Programme Area: Marine

Project: PerAWAT

Title: Large Array Testing

Abstract:

The testing programme devised for producing validation data for the assessment of numerical models of large arrays has been successfully completed. In the process of completing this test programme new methodologies for the testing of WEC arrays have been developed that support the isolation of array interactions from other physical testing artefacts as well as enabling the uncertainty in WEC performance to be estimated. This is considered to be a significant addition to the outcome of this testing programme that will have a major impact on the design of wave tank testing of WEC arrays. Although in general the data quality is high, in the characterisation testing it is lower than desired due to unresolved resonant oscillations in the supporting structure, which was evident to some extent in all the characterisation tests. However, the characterisation testing is not considered to be a critical element of the test programme and has a minimal impact on the extent of validation data produced.

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.

Large array testing

WG2 WP2 D5

DOCUMENT CONTROL SHEET

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Executive Summary

The testing programme devised for producing validation data for the assessment of numerical models of large arrays has been successfully completed. The data has been placed in a set of structured folders and a test catalogue produced as both a plain text file and also an Excel file. In the process of completing this test programme new methodologies for the testing of WEC arrays have been developed that support the isolation of array interactions from other physical testing artefacts as well as enabling the uncertainty in WEC performance to be estimated. This is considered to be a significant addition to the outcome of this testing programme that will have a major impact on the design of wave tank testing of WEC arrays.

Although in general the data quality is high, in the characterisation testing it is lower than desired due to unresolved resonant oscillations in the supporting structure, which was evident to some extent in all the characterisation tests. However, the characterisation testing is not considered to be a critical element of the test programme and has a minimal impact on the extent of validation data produced.

1 Introduction

1.1 Scope of document

The primary component of deliverable WG2 WP2 D5 is the data set of the scale model tests, which is provided separately. The data file catalogue is also provided separately both in plain text and Excel format. This document contains information relating to the structure of the test records so that they can be interpreted correctly. Although not part of the original acceptance criteria, this document also contains further explanation of the testing programme completed and some initial analysis.

1.2 Relationship to other deliverables

The scale model tests included in this deliverable have been specified initially in WG2 WP2 D1 and the design and construction the scale model used for testing in deliverables WG2 WP2 D2-D4 and finally the commissioning of the test facilities in WG2 WP2 D4a.

The data from this deliverable will be used in validation of the numerical models being developed in PerAWaT in WG1; specifically the data will be used for validating the numerical models developed by GL Garrad Hassan in WG1 WP1 D6, the non-linear time domain model in WG1 WP1 D14 and the spectral wave model in WG1 WP2 D5.

1.3 Acceptance criteria

The acceptance criteria for WG2 WP2 D5 is

> *The data set contains a full record of all scale model tests, including parameterisation (and calibration) of set-up. Data provided as plain text files together with an index also supplied as a plain text file. Data set sufficiently commented such that the test conditions producing each result can be clearly understood. Report describes tests undertaken (including methods and all conditions such that a third party could replicate the tests).*

The full data set is contained in the zipped file – WG2 WP2 D5 release.zip
The data catalogue is contained in the plain text file – WG2 WP2 D5 data catalogue.txt
The data catalogue is also contained in the Excel file - WG2 WP2 D5 data catalogue.xlsx

Further details of the testing are included in this document.

2 Test methodology for WEC arrays

2.1 General

The testing programme devised for WG2 WP2 involved testing a significantly larger number of WECs than has previously been tested anywhere worldwide, which has led to the development and use of testing methodologies that may not typically be used when testing WEC arrays. Some of these testing methodologies are essentially pragmatic in that with the large number of devices and data channels greater compromise is required on achieving particular testing conditions than would be desired when testing an isolated or smaller array of WECs in order that the testing programme can be completed in a reasonable time. On the other hand, further testing methodologies are associated with accounting for variability in the wave basin and between models.

