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EquiMar: Development of Best Practices for the Engineering Performance Appraisal of Wave and Tidal Energy Converters

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***Abstract*— At the present time there are no approved standards or recognised best practices being implemented for the performance appraisal and benchmarking of wave and tidal energy converters. As such, this develops considerable misunderstanding between device developers, testing centres, investors/ financiers etc when attempting to quantify the performance of a device since it makes it very difficult to reference and benchmark the performance of a marine energy converter. The EC Framework Programme VII EquiMar project has set out to develop a suite of Best Practices to be adopted when undertaking the performance evaluation of such systems in order to address this deficiency. This paper reports the development of a set of 'Best Practices' within the ECFPVII EquiMar project to be adopted for the performance quantification of wave and tidal energy converters as they evolve from an engineering concept to commercial scale deployment.**

***Keywords*— Standards, Performance assessment**

I. Introduction

The objectives of working with a set of 'Best Practices' is to: provide confidence to developers and investors so that when a device is rated for its performance against these Practices the performance and delivered energy will be within quantifiable limits; and provide a mechanism against which the performance can be bench marked or normalised against. In order to facilitate the progressive development of a marine energy converter, as it evolves from a scale prototype to a full scale commercial technology, these 'Best Practices' have to be able to be applied at each stage of a technologies evolution. For this reason the EquiMar 'Best Practices' have been developed [1] so that they are applicable to the three stages of technology development and performance assessment: i) concept appraisal and small scale tank testing; ii) larger- full scale single device in-sea testing; and iii) Commercial scale, multiple device array performance.

II. The Concept Appraisal Process

Due to the long time lines associated with the development and evolution of a marine energy converter, it is imperative that we identify whether such a technology can be effective at capturing and converting energy from the seas early in the development process. Where this can be demonstrated to be positive, this will facilitate a more timely progression to the development of a physical scale prototype for testing and provide confidence to the investor/ funding body making available the financial resources to deliver this. In order to demonstrate this it is necessary to outline a series of simple steps, semi-independent steps to be taken for the appraisal and parameterisation of device performance which have the following core objectives:

- standardised desk-based quantification of prospective device performance leading to;
- appropriate comparators enabling verification of a proposers performance claims;
- identification of potential barriers to deployment; and
- production of an auditable trail for due diligence purposes.

In order to facilitate this, procedures have to be modularised so as to make it device-agnostic to the greatest degree possible, however as certain configurations are predominant within the industry, some criteria may be more extensively quantified than others, depending on availability of accepted standard procedures.

In the case of tidal energy, while there are a wide range of potential device types. However from a fluid-structure interaction/ fluid mechanics perspective, Tidal Energy Converters (TECs) can be split broadly into 3 categories:

- turbines,
- oscillating and translating hydrofoils,
- venturi devices,

In attempting to arrive at a methodology where competing designs may be compared computationally or numerically, it is important to define a set of parameters which may be compared. In doing this from a power capture-conversion perspective, the following parameters have been selected

- **Power (Coefficient C_P)**: This is the hydrodynamic power captured by the device prime mover and can be non-dimensionalised by the power available in the incident freestream over the power capture area. This may be defined for all devices, and computing this value is a fundamental requirement.

- **Tip speed ratio (λ)**: This is the ratio of the speed of the rotor tip to the incident flow velocity, and while traditionally applied to turbines may be adapted for oscillating and translating foils whereby the blade tip speed is replaced by the maximum or RMS foil translation velocity.

- **Power capture area (A)**: This is the projected frontal area of the device over which power is expected to be extracted from the flow.

- **Thrust (Coefficient C_T)**: This is the total force on the device collinear with and due to the freestream and is the principal force resisted by mooring systems. It is non-dimensionalised by the freestream dynamic pressure over the power capture area.

- **Efficiency**: This is the overall system efficiency of the device. **It is the multiple of all component efficiencies.**

- **Load factor**: This is the ratio of mean power output to maximum power output over a given period of operation.

