Programme Area: Marine

Project: PerAWAT

Title: Array Scale Experimental Test Report

Abstract:
This deliverable, the final deliverable in WG4 WP2 presents a summary of the results of the University of Manchester experimental programme – investigating tidal arrays (up to 15 devices in an array). A detailed test description is presented and methodologies of data acquisition and post processing are described. A description of the database of results is presented to enable the reader to interpret the raw data. The key findings of the experimental testing programme are discussed and it is confirmed that the final test schedule meets the requirements specified in WG4 WP2 D1.

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.

GL Garrad Hassan

ETI MARINE PROGRAMME PROJECT
PERAWAT MA1003
WG4WP2 D5
ARRAY SCALE EXPERIMENTAL TEST REPORT

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Issue	Issue date	Summary
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EXECUTIVE SUMMARY

The first deliverable in this work package, WG4 WP2 D1, explains the data required from experimental study of an array of tidal stream devices. The second deliverable, WG4 WP2 D2, details the design of equipment required to conduct the experiments. Topics covered include the generation of ambient flow conditions, method of measurement of time-varying flow- and mechanical parameters, design of small-scale model of a tidal stream turbine and design of a rotor suitable for the low Reynolds number of these experiments ($3x10^4$ approx.). Engineering drawings are supplied for the main items of equipment. The third deliverable (WG4WP2 D3) provides a summary of the equipment that has been installed and purchased. Photographs were provided of the main items of equipment detailed in WG4 WP2 D2. A modified dynamometer design was also described which comprises a bevel gear and motor mounted vertically above waterline. The fourth deliverable (WG4WP2 D4) details the calibration process employed for the equipment used to measure flow conditions and rotor loading and performance. Measurements of the structure of four ambient flows were presented along with the characteristic of the small-scale rotor and of the structure of the wake of a single turbine and pair of turbines. A database of calibration data and measurements of both rotor loading and flow velocity has been produced that includes data for four ambient flows and fifteen different configurations of rotor array. In conjunction with the database, this report constitutes the fifth and final deliverable of WG4 WP2 and presents a summary of the results of the experimental programme. A detailed test description is presented and methodologies of data acquisition and post processing are described. A description of the database of results is presented to enable the reader to interpret the raw data. The key findings of the experimental testing programme are discussed and it is shown that the final test schedule fulfilled the requirements specified in WG4 WP2 D1.

SUMMARY OF NOTATION

P	Power
D	Rotor diameter
A	Area
hh	Hub height
U(z)	Free stream axial flow speed (varying with depth)
TI	Ambient turbulence intensity
Fx	Axial thrust upon rotor
x_H	Length of the near wake
u(x,y,z).	Velocity field
S	Sequence identifier

Indices

x	reference measurement point
s	representative flow state speed-up/slow down map.
i	device index
j	flow speed index
k	flow direction index
g	device grouping index
t	order of analysis per device grouping

Cartesian Co-ordinate systems

x	Axial co-ordinate
y	Transverse co-ordinate
z	Vertical co-ordinate
s	streamline co-ordinate

Abbreviations

1-d	one dimension (typically in the x-direction)
2-d	two dimensions
3-d	three dimensions
ADP	Acoustic Doppler Profiler
CFD	Computational fluid dynamics
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 PerAWaT project progresses.

DEFINITIONS

A flow field is defined by three components of velocity aligned with the global co-ordinate system (U, V, W) = (U_x, U_y, U_z) where the X-axis is aligned to the direction of flow, Y the lateral component and Z the vertical component. At each x, y, z ordinate time varying velocity is measured as e.g.:

$$U(x, y, z, t)$$

Time averaged velocity is defined as

$$U(x, y, z, t) = \overline{U(x, y, z)}$$

Velocity is normalised to either the baseflow at hub height ($U_{0,h}$) or to the baseflow at the same co-ordinate; either at the same depth (U_0(z)) or the same lateral position (U0(y)), e.g:

$$U_{n0h} = \frac{U(x, y, z)}{U_{0,h}}$$

$$U_{n0}(z) = \frac{U(x, y, z)}{U_0(z)} \text{ or } U_{n0}(y) = \frac{U(x, y, z)}{U_0(y)}$$

Velocity deficit is also defined relative either to the baseflow at hub heigh

normalised baseflow (inflow) hub height Uoh

$$U_{d0h} = \frac{U(x, y, z) - U_{0,h}}{U_{0,h}}$$

normalised base flow depth profile Uo(z)

$$U_{d0}(z) = \frac{U(x, y, z) - U_0(z)}{U_0(z)}$$

For this study the lateral profile of the baseflow is assumed to be uniform (see Section 5) in Y and so Unoh, Unoz, Udoh and Udoz are of particular interest.

Several turbulence parameters are of interest including the turbulence intensity and several components of the Reynolds stress. Time-varying turbulent fluctuations are defined as:

$$u = U - \overline{U}$$

where u, v, w are the turbulent fluctuations of velocity in the x,y,z direction and the overbar indicates the time averaged value. Turbulent kinetic energy (TKE) per unit volume of fluid is

$$TKE = \rho \frac{\overline{u^2} + \overline{v^2} + \overline{w^2}}{2} = \rho \frac{\overline{q^2}}{2}$$

Relative turbulence intensity (u'), also referred to as third moment of turbulence, is defined as the standard deviation of the turbulence fluctuation normalised to a component of velocity:

$$u' = \frac{\sqrt{\overline{u^2}}}{\overline{U}}$$

Similarly, turbulence intensity (TI) is defined as the standard deviation of the turbulence fluctuation normalised to the flow speed (Q). For the x-direction this is written:

$$TIx = \frac{\sqrt{\overline{u^2}}}{Q} * 100$$

Equivalent expressions are written in v for TIy and w for TIz where time averaged speed is:

$$Q = \sqrt{\overline{U}^2 + \overline{V}^2 + \overline{W}^2}$$

The Reynolds stress occurs from the cross correlation of orthogonal velocity components. The lateral $\overline{\tau}_{yx}$ and vertical $\overline{\tau}_{zx}$ Reynolds Stresses are of particular interest:

$$\overline{\tau}_{yx} = \mu \frac{\partial \overline{V}}{\partial x} - \rho \overline{vu} \quad \overline{\tau}_{zx} = \mu \frac{\partial \overline{W}}{\partial x} - \rho \overline{wu}$$

Since the molecular viscosity term will be small (of order of e.g. $\mu = 10^{-4}$ and max(dU/dy) < 1) relative to the cross correlation term (of order of 0.01 hence several orders of magnitude larger), only the cross correlation is considered in this study:

$$\bar{\tau}_{yx} \sim -\rho\overline{vu} \quad \bar{\tau}_{zx} \sim -\rho\overline{wu}$$

1 INTRODUCTION

1.1 Scope of this document

This document constitutes the fifth deliverable (D5) of working group 4, work package 2 (WG4WP2) of the PerAWAT (Performance Assessment of Wave and Tidal Arrays) project funded by the Energy Technologies Institute (ETI). The project partners of this work package are the University of Manchester (UoM) and Garrad Hassan (GH). This work package addresses the influence of bounding surfaces (seabed, other devices and free surface) and the characteristics of the incident flow on performance, loading and wake structure. These issues are addressed by a series of small-scale experiments in which an array of tidal stream turbine rotors are studied in a wide channel. The tests are conducted at approximately 1:70th geometric scale using rotors that are specifically designed to produce similar momentum extraction to a generic full-scale rotor design. Earlier deliverables explain the scaling considerations that influence the design of the tests, the specification of the experimental equipment, the design and construction of experimental equipment, the calibration processes employed and the characteristics of the ambient flows and the rotor.