Identification of individual array interactions for numerical model validation can be extremely demanding because in many cases the interaction effect would be less than typical uncertainty in the testing environment. Four distinct areas of uncertainty have been identified namely

1. The non-ergodicity of the wave basin due to imperfect wave generation and reflections from the wall of the wave basin
2. The repeatability of performance of a specific WEC model when subjected to the same incident wave train
3. The reproducibility of performance between WEC models when subjected to the same incident wave train
4. The influence of the incident wave train shape on the performance of a non-linear (real) WEC in irregular waves

The non-ergodicity of a wave basin is not generally considered in detail because interest is typically focused on the waves at a single point. In testing WEC arrays this is not adequate because the waves at each WEC location are important. A first-order compensation for this non-ergodicity can be achieved by measuring the waves at each location and using this ‘local’ wave data to estimate the relative performance of each WEC. Consequently, the data set includes records from each location that a WEC is located to compensate for the non-ergodicity if required.

The repeatability and reproducibility of WEC models is fundamentally defined by their design and construction. However, an increase in repeatability and reproducibility generally means an increase in cost and complexity of the WEC model. Without using further analysis this would mean that WEC models that are capable of directly isolating array interactions could each be more expensive and complex than those used independently. Multiplying this expense by the number of models could result in excessive model costs and alternative testing procedures should be considered. With this consideration, multiple array tests with WEC models in different combinations can be used to produce reliable estimates of array performance, together with quantitative estimates of uncertainty. This novel technique for array testing has been used for a number of sea-states with the four WEC array layout and focused wave group testing, where it can be seen that array interactions can be isolated with a reasonable level of confidence. A key characteristic is that the standard deviation of the mean is equal to the sample standard deviation divided by the square-root of the number of samples/tests. However, caution is still required in the analysis because this technique will not identify common-mode biases, which affect all WEC models and these must be considered separately.

For irregular waves the wave train at different locations in a wave basin varies as different wave frequency components have different relative phases at different locations. For a linear system this is not significant; however, the influence of the wave train increases as the non-linearity of the WEC increases. The main non-linearity in the WECs tested in WG2 WP2 is due to the coulomb friction brake and in particular when the buoy stops moving. Consequently, for the WG2 WP2 test programme the coulomb friction brake was set at slightly below optimal damping to reduce non-linearity whilst maintaining a realistic damping level.

Wave basin testing in WG2 WP2 has resulted in the development of testing methodologies appropriate for the modelling of WEC arrays. Work remains to further refine these methodologies to ensure that they are robust and optimised in terms of reducing uncertainty in the tests and understanding the residual uncertainty. However, results shown in Section 4 of this report show that for these tests acceptable levels of uncertainty can be achieved with these testing techniques.

2.2 WG2 WP2 standard testing procedures and notes

An illustration of the wave basin layout used for this test programme is shown in Figure 1 for Configuration B. The axes origin is on the front face of the wave paddles and on the centre-line of the wave basin. The curved sections either side of the wave paddles are vertical panels designed to minimise the generation of transverse waves. The side beaches are created using a rubble mound slope, whilst the end beach is formed using a geo-textile mesh. Figure 2 is a panoramic photograph of the wave basin showing it set-up for Configuration B.