The concept appraisal performance metrics which will be used as comparators for undertaking concept device performance appraisal are:

The C_P-λ and C_T-λ curves: From Figure 1, the **C_P-λ** method of data reduction allows the performance characteristics for a device to be easily compared over a range of operating conditions. The key point is the occurrence of peak C_P. This identifies the range of λ values over which a device should operate to maintain optimum power extraction for a given flow condition. This will be constrained by its proximity to the Betz limit, the theoretical maximum a free turbine can extract from the flow ($C_P \approx .59$), the cut out speed which limits the curve to the left hand side, and the cut in speed which limits the curve on to the right. This is the principle parameterisation used for comparison between devices of different specification but same general type.

The **C_T-λ** curve indicates the dependence of device thrust (and hence structural loads) on the performance of the rotor at a given operating point.

The Power-U_∞ and Thrust-U_∞ curves: From Figure 2, the **Power-U_∞** curve provides information which will be valuable in identifying and quantifying the effect of generator rating on pitch regulation requirements and the cut-in, rated and cut-out speeds, and the **Thrust-U_∞** provides indication of any load penalties associated with maximizing power extraction at high system loads. These curves allow comparison between different devices of any type.

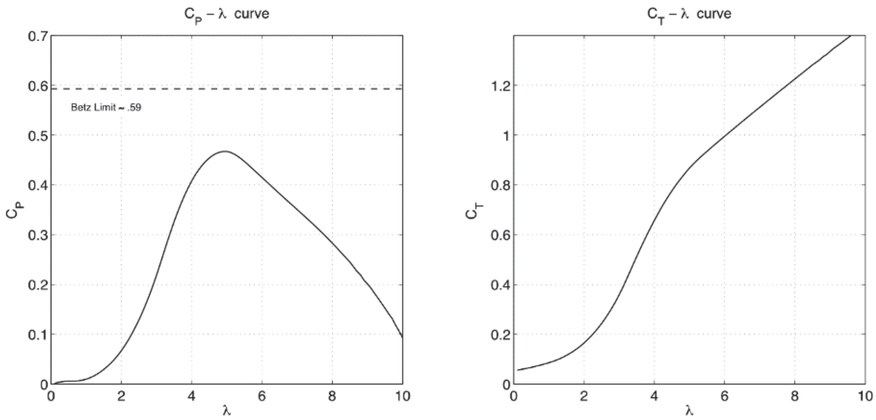

Fig. 1 Example performance curves from a horizontal axis tidal turbine

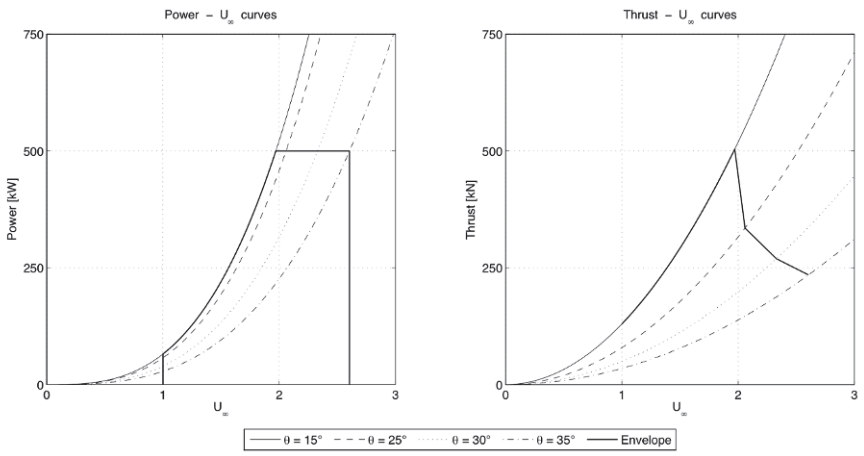

Fig. 2 Example performance curves from a pitch-regulated horizontal axis tidal turbine