In this report, the experimental purpose and scope is reviewed and comparison is drawn to the programme of completed tests. The experimental and calibration processes are summarised and reference to existing documentation is provided. The method of data collection and documentation is described and the content of the database of test data is explained. The post-processing method used to analyse the data is also described in detail. Finally the initial findings from analysis of the experimental results are presented and discussed.

1.2 Specific tasks associated with WG4 WP2 D5

- Test specification of sufficient detail and scope (D1) to: Evaluate the effect of bounding surfaces and device performance characteristics on the device loading. Evaluate the effect of bounding surfaces, ambient flow field and device performance characteristics on the far wake form. Investigate the wake interactions within an array including influence of varying ambient turbulence intensities (seabed, waves and large eddies). Specification will define the details of: operating points (speeds/torques), instrument type, sample frequencies, acceptable error and experimental programme plan.

- Design of test equipment (D2) [GH & UoM]: This document provides a description of the design methodology for the main items of experimental equipment. Details are given of the approach used for generating the range of flow conditions required, and for measurement of flow characteristics at the temporal and spatial resolution required. The dimensions and component specification of the turbine model are summarised and the rotor design process detailed. An overview is also given of the calibration, data collection and data logging procedures that will be implemented.

- Construction of test equipment (D3) [UoM] including: Rotor (blades, hub, nacelle, generator), Instrumentation system, Support structure, and Alteration to facility equipment.

- Calibration of test equipment for physical scale tests (D4) [UoM&GH] including: flow profile, depth, ambient turbulence and waves. A database of calibration data and summary report will be produced summarising the key calibration tests and results such that turbine tests can be correctly calibrated.

- Conduct physical scale model tidal tank tests, issue database of experimental data and testing report (D5) [GH], including; Data post processing for presentation in experimental database (filtering, quality control etc.), Issue database of experimental data obtained under different current, wave and turbulence conditions

1.3 Experimental Programme

The objectives of WG4WP2, as set out in Schedule 5, are to investigate (through physical testing of an array of up to 15 small devices):

1. the effect of bounding surfaces (free surface, seabed and other devices) on device performance and loading
2. the effect of the bounding surfaces, ambient flow field and device performance characteristics on the far wake form
3. the wake interactions within an array including influence of varying ambient turbulence intensities (seabed, waves and large eddies)

These investigations will be conducted by measuring the rotor loading and wake structure for several array configurations. An outline of the test programme was given in WG4WP2D2. For each array configuration, velocity measurements will be obtained along the axial centreline and a horizontal and vertical traverse of the wake will be conducted at several downstream distances.

1.4 WG4 WP2 D5 acceptance criteria

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

a) Issue database of experimental data
b) Testing report

(a) Database of experimental data (rotor thrust and flow field) obtained under the specified different array layout, current, waves and turbulence conditions specified, provided and clearly annotated such that results in different conditions can be clearly identified. Database of experimental data (in common project format).
(b) Testing report describes the methodology (and assumptions) used for the tank testing and presents the results (measuring rotor thrust, and flow field within and around array) for different layout / array set up scenarios defined in the specification. Report discusses the key findings (effect of lateral spacing on device loading; bounding surface effects on device loading; flow field profiles). Demonstration that the final test schedule fulfilled all initial/specified requirements

This report constitutes the Testing report and also provides reference to the database of experimental.

2 EXPERIMENT SCOPE

As outlined in the first deliverable, the purpose of the scale model experiments described here is to provide experimental data to develop and validate the mathematical models that will be developed as part of WG3WP4 to describe the flow-field within and around a tidal turbine array. This includes measurement of turbine performance and of wake characteristics both downstream of individual devices and downstream of an array of devices. The programme of tests will improve understanding of how bounding surface proximity influences both turbine performance and wake structure.

To achieve the set objectives of WG4WP2, detailed in Section 1.3, three different types of tests were conducted. They included: calibration tests, which provide the necessary information to convert the measured signals to absolute dimensioned values; investigative tests, which provide a sufficient set of measurements for comparison purposes; and, detailed tests offer a refined spatial resolution of velocity measurements and increased sample measurement period for the analysis of parameters such as Reynolds Stresses. In addition to the test types, four principal areas of investigation were identified in WG4WP2D1. These included the effects of blockage and of array wake mixing. Further details of the test types and investigation types are provided below.

2.1 Test types

Calibration tests
The types of calibration tests included:

- Evaluation of the required sampling period and frequency at which data is statistically stable. This will be different dependent on the intended analysis of the data, which includes mean flow characteristics, TI and Reynolds Stress analysis.
- Calibration of individual instruments including ADVs, strain gauges and turbine scale models.

Investigative tests
For investigative tests, velocity measurements will be limited to 1 or 2-dimensional variations depending on the subject of the investigation. For example; when studying multiple rows of devices the velocity at the cross section of the downstream row is more important than the one-dimensional variation of velocity with distance from the upstream turbine.

Detailed tests
For detailed tests, measurements of the 3-dimensional wake-structure are taken along with velocity variations along the wake centreline, i.e. 1-dimensional variation U(x), or the velocity variation across vertical planes parallel to the plane of the rotor and crossing the wake, i.e. 2-dimensional variation U(y,z). Combined, these velocity measurements form a 3-dimensional description of the wake structure. During all tests involving rotors, the following parameters will be measured:

Angular speed of each turbine
Mechanical torque applied to the rotor shaft of each turbine
Horizontal thrust on each rotor
Time-varying velocities at various points up- and down-stream of devices

2.2 Investigations

Characterisation experiments
These experiments include:

1. Ambient flow:

Flume characteristics in the absence of rotors i.e. measurement of in-flow conditions characterising the mean velocity and ambient turbulence intensity depth and lateral profile and how these characteristics develop downstream.

2. Rotor characteristics:

Varying rotor speed tests to characterise rotor performance i .e. measurement of the rotor C_T & C_P over a range of operating states (TSRs)

3. Baseline single wake:

Single wake mapping from the near to far wake with sample duration sufficient to evaluate Reynolds Stress (it is of particular interest to find the distance downstream where the shear layer meets the centreline). The wake structure (sectional shape) and velocity deficits also to be measured.

Blockage experiments
These experiments are designed to investigate the effect of blockage on the turbine operating point and the wake structure. This should include the influence of free surface proximity[1] and of lateral spacing on turbine operating point and wake structure.

1. Measurements of the rotor forces
2. Measurements of the local flow field at several locations outside of the turbine streamtube to provide a check for the mathematical modelling of the effect of blockage on the surrounding flow-field.

Multi-row wake experiments
These experiments are designed to investigate the effect of wake boundary conditions on the wake structure.

1. Array configurations where rotor wakes are constrained on one- and/or both- sides by the wake of an adjacent device.
   i. Variation of lateral spacing
   ii. Variation of longitudinal spacing
2. Increasing array size
   i. laterally
   ii. adding additional rows
3. Investigation of staggered array layouts in which downstream device is partially within the wake of an upstream device.

Ambient flow sensitivity experiments
These experiments are designed to investigate the effect of varying ambient conditions on wake structure and recovery, including waves, added seabed roughness and a large eddy flow structure induced by a conical island upstream of the array.

[1] The effect of free surface proximity was relocated to different work package.

3 EXPERIMENTAL SET-UP AND PROCEDURE

The experimental set-up used in this experimental programme can be found in WG3WP4 D2 *Design of Equipment for Scale Model Experiments* and WG3WP4 D3 *Construction of Test Equipment for Scale Model Experiments*. The WG3WP4 D2 report details the design of experimental equipment, including the generation of ambient flow conditions, method of measurement of time-varying flow- and mechanical parameters, design of small-scale model of a tidal stream turbine and design of a rotor suitable for the low Reynolds number of these experiments ($3x10^4$ approx.) and engineering drawings for the main items of equipment. The WG3WP4 D3 report confirms the final experimental set-up and details the data logging system.