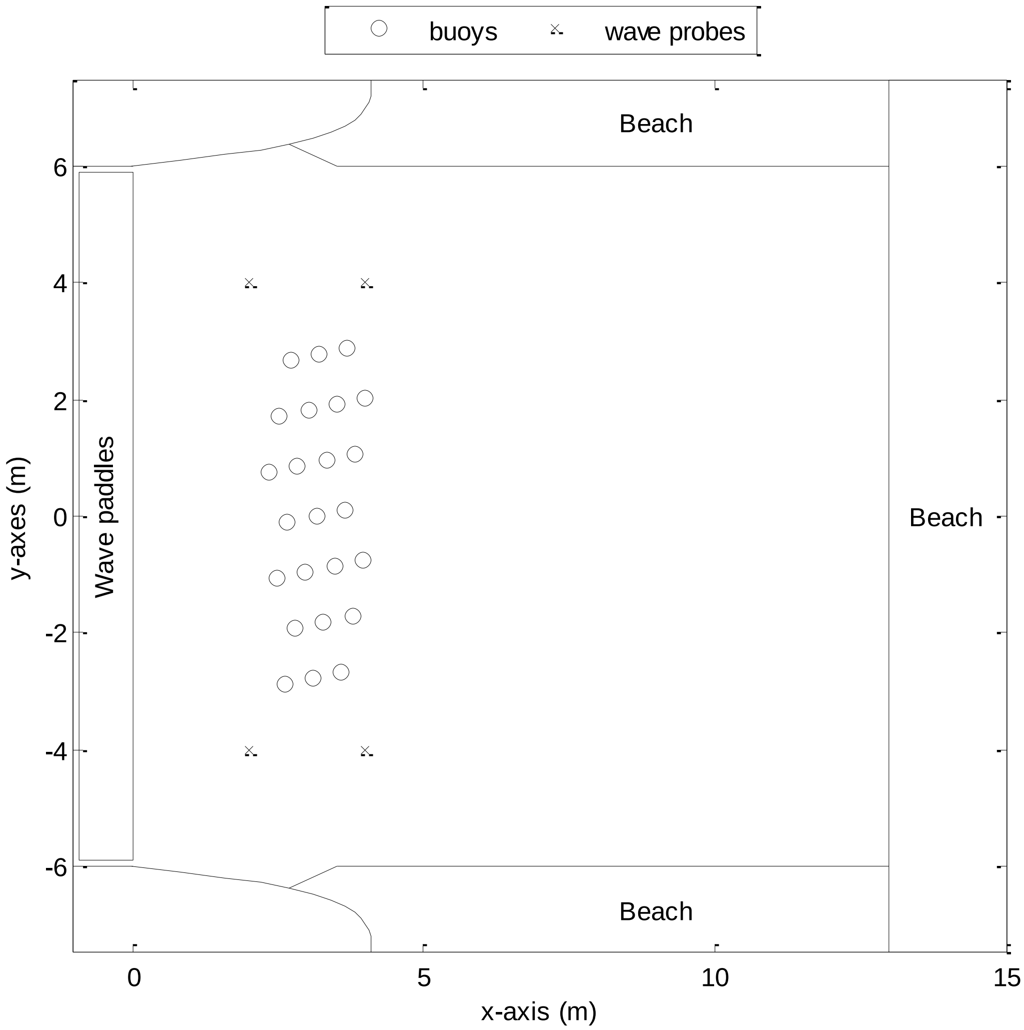

Figure 1: Wave basin coordinate system and layout for Configuration B

Figure 2: Panoramic view of wave basin layout

For each individual test undertaken in WG2 WP2 a standard test procedure was used. This helps to maximise the repeatability of the test results. For all tests, except the focused wave group tests, the basic testing procedure used in WG2 WP2 was to wait until the wave basin reaches a quasi-steady state condition before starting to collect data. The Portaferry wave basin settling time was determined by recording the wave probe signals from wave paddle start-up. The signals from the wave probe signals separated by the repeat time of the wave generation signal are then compared to determine how long it takes for the wave basin to settle (defined as the signal being the same as the signal offset by the wave paddle repeat time). An example of a typical repeat time analysis is shown in Figure 1 where it can be seen that a quasi-steady state condition (the difference between signals separated by the repeat time is less than 0.5 mm) is typically reached after about 40 seconds; a settling time of at least 1 minute was used for all the tests to ensure a quasi-steady state for testing. Figure 3 also illustrates that the variation in response between repeat signals is typically less than 0.5mm, which is confirmed by overlaying the signals after the settling time as shown in Figure 4.