III. Small Scale Tank Testing

When undertaking testing of a small scale marine energy converter within test tanks the procedure to be followed should contain what explicit Design of Experiment (DoE) and uncertainty analysis methodologies which should be considered the minimum requirement for tank testing work. In order to facilitate accurate performance quantification and benchmarking, this should place particular emphasis on repeatability, quantification of uncertainty, estimation of accuracy and elimination of laboratory specific effects. Since the objective of an experiment is to generate physical data to test a hypothesis. The purpose of experimental good practise, manifest in Design of Experiment (DoE), is to optimise in advance an experimental process in order to generate the maximum quantity of high quality data – in other words maximising *value for money* for a particular experiment. In the context of EquiMar, the experimental procedures are those which will provide performance data on the performance of small scale marine energy devices, however the DoE process as well as that of the Uncertainty Analysis are common to a very wide range of engineering fields and thus the domain is well documented and processes and procedures are widely accepted; ITTC 2008 [2], AIAA 2009 [3], ISO 2008 [4] and NIST 2007 [5]. The core purpose of these procedures is thus to allow an experimental test result to be stated in the standard form of either a **standard uncertainty**, i.e.:

$$\text{(Result)}: x\ \text{(units)}\ \text{[with a] standard uncertainty of}\, u_c \text{(units)} \quad (1)$$

or an **expanded uncertainty**, i.e.:

$$\text{(Result)}: x\ \pm U\text{(units)} \quad (2)$$

such that the uncertainty is a combination of all identified, reduced where possible and accounted for uncertainties associated with the experiment. This expanded uncertainty is related to the standard uncertainty via the coverage factor *k*, calculated (under the assumption of normally distributed data) from the Student *t*-statistic where degrees of freedom υ is the number of samples or tests minus 1:

$$U = ku_c \text{ where } k = t_{\alpha/2}\left(\nu\right) \text{ for } \nu \text{ degrees of freedom} \quad (3)$$

The recommendation of this Best Practice is that all experiments are conducted in such a manner that the reported performance of a prototype device is stated with a precision of 5% at a confidence level of 95%. i.e. this requires that 95 times out of 100 the error of a reported value is no greater than 5% of the true value. This requires that the standard uncertainty is calculated for large degrees of freedom such that the coverage factor, *k*, is 0.96 (approximately 2), corresponding to approximately 95% coverage.

When undertaking tank testing, it is likely that the majority of the test programmes will be undertaken in order to achieve one of the following objectives:

Proof of Concept	Unstructured experiment to answer the question **"does it work?"** at some fundamental level. Very short tests likely to proceed in a trial and error manner, often unaccompanied by a mathematical model. *Example: determine whether a wave device moves in a wave field.*
Comparison	Determination of the **significance of levels of a single variable**, identified in advance, on the response. *Example: determine the* C_P – λ *characteristic of a simple rotor.*
Screening	Identification of **a subset of the most important variables**, from a larger set of candidate variables that have been identified in advance, on the response. *Example: identify the key geometric performance variables for a novel wave energy device.*
Response Surface Modelling	**Optimisation** via identifying relationships and estimate interactions between multiple variables and responses, and specifically identify the levels of the important variables which would produce an optimum response. Quadratic surfaces can be fitted to data providing local maximum/minimum. *Example: reduce the two responses* pitch magnitude *and* roll magnitude *as a function of* H_s *and* T_z *for a wave energy device.*
Model Fitting	Identification of a high quality **mathematical model** in terms of goodness of model parameter estimates. *Example: estimate the numerical models of the two responses* C_P *and* C_T *as a function of* blade pitch *and* TSR *for a novel tidal turbine rotor.*

The following breakdown of the pre-test procedures recommends a list of what should be considered mandatory stages, but which will in practise typically be undertaken subconsciously or automatically as part of a well thought out experimental process and therefore do not constitute a significant or onerous burden in time or resource. In common with the technical objectives of the EquiMar project, this considers parts of the 5 stage development schedule, specifically Stage 1: Concept Appraisal and Stage 2: Large Scale Tank Testing. The following concludes the purpose and Design of Experiment stages to be followed within this 'Best Practice'.

1. **Requirement:** Identify test objectives
   Stage 1: Functionality/Proof of Concept; Comparison; Factor Screening
   Stage 2: Optimisation; Variation Reduction; "Robustification"; Model identification.
2. **Requirement:** Identify facility and process (e.g. towing tank –> thrust and power measurements whilst towing)

– Ascertain capabilities and proficiencies of facility
• Availability and quality of measurements & instrumentation
• Availability and types of tests
• Calibration process
3. **Requirement:** Identify primary model and secondary model(s)
– Write data reduction equation(s)
• Perform sensitivity analysis using instrument tolerances & estimated experimental biases -> estimate, tolerate & correct
– Focus resources on reducing estimated result bias below 5%
4. **Requirement:** Design of Experiment
– Statistical Design of Experiment for maximum quality (minimised uncertainty) of data and maximum robustness of interpretation of results
– Different DoE approach depending on objectives, number of factors etc.