The results of the calibration tests are presented in WG3WP4D4 *Calibration report for Scale Model Experiments*. The WG3WP4 D4 report details the calibration of the experimental flow conditions, rotor and electro-mechanical systems. Measurements of the flow structure of four ambient flows, of the characteristic of the small-scale rotor and of the structure of the wake of a single turbine and pair of turbines are also presented.

3.1 General set-up

All tests were conducted in the University of Manchester wide flume at a water depth of 0.45 m. The flume is 5 m wide and the test section is 12 m in length. A porous weir has been installed at the inflow as detailed in WG4WP2D3. For all tests the fixed pitch rotor of diameter D = 270 mm is located at mid-depth and the first row located at X = 6 m measured from the inflow weir (Figure 3-1 and Figure 3-2). A left-handed global co-ordinate system is used in which X is aligned with the direction of the flow, Y is horizontal across the width of the flume and z is vertical (positive upwards). The experimental data defining the location of each rotors is provided in this global coordinate system, however, the measured flow data is supplied in a coordinate system relative to the ADV orientation. Details of the local ADV coordinate system are specified within the data log documentation (see Section 4 for further details). Within the post-processing analysis the data is non-dimensionalised into rotor diameters and made relative to the rotor located at the centre of the flume (i.e. in multiples of rotor diameter D = 270 mm away from the rotor nearest the flume centre) or to the flow depth (i.e. in multiples of flow depth h = 450 mm).

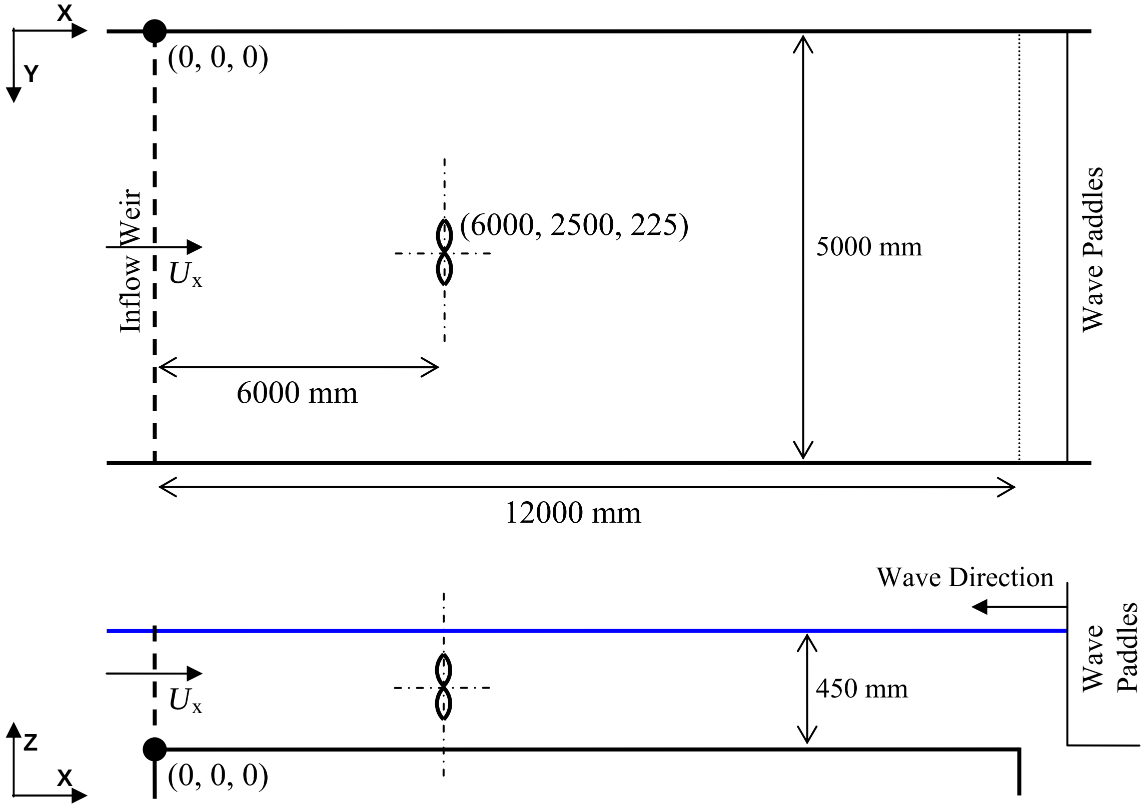

Figure 3-1: Longitudinal arrangement of flume indicating key dimensions and global co-ordinate system. NOT TO SCALE.

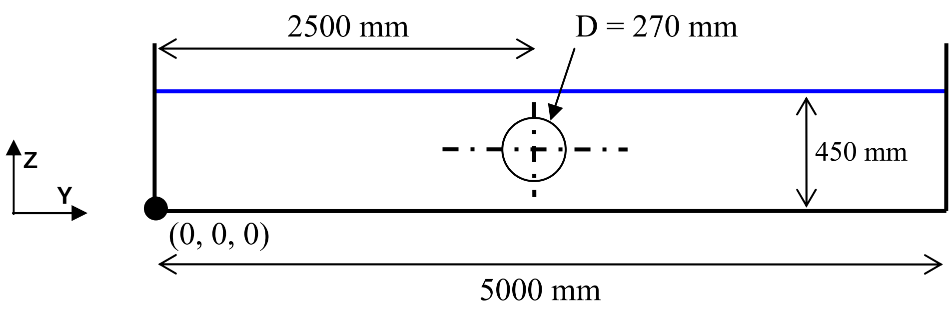

Figure 3-2: Lateral arrangement of flume indicating key dimensions and global co-ordinate system. NOT TO SCALE.

3.2 Experiment procedure

For each of the array configurations or flow conditions detailed in Section 4, the same equipment and procedure was employed. Arrays were studied in order of increasing rotor number. Prior to the first use of each dynamometer a series of calibrations were conducted according to the procedures detailed in WG4WP2D4. The main stages of calibration are summarised in 3.2.1. For each array configuration, a series of set-up activities were conducted (3.2.2) prior to data collection (3.2.3). Time-varying data is stored in a comparable format for all experiments as described in 3.2.4.

3.2.1 Dynamometer Set-Up Procedure

The WG3WP4 D2 report details the hydrodynamic, mechanical, electrical and structural design of the 1/70th scale rotor used in the experiments.

For each dynamometer the following are obtained:

Motor torque constant (Nm/A):	Calibration at UoM prior to dynamometer construction.
Assist current to voltage scale (A/V):	Calibration prior to use of dynamometer.
Strain gauge calibration (N/V)	Calibration prior to use of dynamometer.

Details of these values are proved in the documentation associated with each test.

Note that the scale factor between current and voltage is only required since the measured bridge current is output as a voltage. The scale factor is specified within the firmware for all dynamometers as V = A-xx +2.5 but differs slightly between devices due to different cable lengths employed.

3.2.2 Array Test Procedure

For a particular array configuration, set-up was conducted in the following stages

- All instrumentation connected to NI datalogger.

- ADV operation confirmed:
- Flow sample of 60 s duration recorded with all ADVs using NORTEK software Polysync, data saved in binary format (*.nor file) and ascii files of both SNR (*.snr) and COR (*.cor) extracted using NORTEK Polysync software.
- Files generated: testdescription.nor
  testdescription.snr
  testdescription.cor

- Note: SNR and COR are only recorded prior to collection of time-varying velocity and dynamometer measurements. Since average SNR and COR are a function of measurement volume and flow seeding it is assumed that these properties will not vary between measurements. Comparison of subsequent tests confirms this assumption.