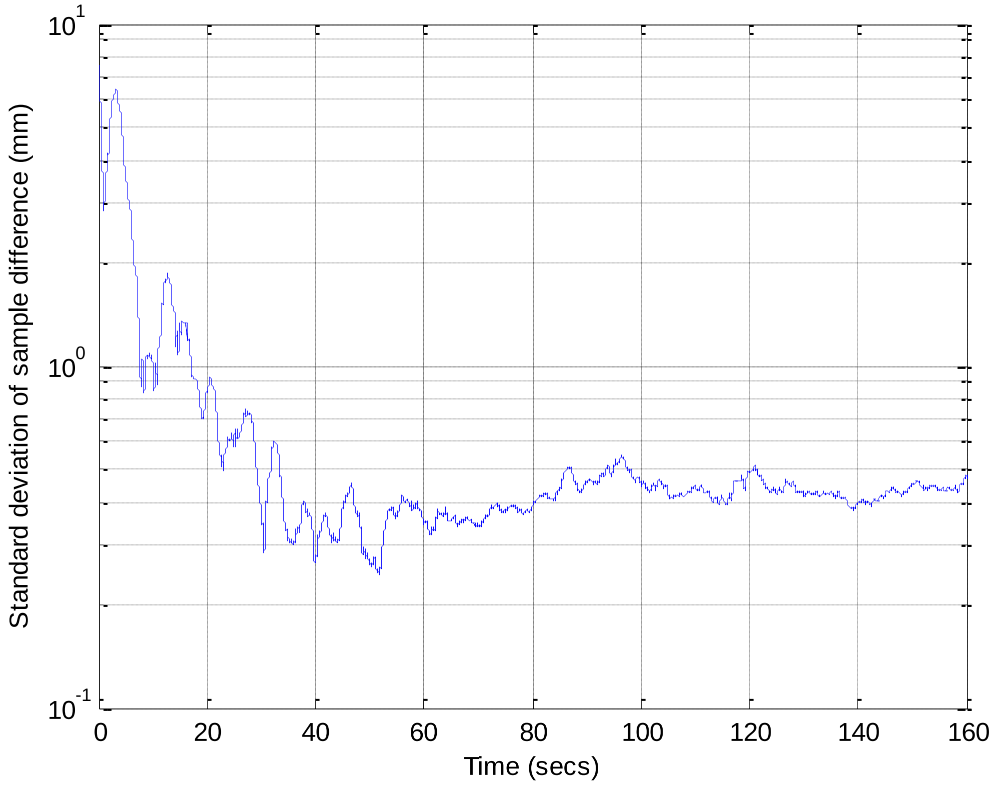

Figure 3: Example settling time analysis for the Portaferry wave basin

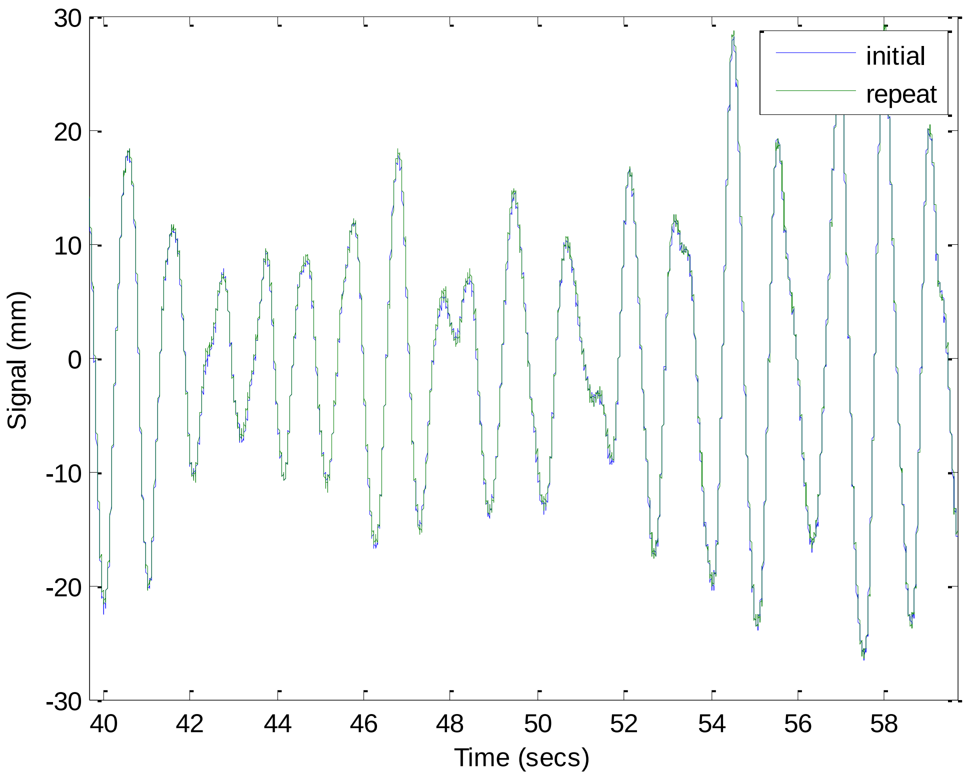

Figure 4: Comparison of initial and repeat signalsfor Portaferry wave basin

Constraints in data collection meant that the wave probe and WEC model signals could not be synchronised, although they were generally started within one second of each other.This is not considered to be a significant limitation since with the large arrays the main focus of the testing is analysis of the statistical response (average power captures and buoy motions) rather than the deterministic response. Moreover, because of the good stability of the generated waves, as illustrated in Figures 3 and 4, the statistical response will be the same irrespective of when the sampling is stated provided that the sample time equals the repeat time. This is true for both the monochromatic waves, which have a sample time and repeat time of 64 seconds and the polychromatic waves, which have a sample and repeat time of 256 seconds. In addition, the tests were not started until the root-mean-square (RMS) of the damping force was within at least 10% of their target values. Typically, this meant that there was between 1 and 5 minutes between starting the wave paddles and collecting data. In test cases where a WEC model could not be controlled to achieve the desired RMS of the damping force, then either the WEC was replaced if the difference was significant, or the test was started when the controller was saturated, i.e. the damping force could not be adjusted any further. Because the damping force is recorded this can be seen in all tests where this occurred.

Data collection (wave probe and WEC model) for the focused wave groups was started with a trigger from the wave paddles. This ensures that the data signals for tests with different phases can be added together easily, which is required when trying to isolate second and higher order components in the data signals.