IV. Larger Scale Device Sea Trials

A. *Introduction*

Single device sea trials are the natural progression from tank testing smaller scaled devices and the pre-cursor to economic demonstration of small arrays of multiple devices. The structured development programme for a wave energy device is shown in Figure 3, in which sea trials cover Stage 3 (circa ¼ scale sub-system testing) and Stage 4 (circa full scale device proving) of the schedule. A key consideration throughout the EquiMar project has been to co-operate with other groups concerned with the development process of ocean energy devices. In particular the 5 Stage development programme is based on the International Energy Agency-Ocean Energy Systems Implementing Agreement, Annex II (OES_IA) [6]. It is also in line with the US Department of Energy's Marine Hydrokinetic (DOE MHK) programme Technology Readiness Level (TRL) approach. The relationship between the 5 Stages & the 9 TRLs is also shown in Figure 3. In 2007 the International Electrotecnical Commission set up a new technical committee (IEC TC114) to address ocean energy matters. Two project teams were tasked with developing a technical specification for the evaluation of the performance of wave and tidal energy converters respectively. The EquiMar sea trial manuals have closely referenced these documents to ensure there are no contradictions in the approaches, indeed ensuring that they are complementary.

The rationale for Sea Trials, when conducted correctly in an unrestrained ocean environment, is to build confidence in the functionality, maintenance, operation and power performance of a device and its ability to survive in extreme conditions.

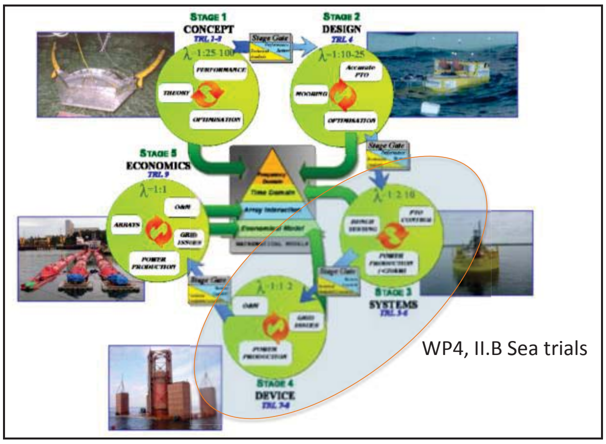

Fig. 3 Structured sea development testing programme

B. *Verifying an Ocean Energy Converter is fit-for-purpose and can be certified for service*

Working in co-operation with leading device developers the objective of the EquiMar project was to establish standard test programmes, monitoring approaches and analysis and presentation methodologies that are robust enough to cope when the environmental conditions are no longer controllable and must be accepted as they occur. To achieve these objectives three documents were produced:

- A separate Sea Trial Manual for wave and tidal energy converters, (WECs & TECS);
- A methodology for evaluating sea trial data that reduces uncertainty in the findings before the full test programme has been completed;
- A summary of the test centre infrastructure being established around Europe to assist the device developers to conduct the sea trials safely and successfully with minimal technical and economic risk.

C. *A Sea Trial Manual*

Every The passage through Stage 3 and Stage 4 is a demanding technical development path that to date only the vanguard device developers who have attempted to complete it can fully appreciate. Experience to date has shown that to accomplish the development process a device must progress through 3 phases, as identified in Figure 4:

- a pre-prototype scale unit of approximately ¼ size that will verify all the sub-systems;
- a pre-production prototype at approximately full size that will verify the design;
- a pre-commercial full size prototype that incorporates the modifications and re-fits discovered necessary during the sea trials of the previous unit.

Fig. 4 The three stages of larger scale development

Another key requirement taken into consideration for a Sea Trial 'Best Practice' is that it would be based on the philosophy of *learning-from-previous-experiences.* Some of the leading technology teams were consulted throughout document production to ensure any difficulties they discovered would be included in a *Lessons Learned & Shared Experiences* section.