- Rotor operation confirmed:
- Thrust and tip-speed ratio measured for each rotor either in isolation or at wide spacing on a single row (lateral spacing > 3D) to confirm applied torque is sufficient for rotor to operate at TSR ~ 4.5. Applied torque is specified as an applied retarding current (Igen) and an assisting current (Ifric). The assisting current is selected to avoid the onset of stall and so differs between dynamometers. Applied torque is recorded as a voltage that is proportional to the current applied to the motor.
- Files generated: **PerAWaTNN_igenNNN_ifricminusNNN_1.dat**
  Three repeats. NN will either be a two-digit number referring to the PerAWaTxx dynamometer tested in isolation or a concatenation of multiple two-digit numbers when multiple rotors tested simultaneously.

- Note: If large changes observed in Ifric or Igen since the previous test with same dynamometer then remedial action taken and data re-recorded to confirm operation.

- Install rotors in test configuration.

3.2.3 Data Collection Procedure

After set up of the array, the following stages were conducted for each traverse:

- Position gantry at required longitudinal position (X-). Note that longitudinal positioning of the gantry (X-) is a manual process whereas lateral (Y-) and vertical (Z-) traverses are automated. Longitudinal positions were marked along both sides of the flume relative to the rotor plane to ensure the same measurement increments were employed.

- Measure baseline:
- Zero offset measured for all instruments prior to commencing flow (noflowhanging,dat). This has the same format as each of the *.dat files recorded during the experiment.
- File generated: **noflowhanging.dat**
  For large arrays, filename is prefixed by list e.g. p1p2p3 of the dynamometer column order (see readme file corresponding to test).

- Traverse table co-ordinates defined as list of horizontal, HZ = xxx, and vertical VT = zzz, co-ordinates. Note that the position of each of the ADVs located on the traverse table is defined relative to HZ and VT in the readme file for each experiment. See section 5.3.3. For a longitudinal traverse, this stage comprises a single point.

- Data logging. A Labview interface At each traverse table position:
  - Horizontal and Vertical position read from filename 'coords.dat'
  - Traverse table driven to specified co-ordinates and position confirmed.
  - A filename for time-varying data is generated based on traverse table position.
  - File generated: **ADV_Data_HZxxxx_VT_zzz_.dat**.
  - All instruments sampled at 200 Hz for 60 s and data written to file in ascii format.
  - File closed, traverse table repositioned to next co-ordinate, 60 s delay, repeat measurement process at next position.

3.2.4 Data File Structure

Format of File ADV_Data_HZxxxx_VT_zzz.dat is defined in a '**readme.doc**' file.
Format of File ADV_Data_HZxxxx_VT_zzz.dat is identical to noflowhanging.dat for the same test.
A unique readme.doc is produced for each traverse.

A description of the readme file and typical column order of ADV_Data_HZxxxx_VT_zzz.dat is given below, further details of data analysis process are given in Section 5.1. In all cases the column order of the *.dat files is (from left to right):

ADV measurements: 4 No. columns for each of N ADVs
Ux Uy Uz Uz'
where the suffix denotes ADV co-ordinate system.
Units: cm/s for all columns
Nth ADV (i.e. last four columns of ADV data) is the incident flow.

Thrust Measurements: 1 column per force measurement
Units: voltage. Conversion scale (V/N) given in readme.doc.

In general, tests with multiple rows or more than 3 rotors include measurement of Fx only; one force component per dynamometer. However, the readme file should be checked for each test.

Angular Position: 1 column per dynamometer
Units: rad. Obtain angular speed by differentiation.

Torque Voltage: 1 column per dynamometer
Units: voltage. Conversion scale (A/V, Amps per Volt) to obtain instantaneous current and subsequently conversion (Torque per Amp) given in readme.doc

Note that the column order of the thrust measurements (e.g. PerAWaT01, 02,03) is NOT always the same as the column order for Angular Position and TorqueVoltage (e.g. these may be PerAWaT02, 01, 03). Column order of Angular Position is always the same as TorqueVoltage.

Thus, for N = 2 ADVs and M = 3 dynamometers measuring one force component (Fx) only on each dynamometer there are 17 columns of data and the column order is as follows:

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
ADV1				ADV2				Forces			Angular Position			TorqueVolt		
Ux	Uy	Uz	Uz’	Ux	Uy	Uz	Uz’	Fx1	Fx2	Fx3	ϕA	ϕB	fC	vA	vB	vC

Note: this section provides an overview of the structure of the data files but the readme.doc specific to the test-data analysed should always be employed.

4 DATA COLLECTION

Data has been collected for several types of experiment . These are grouped into four categories:

- Characterisation
- Blockage
- Multi-Row wakes
- Ambient flow sensitivity

These investigations include four different incident flows, a study of a single rotor and fifteen different configurations of rotor array. The data collected addresses the requirements for Calibration Tests, Blockage Tests and Array Wake Tests described in Section 4 of WG4 WP2 D1. A brief description of each type group of tests is given in Sections 4.1-4.4 and a complete list of both the flow-conditions and array configurations studied is given in Table 4(a) – 4(d). This table describes the configuration of the rotor array and range of flow measurement positions for each test. A sketch of each configuration is also given in Appendix A.

For each detailed wake study, two types of traverse were conducted:

- Longitudinal traverse comprising Nx points over the range xmin to xmax downstream of each rotor and on the axial centreline of each rotor.
- Automated traverse at each of NXPOS downstream positions. Each traverse comprises:
  - A spanwise traverse U(Y) across the expected width of the wake
  - A depth profile U(Z) across the centreline of each roto

For all studies including a rotor, the time-varying thrust, angular speed and torque were recorded.

In the following sections, a summary is given of the completed tests and comparison drawn to the programme of experiments summarised in Table 4.4 of WG4WP2D1.

4.1 Characterisation experiments

The spatial variation of flow velocity across the vertical plane has been measured at a minimum of two longitudinal ordinates of four baseflows. This provides the depth profile of mean velocity and turbulence characteristics over the extent of the wakes studied.

Four baseflows are given in:

- Test No. 3: Ambient Flow (Table 4(a), also see WG4WP2D4 for details)
- Test No. 2: Ambient Flow with waves (Table 4(a), also see WG4WP2D4 for details)
- Test No. 25: Rough Bed, Table 4(d).
- Test No. 26: Oscillatory flow downstream of conical island, Table 4(d).

Sufficient rotor data has been obtained to provide a baseline against which the effects of lateral spacing, of row spacing and of flow modification on both thrust coefficient and wake structure can be evaluated.

A rotor CT(TSR) curve is given in:

- Test No. 4: For two dynamometers

A study of the wake of a single rotor is given in:

- Test No. 5: Due to the ambient flow of Test 2
- Test No. 26a: Due to the rough-bed flow of Test 25.