Unfortunately, some difficulties were experienced with the wave probe data acquisition during the initial testing of the isolated WEC model. The primary purpose of collecting wave probe data during testing of a WEC model is to provide additional confirmation that the correct sea-states were being used for each test. Consequently, although unfortunate this is not considered to be a significant limitation of the data set and re-running of these tests is not necessary. The tests where wave probe data is not available can be clearly identified because they do not have an associated "_WP" file with the same filename root.

3 Data record format

The data for each test is separated, where necessary, into two files; a file containing data from the wave energy converter (WEC) models and a file containing data from the wave probes. For each test the names of the two data files have the same root, but the wave probe filename has the suffix "_WP". Thus, it is possible from inspection to associate the wave probe data with the WEC model data.

Each data record contains a header that describes the test configuration as well as preliminary analysis of the records. Together with the description of the testing procedures provided in Section 2.2 above it should be possible to replicate any of the tests. Example contents of the file headers are provided in Appendix A and B for the WEC model files and the wave probe files respectively. It can be seen that they contain all the relevant information regarding the test set-up (sea-state, water depth, buoy number, target RMS force and location) and the test conditions (date, time and operator).

The header also contains some initial statistical analysis of the data including the representative wave period and height for the wave probe data and the actual RMS force, RMS displacement and average power capture for the WEC model data. This statistical analysis was done without filtering the data and is intended only to provide an initial indication of the data output during testing so that possible testing faults could be detected early. Further data processing may be required to provide greater confidence in the test results.