Sea Trials are about more than just the power performance of an ocean energy converter. They must cover all aspects specified in the rationale above and should have the underling requirement to de-risk the development path. This means the testing manual must include all the processes involved in operations from sea-to-grid, or wave-to-wire as it is often referred. The photographs in Figure 5 depict the various energy conversion stages that occur in typical wave and tidal machines and clearly shows the multi-disciplinary nature of the two technologies. Any test manual must be capable of dealing with this mixed engineering, including specific Stage Gate criteria for each sub-system that must be applied at the conclusion of a test set to assist the design team in the evaluation process. From these due diligence reviews the decision on the continuation of the device development can be made.

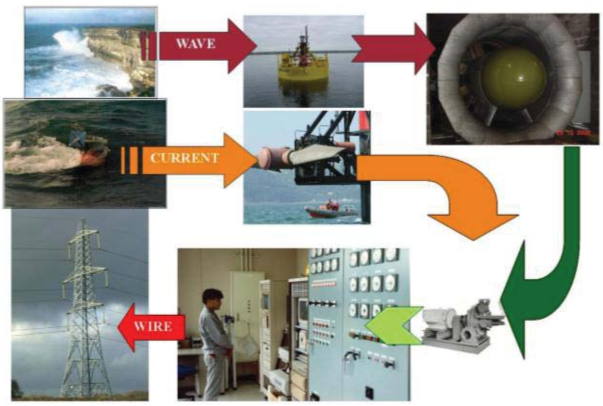

Fig. 5 The energy conversion processes and Ocean Energy Converter Facilities

In a similar manner to small scale tank testing procedures, separate sections are written for each of the 5 identified sub-system and based on a standard format to describe:

- The purposes of conducting the reported tests;
- The objectives of the tests;
- Pointers for the successful completion of the tests;
- At which Stage of the sea trials a particular type of test should be conducted;
- The data acquisition required and monitoring parameters to include;
- The measuring sensor options;
- The analysis to be performed on the recorded data;
- The recommended data presentation approach;
- The Stage Gate Criteria to apply on conclusion of the programme
- Lessons Learned and Shared Experiences

D. *Sea Trial Data Evaluation*

Despite the best of intention, planning and preparation it is likely that when the sea trial data is being evaluated gaps will be found and missing configurations located. Also, design teams will probably attempt to evaluate the device's overall suitability during the trials before all the configurations or seaways have been experienced. To assist in this process a new methodology is introduced that will help reduce the uncertainty in the evaluation of the limited data sets. The confidence limit that can be applied to the analysed results increases as more raw files are added to the records and the technique for doing this statistical procedure is explained.

V. ARRAY-SCALE DEVICE INSTALLATION

In the short to medium term wave and tidal energy devices will be installed in multiple numbers at a given site. Such installations are commonly known as farms or arrays. It is expected that the scale of arrays will increase in time from a few MW initially to perhaps many hundreds of MW much the same as offshore wind energy. As arrays become larger in size (in terms of number of devices and energy extracted) interaction effects between devices are expected to increase in magnitude and complexity. With limited research work having been completed to date regarding array performance and interaction effects the need for guidance is clear.

It is expected that progress in array development will increase rapidly in order to reduce the cost/installed power capacity ratio such that parity with similar renewable energy technologies is reached in a timely manner [7].

Part IIC of the EquiMar protocols address a range of issues relevant to both pre-deployment actions and performance assessment of marine energy arrays. Pre-deployment guidance is given on supply chain development/evolution, characterisation of the key operation and maintenance issues, configuration of electrical connection, matching devices to site and the assessment of device interaction within arrays.

At present a number of small arrays worldwide are at the consenting and planning stage. The primary purpose of these installations is to (a) Demonstrate that multiple device deployments at the same site and connected in an array to shore, (b) to demonstrate high availability and power delivery to the electrical grid, (c) to act as a platform for learning with emphasis on O&M actions, device interaction (if any) and control of the array.