Table 4(a): Characterisation of baseflow, single rotor performance and wake

REF	Description	Array Configuration Nrow	Nrotor	Spacing C-C	Spacing Row	Longitudinal U(x) (Diameter multiples) nX	Xmin	Xmax	Lateral Traverse - U(Y) (dY = Width from CL) nXPOS	XPOS	dY	Depth Profile, U(Z) (per traverse) nXY(Z)	nZ
2	**Baseflow & waves (with weir)**	0	0	n/a	n/a	**0**	n/a	n/a	**2**				
2.1	Contour at 7.5 m from weir									7.5 m	wall	**18**	40
2.2	Contour at 9.0 m from weir									9.0 m	wall	**18**	40
3	**Baseflow**	0	0	n/a	n/a	**0**	n/a	n/a	**3**				
3.1	Contour at 6 m from weir									6.0 m	wall	**18**	40
3.2	Contour at 7.5 m from weir									7.5 m	wall	**18**	40
3.3	Contour at 9.0 m from weir									9.0 m	wall	**18**	40
4	**Rotor Characterisation**												
4.1	Single device performance		1	n/a	n/a	**0**	n/a	n/a	**1**	1D	-	**0**	-
4.2	Single device performance		1	n/a	n/a	**0**	n/a	n/a	**1**	1D	-	**0**	-
4.3	Single device performance		1	n/a	n/a	**0**	n/a	n/a	**1**	1D	-	**0**	-
5	**Wake Characterisation**												
5.1	Longitudinal		1	n/a	n/a	**10**	1.5	20	**2**	at 2D, 4D			
5.2	Traverse at 2D									2D	2	**1**	40
5.3	Traverse at 4D									4D	2	**1**	40

Isolated device baseline data (from Table 4.4 of WG4WP2D1)

Test description	**Variables and ranges**	**Measurements**	**Test Type**	**Blockage (Y/N)**	**Wake (Y/N)**	**Complete**
Operating point beneath free-surface	Operating point (TSR & C_{T0})	Thrust and power, Flow field, Reynolds stresses	Detailed	Y	Y	Y

4.2 Blockage experiments

The effect of blockage on operating point (rotor thrust & tip speed ratio) and wake structure has been studied for lateral rotor spacing of 1.5D to 3.0D (Table 4.b). Detailed wake studies have been conducted for rows of 2 (Tests 6-8), 3 (Tests 9–11, 13) and 5 (Test 18) rotors. For all blockage tests, dynamometer torque was specified such that the average operating point of each rotor when in isolation corresponds to TSR ~ 4.5. This was confirmed for each dynamometer prior to each test. As discussed in WG4WP2D3, this operating point corresponds to the predicted maximum of power coefficient for the scale rotor employed. Blockage measurements have not been obtained for different operating points (e.g. different average CT(TSR)) due to the relatively narrow range of operating speeds of the small-scale rotor and to allow direct comparison between all tests.

Table 4(b): Array configurations and corresponding measurement ranges: **single row**

		Array Configuration		Spacing		Longitudinal U(x) (Diameter multiples)			Lateral Traverse - U(Y) (dY = Width from CL)			Depth Profile, U(Z) (per traverse)	
REF	Description	Nrow	Nrotor	C-C	Row	nX	Xmin	Xmax	nXPOS	XPOS	dY	nXY(Z)	nZ
	Blockage study: TWO rotors												
6	2 device blockage (A)	1	**2**	1.5	n/a	**13**	1.5	20	**2**	2D, 4D	2.25	**2**	40
7	2 device blockage (B)	1	**2**	2	n/a	**13**	1.5	20	**3**	2D, 4D	2.5	**2**	40
8	2 device blockage (C)	1	**2**	3	n/a	**13**	1.5	20	**3**	2D, 4D	3	**2**	40
	Blockage study THREE rotors												
9	3 device blockage (A)	1	**3**	1.5	n/a	**13**	0	20	**2**	2D, 4D	3	**3**	40
10	3 device blockage (B)	1	**3**	2	n/a	**13**	1.5	20	**2**	2D, 4D	3.5	**3**	40
11	3 device blockage (C)	1	**3**	3	n/a	**13**	1.5	20	**2**	2D, 4D	4.5	**3**	40
12	3 device blockage + WAVES		**3**	1.5	n/a	**13**	0	20	**2**	2D, 4D	3	**3**	40
13	**As test 9, traverses at 6D, 8D, 10D, 12D**												
13.1	Longitudinal	1	**3**	**1.5**	n/a	**13**	**1.5**	**20**	**4**	from 6D to 12D			
13.2	traverse at 6D									6	3.5	**3**	40
13.3	traverse at 8D									8	3.5	**3**	40
13.4	traverse at 10D									10	3.5	**3**	40
13.5	traverse at 10D (WITH WAVES)									10	3.5	**3**	40
13.6	traverse at 12D									12	3.5	**3**	40
	Blockage Study FIVE rotors												
18	**One row of 5 devices, FIVE traverses**												
18.1	Longitudinal	1	**5**	**1.5**	n/a	**13**	1.5	20	**5**	from 2D to 12D			
18.2	traverse at 2D									2	4.5	**5**	40
18.3	traverse at 4D									4	5	**5**	40
18.4	traverse at 8D									8	5	**5**	40
18.5	traverse at 10D									10	5	**5**	40
18.6	traverse at 12D									12	5	**5**	40

These measurements do not directly address the sensitivity of blockage effects to yaw angle, depth to diameter ratio and flow speed (Table 4.4 of WG4WP2D1) since each are the subject of detailed analysis in other work packages. All blockage tests were conducted in the same incident flow (Test No. 3) with a mean speed of approximately 0.46 m/s. However, some data for rotors in a flow of reduced mean velocity, but different depth profile, is available from Tests 15, 19, 20A, 23 and 24 (Table 4.c) in which a second row is located 8D downstream of a row of 3 rotors (see Section 4.3). The effects of operating point and flow speed on wake structure are studied WG4WP1 and WG3WP4. The effect of depth to diameter ratio has not been studied due to the combined constraints of maximising flume width and maximising rotor diameter (see scaling considerations of WG4WP2D2). Free surface proximity will be addressed in WG4WP1.5. Yaw effects are not practical at this scale.

Effect of blockage on performance & wake structure (Tests with 2 - 3 turbines) (from Table 4.4 of WG4WP2D1)

Test description	**Variables and ranges**	**Measurements**	**Test Type**	**Blockage (Y/N)**	**Wake (Y/N)**	**Complete**
Operating point	TSR, C_{T0} 0.3 – 0.9	Thrust and power, Rotor speed, Flow field	Calibration	N	N	Y
Lateral spacing	~0.5D increments		Detailed	Y	Y	Y
Yaw angle	~10 degree increments.		Investigative	N	Y	N
Depth/Diameter ratio	Depth ~1.5D-3D		Investigation	Y	Y	WP1.5
Flow speed	Flow rate		Investigation	Y	Y	Y

4.3 Multi-Row wake experiments

Seven arrays of two rows and one three-row array (Table 4.c) have been studied to assess the effects of longitudinal spacing and lateral spacing (Table 4.4 of WG4WP2D1). For each multi-row test, a detailed wake study is conducted downstream of the second row only (i.e. not between rows).

The effect of longitudinal spacing is addressed by comparison of:

- Tests No. 14 & 15: for rotors with axis aligned
- Tests No. 20, 20A and 21: for rotors arranged in a staggered array.

For these five tests, incident flow to the second row is included in the wake measurements of Test 13.

The effect of lateral spacing is addressed by comparison of:

- Tests 15 & 23: three rotors
- Tests 19 & 24: five rotors, 2^{nd} row incident flow obtained from Test 18.

As for the blockage tests, the operating point is equal for all rotors and the depth to diameter ratio is equal for all tests.