In all cases, except for the optimum damping tests, the test version number (A – Z) is used for tests repeated with nominally identical conditions. Differences between these tests include changing the buoys used to investigate reproducibility and simply repeating the test to investigate repeatability. Whether reproducibility or repeatability is being investigated can be determined by interrogation of the header in each file. In the optimum damping tests the test version number is used for different damping levels to enable production of the optimum damping curves.

4 Preliminary assessment and analysis of specific data sets

4.1 Characterisation testing

Characterisation testing involved measuring the force on the WEC model when it was held stationary in waves and measuring the force on the WEC model when it is driven in still water. Results from these tests can be used to determine the wave force, added mass and added damping coefficients of the WEC model. The need for characterisation testing developed in wave energy when other methods of producing the hydrodynamic coefficients did not exist. The requirement for characterisation testing is less significant now, but remains part of a typical test programme.

Practically, the WEC model was held stationary by clamping the load cell onto the drive cable so that there is no rotation of the drive pulley. The forced oscillation was achieved by driving the WEC model using an unregulated DC motor through an additional load cell using a crank and throw arrangement. Although the unregulated motor meant that at low frequencies the motion was slightly distorted due to the change in required motor torque with angle of rotation, the distortion was not considered significant.

Unfortunately, during testing an oscillation could be seen in the force measurement associated with a natural frequency within the drive train; the motion was not significantly affected. Possible sources of this oscillation include the support structure, the cable drive and the load cell. However, the limited time in the test programme together with the potential difficulties in locating and resolving the source of oscillation meant that further characterisation tests were not undertaken. Notwithstanding this, it may be possible to filter the force measurement signal to extract the components of interest at the wave or driving frequency and the characterisation test data files are included in the data set.

4.2 Four-buoy array

The four-buoy array was used to assess the reproducibility of the WEC models to determine whether array interactions could be isolated from variation in the WEC model characteristics. A total of 11 sea-states (5 polychromatic and 6 monochromatic) were repeated a total of 12 times. A total of 24 different buoy models were used during this test programme with each buoy used in two different test sets. To minimise the potential for common mode effects to influence the results two different locations were used for each buoy model in the different test sets, together with 3 different buoy models at the other array locations. Not only should this minimise the impact that a single buoy model may have on a particular location, but also provide some indication of the characteristics of each buoy model relative to the response of the average buoy model. Figure 5 below shows the average power capture for the 4 buoy locations with 95% confidence limits in two different sea-states. In the monochromatic sea-state 04 it is clear that there are statistically significant different responses from the 4 buoys. In the polychromatic sea-state 04 any statistical significance is marginal. The statistical significance could be improved by further testing if greater confidence in the results were required. However, it is clear that the methodology described in Section 2 is capable of producing results that are statistically significant and that the WEC model was of sufficient quality to enable array interactions to be isolated.

