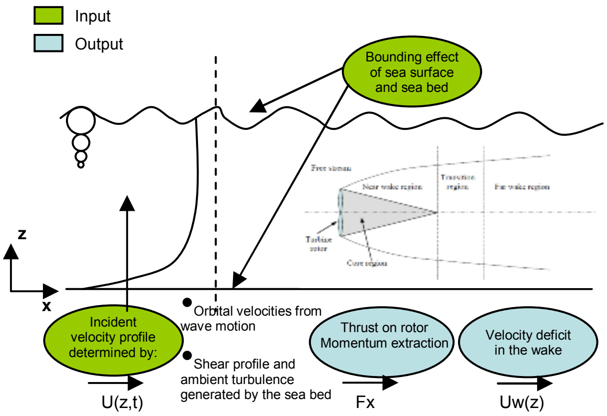


Figure 5 Device scale flow field

The tidal stream generated flow is affected by the presence of the free surface and the seabed such that:

- Wave motion at the surface induces orbital velocities within the water column, the magnitude of which decay with depth.
- The no slip condition at the seabed generates a velocity shear profile
- Turbulence is generated, the intensity of which depends on the roughness of the seabed.

In addition larger scale turbulent eddies can be generated by the presence of large obstructions in the upstream flow field e.g. headlands.

A tidal turbine will extract momentum from the flow generating a thrust load on the rotor and a region of lower flow speeds and increased turbulence intensity, the rotor wake, down stream.

The increase in turbulence and velocity deficit in the rotor wake is dependent on the momentum extracted and can therefore be expressed as a function of the rotor thrust. The shape of the rotor wake will also be affected by the free surface and seabed which will constrain the expansion of the wake in the vertical plane. Any constraint on the expansion of the rotor wake will impact on the wake induced velocity seen at the rotor resulting in a 'feedback loop' that affects both rotor performance and loading [6].

A robust and methodical approach to physical and numerical modelling of the physical process is required to determine the absolute (and relative) influences of the physical processes described above. GH has previously been involved in a collaborative R&D project with the University of Southampton [7] that investigated the influence of a sub-set of the parameters and adapted semi-empirical models of wake development originally developed for wind turbines. By building on this experience and that within the project consortium the following sub-tasks within the tidal work stream have been defined:

- Device scale numerical modelling (CFD) to be performed by UoOx and UoE who will investigate different types of Fundamental Device Concept including Open Centre and Ducted as well as the standard 'wind turbine' unducted 3 Bladed type. Standard CFD models will be modified to include a free surface with and without waves and turbulence.

- GH will further adapt the semi-empirical models originally developed in the wind energy sector

- Device scale physical testing will be performed by EDF (at 1/30th model scale) at a range of turbulence intensities, water depth to turbine diameter ratios and with different incident waves. The parameters to be measured to include rotor power (torque and speed) and thrust, flow velocity up and down stream of the rotor using high frequency Acoustic Doppler Velocimetry so as to capture both mean, periodic and stochastic velocity components.

3.2 Array scale

When a number of rotors are arranged in an array, see Figure 6, the individual wakes will impinge on down stream devices which will then generate a 'multiple' wake, the expansion of the wakes will also be affected by rotors on either side and further downstream wakes will merge. Although much is known about unconstrained wakes from numerical and experimental studies of wind turbines, e.g. [8], few studies have addressed the behaviour of tidal stream arrays subject to the additional constraints imposed by free surface proximity and high turbulence. Studies of tidal stream arrays [9,10] typically represent devices as porous discs which do not reproduce the near-wake structure or speed-dependent performance of rotating devices

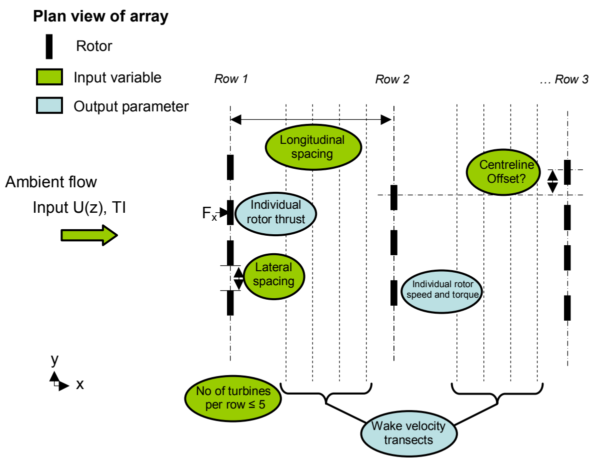


Figure 6 Array scale flow field

An approach similar to that described above for the device scale will be used to investigate the array scale:

- Array scale numerical modelling (CFD) performed by UoE using a parameterised description of individual turbine wakes derived from the device scale modelling.

- Development of a rationalised 'engineering' model of the flow field and far wake development by GH.

- Array scale physical testing (at 1/70th model scale approx.) by the University of Manchester for different array layouts to quantify the effect of lateral and longitudinal blockage on both the wake structure and loading of open-bladed horizontal axis devices. Each device will comprise a 3-bladed rotor and strain-gauged dynamometer rather than a porous disc or strip. Flow conditions studied will include turbulent steady flow, bed generated turbulence, large eddies and combined waves and currents. Measurements include rotor thrust and power (as product of torque and velocity) as well as flow-field velocity measurements in the vicinity of the array. Velocity measurements will be sampled using high frequency micro-ADVs to capture both mean and stochastic characteristics. Particular attention will be given to quantifying the effect of wake boundary conditions on wake structure. To investigate boundary and interaction effects on wakes at scale, similarity of the extracted momentum and the mixing process is required. To allow testing of an array of devices, these experiments will be conducted at a small geometric scale and hence the Reynolds number based on chord length will be low. However, kinematic and dynamic similarity of the small-scale and full-scale rotor, and geometric similarity of the flow structure, can be maintained by appropriate selection of the rotor geometry. A blade form has been designed specifically for this low Reynolds number application to maintain similar momentum extraction to a representative full-scale device. Data from this package will improve understanding of the effect of blockage on far-wake structure and will be used for development and validation of the GL Garrad Hassan engineering model.

- Physical testing of multiple rotors (at 1/10th model scale) in the open sea (Strangford Lough) by UoE.

3.3 Coastal basin scale

The impact of large scale energy extraction on the regional flow field will be assessed through:

- The development by EDF of numerical models (using Telemac) of coastal basins in which the presence of large scale tidal farms is represented using parameterised elements derived using the results of the device and array scale investigations described above. Most of the analysis will use 2D shallow water models although limited 3D modeling will also be carried out to provide for cross comparison.
- The parallel development of an independently derived 2D coastal basin model by UoOx for cross comparison and verification.
- Physical testing of a 1/1000th model scale coastal basin with and without the inclusion of an array emulator system (made up of porous strips).

4. Progress to date

PerAWaT is scheduled to run for 4 years with completion due at the end of 2013. In the first year of the project work has focused on the development of detailed specifications for all work packages, the design, build and commissioning of equipment to be used in the scale model physical testing and the definition of the methodologies that will underpin the numerical models to be produced.

5. Summary and concluding remarks

The understanding of the performance and behaviour of marine energy conversion devices when acting in arrays is critical to their cost effective deployment at large scale. The interaction of individual devices' hydrodynamic properties, control system and power take off arrangement will be strongly influenced by the temporal and spatial variations of the available energy flux within an array which in turn will be affected by the presence of the array possibly leading to feedback mechanisms that may determine the maximum extractable energy from a given area. Optimisation of the layout of an array and the design of the control strategies used in order to maximise the energy extraction at any particular site is therefore dependent on a thorough understanding of the physical mechanisms involved throughout the system.

Through the development of robust, validated, numerical models at device, array and regional scale, and by coupling these models together to fully investigate the interaction of devices within arrays and of arrays of devices with the energy flux in the wave and flow fields the PerAWaT project will deliver tools that will be crucial in enabling the cost effective large scale deployment of wave and tidal energy. The project will therefore directly address the ETI core objective of accelerating the development and commercial deployment of energy technologies that reduce greenhouse gas emissions and help to achieve energy and climate change goals.

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