Table 4(c): Array configurations and corresponding measurement ranges: **multiple rows**

		Array Configuration				Longitudinal U(x) (Diameter multiples)			Lateral Traverse - U(Y) (dY = Width from CL)			Depth Profile, U(Z) (per traverse)	
				Spacing									
REF	Description	Nrow	Nrotor	C-C	Row	nX	Xmin	Xmax	nXPOS	XPOS	dY	nXY(Z)	nZ
	Multiple Rows of 3 at 1.5D lateral spacing												
14	**Two rows of 3 rotors (interrow = 10D)**												
14.1	Longitudinal	2	**6**	1.5	**0,10**	**8**	11.5	20	**0**	no traverses			
15	**Two rows of 3 rotors (interrow = 8D)**												
15.1	Longitudinal	2	**6**	1.5	**0,8**	**10**	9.5	20	**2**	at 10D, 12D			
15.2	traverse at 10D (2D from rotors)									10	3.5	**3**	40
15.3	traverse at 12D (4D from rotors)									12	3.5	**3**	40
16.1	traverse at 12D (4D from rotors WITH WAVES)									12	3.5	**3**	40
16.2	Longitudinal (WITH WAVES)					**10**	9.5	20	**0**				
	Multiple rows of >3 at 1.5D lateral spacing												
19	**Two rows of 5 devices (aligned)**												
19.1	Longitudinal	2	**10**	1.5	**0,8**	**10**	9.5	20	**2**	at 10D, 12D			
19.2	Traverse at 10D									10	5	**5**	40
19.3	Traverse at 12D									12	3.5	**5**	40
20	**Two rows staggered 3 and 4**												
20.1	Longitudinal	2	**7**	1.5	**0,4**	**10**	5.5	20	**4**	from 6D to 12D			
20.2	Traverse at 6D									6	3.875	**4**	40
20.3	Traverse at 8D									8	3.875	**4**	40
20.4	Traverse at 10D									10	3.875	**4**	40
20.5	Traverse at 12D									12	3.875	**4**	40
20A	**Two rows staggered 3 and 4**												
20a.1	Longitudinal	2	**7**	1.5	**0,8**	**10**	9.5	20	**2**	at 10D, 12D			
20a.2	Traverse at 10D (from 1st row)									10	3.875	**4**	40
20a.3	Traverse at 12D (from 1st row)									12	3.875	**4**	40
21	**Three rows staggered 3, 4 and 5**												
21.1	Longitudinal	3	12	1.5	**0,4,8**	**10**	9.5	20	**2**	at 10D, 12D			
21.2	Traverse at 10D									10	4.25	**5**	40
21.3	Traverse at 12D									12	4.25	**5**	40
	Multiple rows at 2.0D lateral spacing												
23	**Two rows of 3 rotors (narrow row spacing)**												
23.1	Longitudinal	2	6	2	**0,8**	**10**	9.5	20	**2**	at 10D,12D			
23.4	traverse at 10D (from 1st row)									10	3.5	**3**	40
23.5	traverse at 12 D (from 1st row)									12	3.5	**3**	40
24	**Two rows of 5 devices (aligned)**												
24.1	Longitudinal	2	10	2	**0,8**	**10**	9.5	20	**2**	at 10D, 12D			
24.2	Traverse at 10D									10	5	**5**	40
24.3	Traverse at 12D									12	3.5	**5**	40

Multi-row arrays in currents (up to 3x5) (from Table 4.4 of WG4WP2D1)

Test description	**Variables and ranges**	**Measurements**	**Test Type**	**Blockage (Y/N)**	**Wake (Y/N)**	**Complete**
Operating point	TSR & C_{T0}	Thrust and power, Rotor speed, Flow field	Detailed	Y	Y	See text on p.18
Longitudinal spacing	~2D increments		Detailed	Y	Y	Y
Lateral spacing	~0.5D increments		Detailed	Y	Y	Y
Depth/Diameter ratio	Depth ~1.5D-3D		Investigative	Y	Y	(WP1.5)

The rotor set points were not varied within the multi-row tests as originally planned for the same reason given in Section 4.2. A more detailed investigation of rotor operation on near wake form will be undertaken in WG4WP1.

Note that the multi-row configurations listed in Table 4.c differ slightly from the test programme proposed in WG4WP2D4. The main change to the programme is that tests of multiple rows of aligned rotors at 4D longitudinal spacing have been removed, these include:

- Two rows of 3 rotors at 4D longitudinal spacing.
- Two rows of 5 rotors at 4D longitudinal spacing.
- Three rows of 3 rotors at 4D longitudinal spacing.

Staggered arrays (Tests 20A and 21) or wider spacing (Test 23) were studied instead. Aligned rotors at 4D longitudinal spacing were not studied since preliminary tests indicated that all rotors on the second row remained stalled. At 4D downstream of a row of 3 rotors (Test No. 09) the centreline velocity deficit is approximately 40% and so flow velocity is too low for the rotor to operate. For the same reason, the two-row configuration was not tested for either the rough-bed or island-wake incident flows. This allowed a focus on the effect of turbulence on the wakes of a single rotor and row of three rotors.

4.4 Ambient flow sensitivity experiments

The ambient flow for the majority of blockage and multi-row tests corresponds to Test No. 3 (Table 4(a). Sensitivity of rotor performance and wake structure to different ambient flows is considered for a single-rotor and for a row of three rotors at 1.5D lateral spacing.

A detailed study of sensitivity to opposing waves (Test No. 2) is given by:

Test No. 12: blockage study comparable to Test No. 9
Test No. 16: multi-row study comparable to Test No. 15.
Test 16 10D wake traverse is also comparable to Test 13 2D wake traverse.

A detailed study of wake recovery due to the elevated turbulence intensity generated within the boundary layer of a rough bed (Test No. 25) is given by:

Test No. 26a: single rotor characterisation comparable to Test No. 5
Test No. 26: blockage study comparable to Test No. 9

Details of the rough bed material – geogrid – are given in WG4WP2D3. The grid is 45 mm thick. A panel of 2.5 m width and 4m long upstream and 4.5 m downstream of the line of rotors (centre of the flume) was employed. This size of plate ensures the flow is developed by the time it reaches the rotors and that it remains developed over the length of the test section.

An investigative study of rotor loading and wake recovery due to a flow with large-horizontal length-scale generated by flow separation around an immersed conical island (Test No. 28B) is given by:

Test No. 30B: single rotor characterisation comparable to Test No. 5
Test No. 29B: blockage study comparable to Test No. 9

The island wake studies 28B, 29B and 30B are in a water depth of 500 mm not 460 mm as used for all other tests. The island flow therefore differs from the island wake reported in WG4WP2D3 measured for a water depth of 460 mm. A detailed loading and wake study was completed for a row of three rotors in 460 mm depth but frequent rotor stall was observed. Preliminary analysis suggests that this is due to the angle of the incident flow varying through a range of $\pm 20^{o}$ during each oscillation cycle. Data for both the ambient flow of the island wake at 460 mm depth and the three-rotor wake study are referenced as Test No. 28 and 29 respectively for use as supplementary data.

These single-rotor and blockage studies allow assessment of the effect of unsteady ambient flow on arrays for rotors at a comparable operating point (se Table 4.4. of WG4 WP2 D1).

Table 4(d): Array configurations and corresponding measurement ranges: **rough bed**

		Array Configuration				Longitudinal U(x) (Diameter multiples)			Lateral Traverse - U(Y) (dY = Width from CL)			Depth Profile, U(Z) (per traverse)	
				Spacing									
REF	Description	Nrow	Nrotor	C-C	Row	nX	Xmin	Xmax	nXPOS	XPOS	dY	nXY(Z)	nZ
	Added TI: wake modification												
25	**Flow over rough bed**	0	0	n/a	n/a	**0**	n/a	n/a	**2**				
25.1	Contour at 6 m									6 m	1.25 m	**9**	40
25.2	Contour at 7.5 m									7.5 m	1.25 m	**9**	40
26	**Single row (3 devices) on ROUGH bed**												
26.1	Longitudinal	1	3	**1.5**	0	**13**	1.5	20	**2**	at 2D, 4D			
26.2	Traverse at 2D									2	4.5	**3**	40
26.3	Traverse at 4D									4	5	**3**	40
26.4	Traverse at 8D									8	5	**3**	40
26.5	Traverse at 10D									10	5	**3**	40
26a	**Single rotor on ROUGH bed**												
26a.1	Longitudinal CL					**13**	1.5	20	**6**	from 2D to 12 D			
26a.2	Traverse at 2D									2	4.5	**1**	40
26a.3	Traverse at 4D									4	5	**1**	40
26a.4	Traverse at 6D									6	5	**1**	40
26a.5	Traverse at 8D									8	5	**1**	40
26a.5	Traverse at 10D									10	5	**1**	40
26a.6	Traverse at 12D									12	5	**1**	40