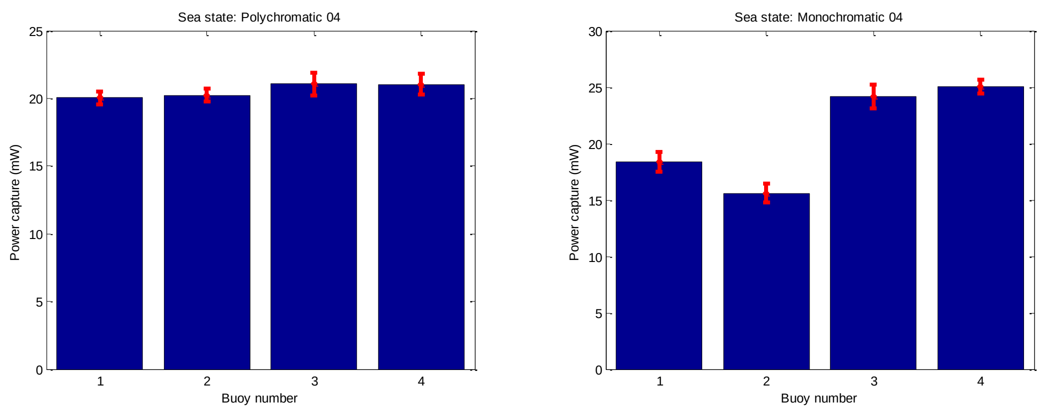

Figure 5: Average power capture with 95% confidence levels of 2 sea-states

4.3 Wave farm

The principle focus of the testing in WG2 WP2 is the testing of large arrays of WECs for validation of the numerical models produced in WG1. Different levels of validation are possible ranging from an array level validation, where the array average power capture is used to a buoy level validation where the average power capture of each buoy is used. Figure 6 shows the variation in average power capture for polychromatic sea-state 3 for three configurations of the array. In these cases the waves are approaching from the left and it can be seen that there is a clear reduction in power capture from left to right consistent with an extraction of wave energy by the WECs. This implies that the data should be of sufficient quality to enable the numerical models to be validated.

In general the data acquisition system worked without issues for the majority of the buoys and tests. However, after completing the testing of Configuration A it was found that the cable to buoy 31 was incorrectly connected and the data from this buoy corrupted. A note of this cable failure is included in all of the affected data files and “NaN” used in Figure 6 below to indicate that no data is available for this buoy. As one of twenty-two buoys the lack of control and data from this buoy is not expected to significantly impact the utility of the validation data and it was decided to not repeat these tests.