Most early arrays are small and the EquiMar protocols define demonstrator arrays as being composed of approximately 10 devices and with installed rated power capacity of less than 10MW. The cost per installed unit of rated power will still be high compared to other technologies but the information gathered from such installations will inform individual device and array design for future arrays leading to increased power production, lower installed costs and more streamlined O&M actions. Two key areas addressed in the protocols for early demonstrator arrays are the nature of the marine energy supply chain and array layout. The latter also concerns the propensity for device interaction within arrays.

A. *Commercial scale – marine energy supply chain*

The marine energy supply chain is at an embryonic stage. Dedicated suppliers are not yet abundant due to the relatively small scale of the industry but suppliers in related applications may have the capacity to modify their existing products/services to supply the marine energy sector. Present experience of the marine energy supply chain is that many major components such as gearboxes, blades, hydraulic generators etc. that would eventually be mass-produced are currently being manufactured as custom (one-off) units. Therefore costs are high with full design, development and custom tooling/fabrication often required. This increases costs and lead times for prototypes, both of which are likely to be reduced for arrays. Figure 6 demonstrates an appropriate scenario for the continual development of the marine energy supply chain.

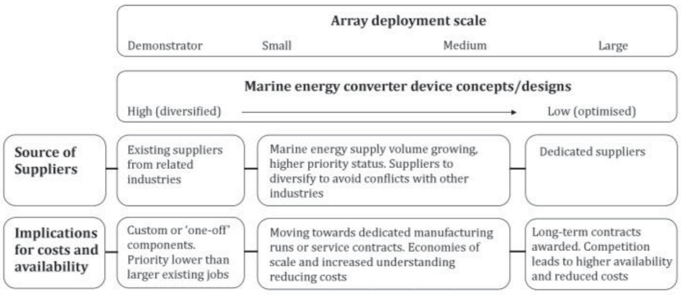

Fig. 6 Evolution of the marine energy supply chain

There are two fundamental aspects that are hindering the marine energy supply chain – diversity of concepts, and lack of standards. The diversity of concepts has prevented (or at least complicated) the development of series built components as different devices (which are almost all at present one-off prototypes) have very different requirements, meaning that suppliers are required to perform full checks and design reviews on every component produced. Lack of standards is also hindering the development of series built products as suppliers cannot always use off-the-shelf equipment which may satisfy existing standards from other industries.

B. *Commercial scale – spatial arrangement of arrays*

It is most likely that 1st-generation marine energy arrays will be of a single row configuration arranged perpendicular to the predominant direction of tidal flow or wave (Figure 7). Here the region of flow influenced by the devices (wake) is shown as a shaded region propagating downstream/down wave. In general for wave energy converters the down wave radiated wake will be wider than for tidal energy devices (more comprehensive guidance on this can be found in EquiMar deliverable 5.4).

The principle device interaction parameter is the distance A laterally between the devices. It is assumed that this arrangement will be beneficial for a number of reasons:

- Devices will not operate in the wake flow or radiated wave field region
- Distance A probably will need to be small for interaction effects to occur
- Initial arrays are likely to be composed of up to 10 devices thus lateral coverage at most sites will be small
- Access for installation/maintenance craft is good

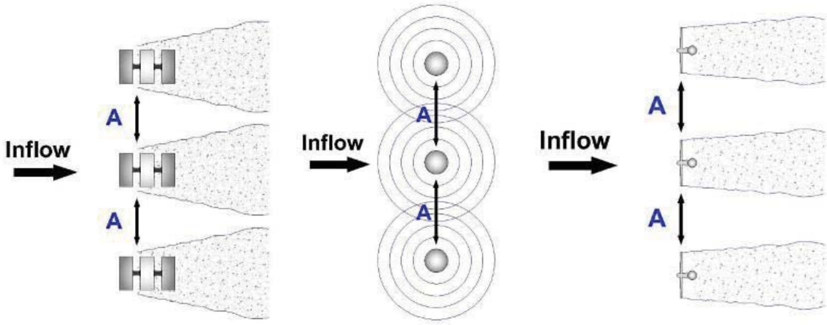

Fig. 7 Single row 1st-generation arrays; line absorber (left), point absorber (centre) and tidal turbines (right)

There are obviously a number of caveats and exceptions to such an idealised arrangement of devices. An example for wave energy is the nature of the radiated wave field and the findings that under small-scale conditions point-absorber devices can increase power production when in a closely-spaced arrangement. Tidal energy is quite sensitive to the installed depth and therefore the bathymetry at a site may well preclude a relatively wide single row of devices. Indeed this appears to be the case with the planned array at Paimpol Brehaut in France [8].