Table 4(d) cont. : Array configurations and corresponding measurement ranges: **conical island**

		Array Configuration				Longitudinal U(x) (Diameter multiples)			Lateral Traverse - U(Y) (dY = Width from CL)			Depth Profile, U(Z) (per traverse)	
				Spacing									
REF	Description	Nrow	Nrotor	C-C	Row	nX	Xmin	Xmax	nXPOS	XPOS	dY	nXY(Z)	nZ
	Added Horizontal Oscillation - Island Wake												
28B	**Island Wake (island centre at 5 m)**	0	n/a	n/a	n/a	**0**	n/a	n/a	**2**				
28B.1	Contour at 7.5 m									7.5 m	3	**3**	40
28B.2	Contour at 9.0 m									9.0 m	3	**3**	40
29B	**Single row (3 devices) - Island wake**												
29B.1	Longitudinal	1	3	**1.5**	0	**13**	1.5	20	**2**	at 2D, 4D			
29B.2	Traverse at 2D									2	4.5	**3**	40
29B.3	Traverse at 4D									4	5	**3**	40
30B	**Single rotor - island wake**												
30B.1	Longitudinal CL	1	1	**n/a**	n/a	**13**	1.5	20	**6**	at 2D, 4D			
30B.2	Traverse at 2D									2	4.5	**1**	40
30B.3	Traverse at 4D									4	5	**1**	40

Effect of unsteady ambient flow on arrays (at selected operating set points) (from Table 4.4 of WG4WP2D1)

Test description	**Variables and ranges**	**Measurements**	**Test Type**	**Blockage (Y/N)**	**Wake (Y/N)**	**Complete**
Wave-forcing	Irregular waves, H & T represent full scale	Thrust and power, Rotor speed, Flow field	Detailed	N	Y	Y
Ambient TI (bed-generated)	Flow rate /profile		Investigative	Y	Y	Y
Large Eddy Structures	Bed form	Thrust and power, Rotor speed, Flow field	Detailed	N	Y	Y

5 DATA PROCESSING

To convert the multiple samples of time-varying data generated during each experiment into a manageable form and present the results required for analysis, processing scripts (written in MATLAB code) were used. In this section, the methods employed to process the data are explained.

5.1 Raw data processing

The first stage in the data processing is to create a working file structure. In order to minimise the changes required to the processing scripts between experiments, the file structure shown in Figure 5.1 was used for each test.

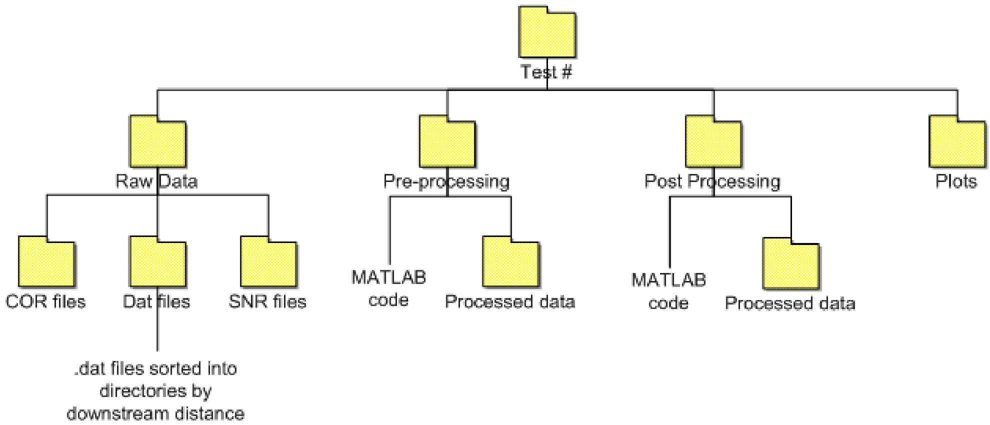

Figure 5-1 File structure used for the processing of data

The data (.dat) files should be grouped in container directories whose names correspond to the X (downstream) position of the measurement probes at that traverse of the flume. As explained in section 3.2.4, the Y (lateral) and Z (vertical) position of the first probe in the wake is given by the name of each data file. Longitudinal results measured far downstream along the rotor centreline do not follow the same naming convention and are placed in a folder named 'longitudinal'.

The tasks required to analyse data were split into two sections: pre-processing and post-processing. In pre-processing, key parameters are calculated from the raw data and stored in matrices ready for plotting. In post-processing, these matrices are accessed, and relevant graphs produced from the pre-processed data.

To help explain the methods used in the analysis of data, the processes for obtaining rotor and flow field plots are considered separately. Sections 5.2 and 5.3 explain the procedures used for pre and post processing respectively.

5.2 Rotor processing

Figure 5.2 shows a flowchart of the tasks involved in the pre-processing of rotor data for each experiment. The following sections correspond to those in the chart.