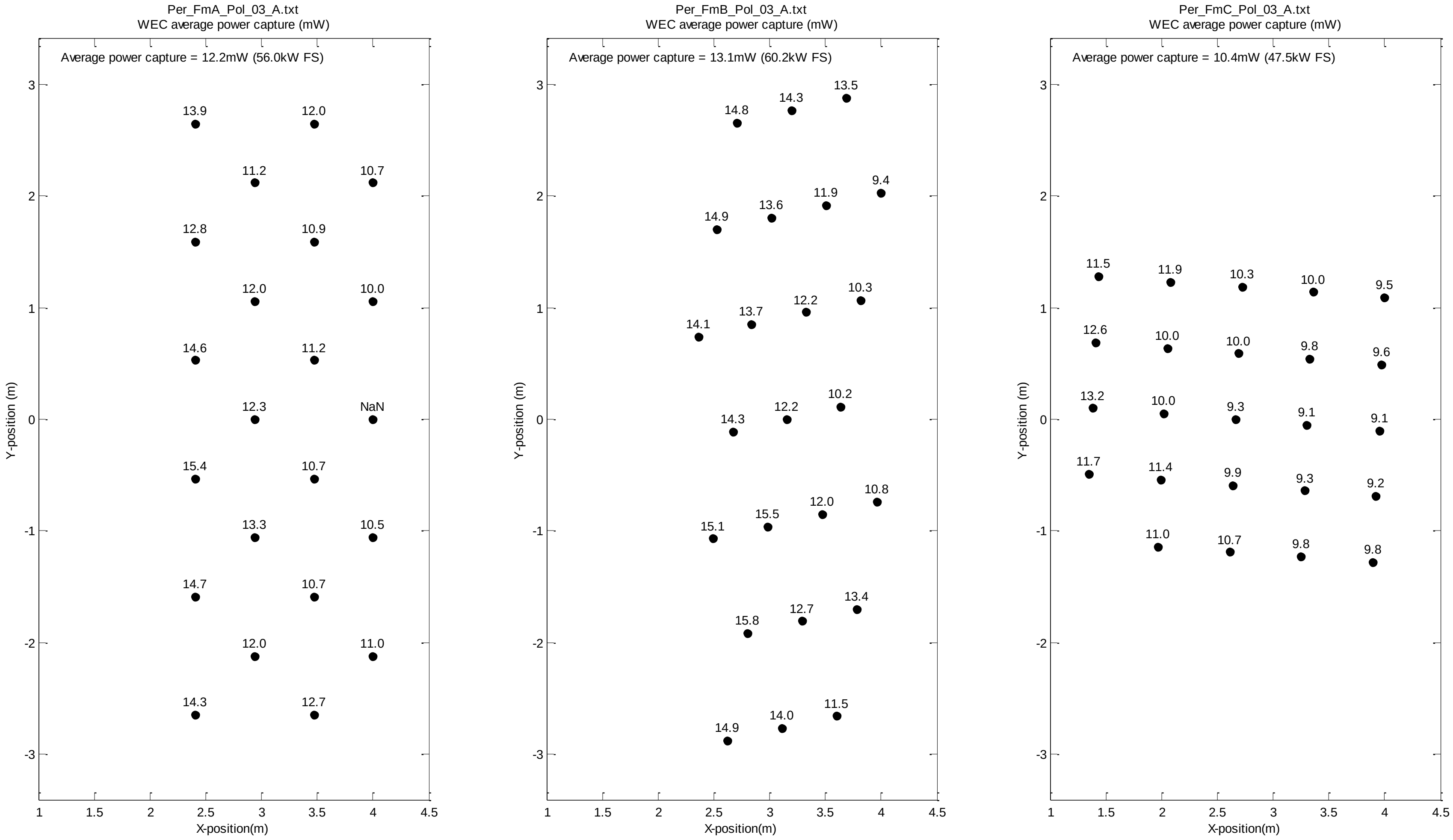

Figure 6: Comparison of WEC average power capture for three large array configurations

Appendix A – WEC model file header

Filename: Per_Squ_Pol_01_A.txt

Date: 25/05/12
Time: 13:10:34

Operator: PLK/MF
Project: WEC array
Configuration: Square
Type of test: Polychromatic
Test number: 1
Version: A

Water depth: 0.625 m
Sampling frequency: 128 Hz

Notes:

Number of WECs: 4

WEC	X	Y	Target RMS Force	Actual RMS Force	RMS displacement	Average power
Unit	metres	metres	Newtons	Newtons	millimetres	milliWatts
1.000	4.000	0.000	0.400	0.414	2.252	4.308
2.000	4.000	-0.750	0.400	0.404	1.995	3.466
3.000	3.250	0.000	0.400	0.414	3.238	6.773
5.000	3.250	-0.750	0.400	0.420	3.296	5.866

Number of data columns: 9

Time	Force_01	Force_02	Force_03	Force_05	Displacement_01	Displacement_02	Displacement_03	Displacement_05
Seconds	Newtons	Newtons	Newtons	Newtons	millimetres	millimetres	millimetres	millimetres
0.008	0.338	0.406	-0.594	-0.510	-2.404	-2.013	-4.340	-2.962
0.016	0.374	0.467	-0.625	-0.437	-2.513	-2.081	-4.230	-2.810

.....

Appendix B – Wave probe file header

```
Filename: Per_Squ_Pol_01_A_WP.txt

Date: 25/5/2012
Time: 13:12:3

Operator: MF/PLK
Project: WEC array
Configuration: Square
Type of test: Polychromatic
Test number: 1
Version: A

Water depth: 0.625 m
Sampling frequency: 128 Hz

Notes:

Number of wave probes: 4
WP          X           Y              Te                Hs
Units       metres      metres         seconds           millimetres
 1          2.000       -4.000         0.749             26.134
 2          2.000       4.000          0.745             25.836
 3          4.000       -4.000         0.745             25.994
 4          4.000       4.000          0.747             27.220

Number of data columns: 5
Time        WP1         WP2            WP3               WP4
seconds     millimetres millimetres    millimetres       millimetres
0.000       -10.889     -10.452        4.146             4.741
0.008       -11.011     -10.629        3.743             4.584
......
```