It is likely that first generation demonstrator arrays will be increased in size once the initial array deployment has demonstrated reliable generation of power over a specific period of time. Expanding small demonstrator arrays holds certain benefits including:

- Having consent and knowledge of consenting process
- An understanding of site conditions
- Ability to share certain systems such as electrical connection

It is expected that as the size of marine energy converter arrays increases a dual row arrangement could be considered. Scale model testing supports the offset row arrangement as shown in Figure 8.

It is intuitive that if distance *A* is large then the wave/tidal field moving through the gap between 2 devices will remain relatively unchanged towards the centre of the gap. As distance *A* is reduced the amount of undisturbed resource will also reduce. At some small value of *A* adjacent devices will affect each other and this is likely to be a negative interaction. It also now follows that there must be an optimal value of A where adjacent device spacing is acceptably small but also where enough of the wave/tidal resource can pass through the gap. Now we have the ideal scenario for an expanded 1st-generation array with 2 rows. Distance B will be optimised where the downstream/wave row is operating in flow conditions similar to that of the first row. An exception may exisit for heaving point-absorber wave energy devices where evidence exists that for certain wave climates the radiated fields of devices can enhance the power generated from adjacent machines. If this proves to be the case over a range of inflow conditions then the guidance will clearly have to be amended. For other types of wave energy converter (and for tidal) the device wake will tend to diverge which further supports the theory that there is an optimal value of B depending upon device type, operation and met-ocean conditions. Whilst we cannot give definitive values for A and B we can inform device developers in a generic manner to empower the industry to acquire data to optimise inter-device spacing. 2-row arrays will hold a number of benefits:

- Devices can experience the same inflow characteristics
- Distance B probably will need to be small for interaction effects to occur
- Almost double power output over single row array for similar array lateral width
- Installation/maintenance craft can attain clear access to all devices from upstream and downstream side

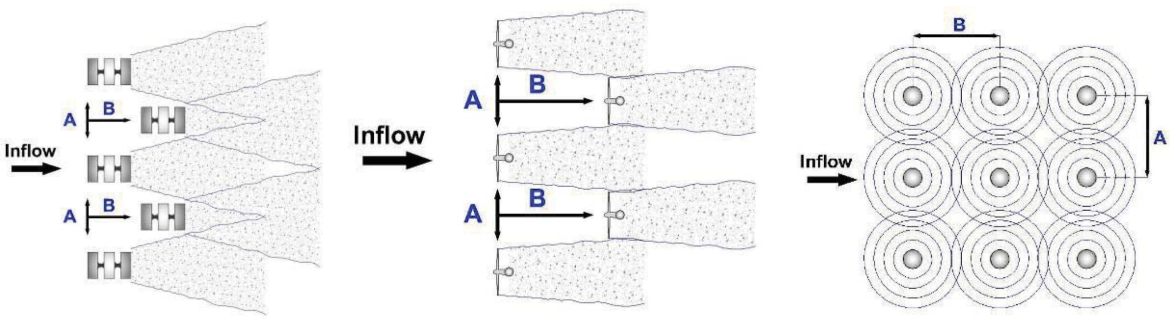

Fig. 8 Dual row arrays (line absorber (left), tidal turbines (centre)) and multi-row point absorber array (right)

Once arrays reach sizes whereby the offset 2-row arrangement occupies a disproportionately large lateral distance of a tidal channel then devices will need to be arranged in larger numbers with additional rows of devices. Here the device interaction effects and inter-array flow effects will become increasing complicated to both measure and predict. However, by developing a progressive strategy to installation and learning (measuring) as much as possible from previous installations the marine energy industry will be best-equipped to solve such engineering challenges. It is for this purpose that EquiMar aspires to provide a seminal platform for future actions.

ACKNOWLEDGMENT

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