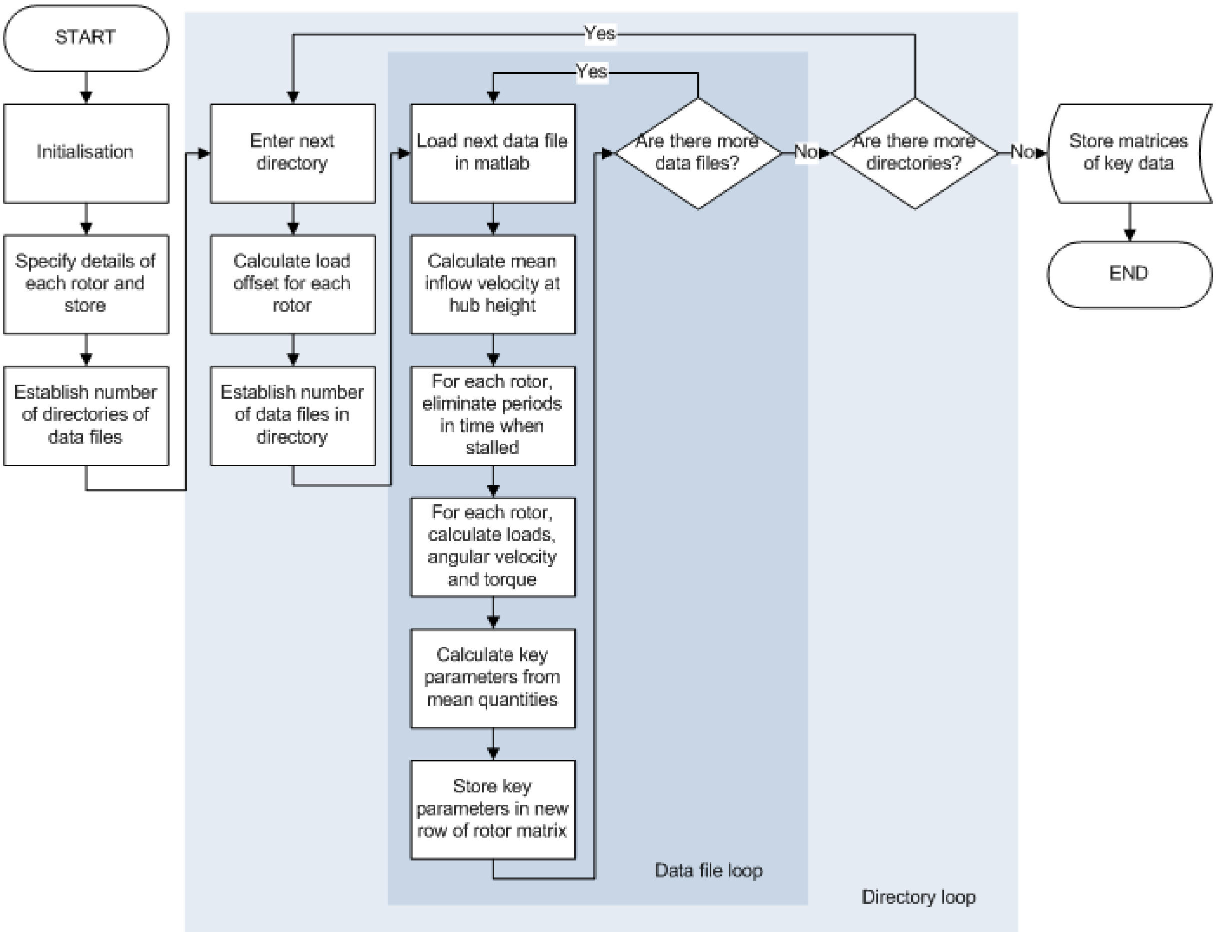

Figure 5-2 Flowchart showing the tasks involved in rotor pre-processing

5.2.1 Initialisation

The first task is to specify key details for each rotor in the experiment:

- ID (e.g "2" for a rotor named PerAWaT02)
- Coordinate position
- The numbers of the columns which relate to the axial load strain gauge, angular displacement and torque voltage

These values are obtained from the Readme files for each test. The MATLAB scripts used stores details for each rotor as the single row of a matrix which is then accessed later in the programme. Care should be taken to ensure that any changes to the order of data file columns for different traverses of the flume are accounted for within the processing.

When processing multiple rotor data, a loop is used to cycle from "1" to the total number of rotors. At each loop the details for each rotor can be found from the matrix created above.

The second step in initialisation is to evaluate the number of directories of data and start a loop to access each in turn.

5.2.2 Directory Loop

Each directory represents a traverse of the probes across the flume at a single downstream distance.

To accurately measure the load on each turbine when operational, the load measured when in stationary water must be subtracted from the total. This data is given in the directory for each traverse as an additional "noflowhanging" data file. The exact name of the file is included in the Readme documents and its format usually follows that of other data files in the test. Once loaded to MATLAB, the axial force measurements for each rotor are calculated from strain gauge voltage using equations given in the Readme. To select the correct equation and axial load column for each rotor, the ID and column numbers are called from the matrix created during initialisation. The axial force is then averaged for the duration of the sample and stored for use throughout the current directory.

5.2.3 Data file loop

The data associated with each rotor and the reference flow speed ADV measurements is loaded via a reading script loop. All data files in the current directory are read in on each loop (excluding the "noflowhanging" file).

For the calculation of tip-speed ratio (TSR), coefficient of thrust and coefficient of power, the incident flow speed on the rotor, U_0, is required. This is obtained from the inflow ADV probe, mounted at rotor hub height to the side of the array. The column of data giving its axial velocity is given in the Readme documents. The time series of ADV flow speed is averaged to give the reference incident flow speed as a single value in cm/s.

During the tests the rotors may experience stalling, where the rotor torque drops and the rotor is not longer operating at is optimum design point. It is important to remove periods of data collected during rotor stalling. The method used is based on the sudden drop in torque seen during stall conditions, as shown in Figure 5.3. To calculate torque from the torque voltage given in the data files, the below relationship is used:

$$\tau = K_t * I_{net} \quad Nm$$

where K_T is the motor torque constant and $I_{net} = I_{inst} + I_0$ the applied current obtained as the sum of the instantaneous current I_{inst} developed by the dynamometer and a friction offset I_0 defined in the readme file for each test. The instantaneous current is constant (positive value) during rotor rotation but becomes negative to minimise stall at low speed. I_{inst} is recorded as a time-varying voltage V_τ with the following conversion:

$$I_{inst} = 0.793 * (0.103 * V_\tau - 0.257)$$

Once the torque is calculated high frequency changes are removed using a Fourier transform method. An index is then created for each individual rotor, containing the locations of torque measurements which sit above a set percentage of the maximum. This index is stored for use on axial load and angular velocity later. The mean average torque for each rotor in normal operation is evaluated at this point.

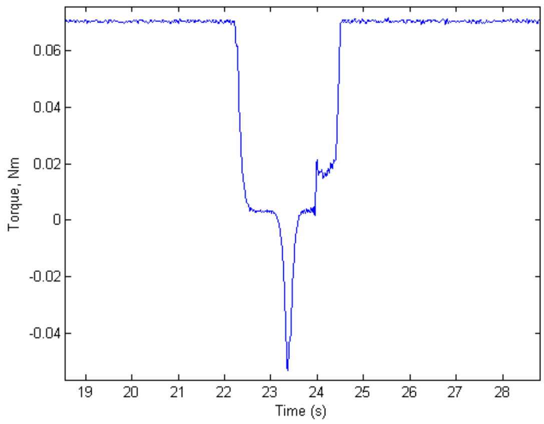

Figure 5-3 Sudden drop in torque seen when a single rotor stalls

To calculate the axial load on each rotor, the equations given in the Readme documents are used to convert strain gauge voltage for non-stalled values into force. However, the load offset calculated previously and tower load must be subtracted (see WG4WP2D4) to give the load on the rotor only. Some basic filtering then removes any sudden spikes and then the mean load is evaluated

Before cutting stalled values from the angular displacement, it must be converted to angular velocity. For all tests, results were collected at a sample rate of 200Hz, equivalent 5ms between readings. The angular velocity in radians per second is then obtained by a first order forward difference as:

$$\omega = \frac{\Delta s}{\Delta t} = \frac{s_1 - s_2}{0.005}$$

where *s* is angular displacement. The index of non-stalled values can then be applied at this angular velocity to cut out values when stalled.

Using the incident flow speed, axial load, angular velocity and torque for each rotor, the tip-speed ratio and coefficients of power and thrust can be found using the below equations:

$$C_P = \frac{\tau.\omega}{\frac{1}{2}\rho U_0^3 A}$$

$$C_T = \frac{T}{\frac{1}{2}\rho U_0^2 A}$$

$$TSR = \frac{\omega r}{U_0}$$

These three quantities along with torque, rotor number and rotor coordinates are then stored in a new row of a rotor matrix. Once all data files from all directories have been processed, this matrix is saved as a MATLAB (".mat") file for use in post-processing.

A small number of plots are produced during the pre-processing analysis to show the number of data points used for each rotor processing analysis across all .dat files. This enables a review of rotor stalling and the extend of data removed during filtering. If too severe the data removal criteria can then be reviewed.

5.2.4 Rotor post-processing

The rotor post-processing script plots data from the saved pre-processed file . Once the pre-processed data is loaded into MATLAB, the first step is to establish the number of rotors in the experiment. This can easily be done by applying the 'unique' function to the rotor number column of the matrix. A loop is then used to cycle through each rotor number, and on each iteration create an index containing the locations of matrix rows for which the rotor number matches. The data for each rotor is then plotted Additionally, the mean values of the filtered rotor data are evaluated, and results for different rotors plotted against each other.

The prediction curves for coefficient of thrust and coefficient of power are stored in tabular form in .mat files under the name:

- 'coeffs_pred.mat' – Hassan predicted curves
- 'coeffs_miley.mat' – Miley predicted curves

In these matrices, the first column gives tip-speed ratio, second column coefficient of thrust and the third column coefficient of power. These files are held within the result database.

5.3 Flow field processing

Figure 5.4 gives an overview of the tasks involved in the pre-processing of flow field data for each experiment. Due to the different naming convention of longitudinal results, they are processed using a slightly modified script and will be discussed towards the end of this section.

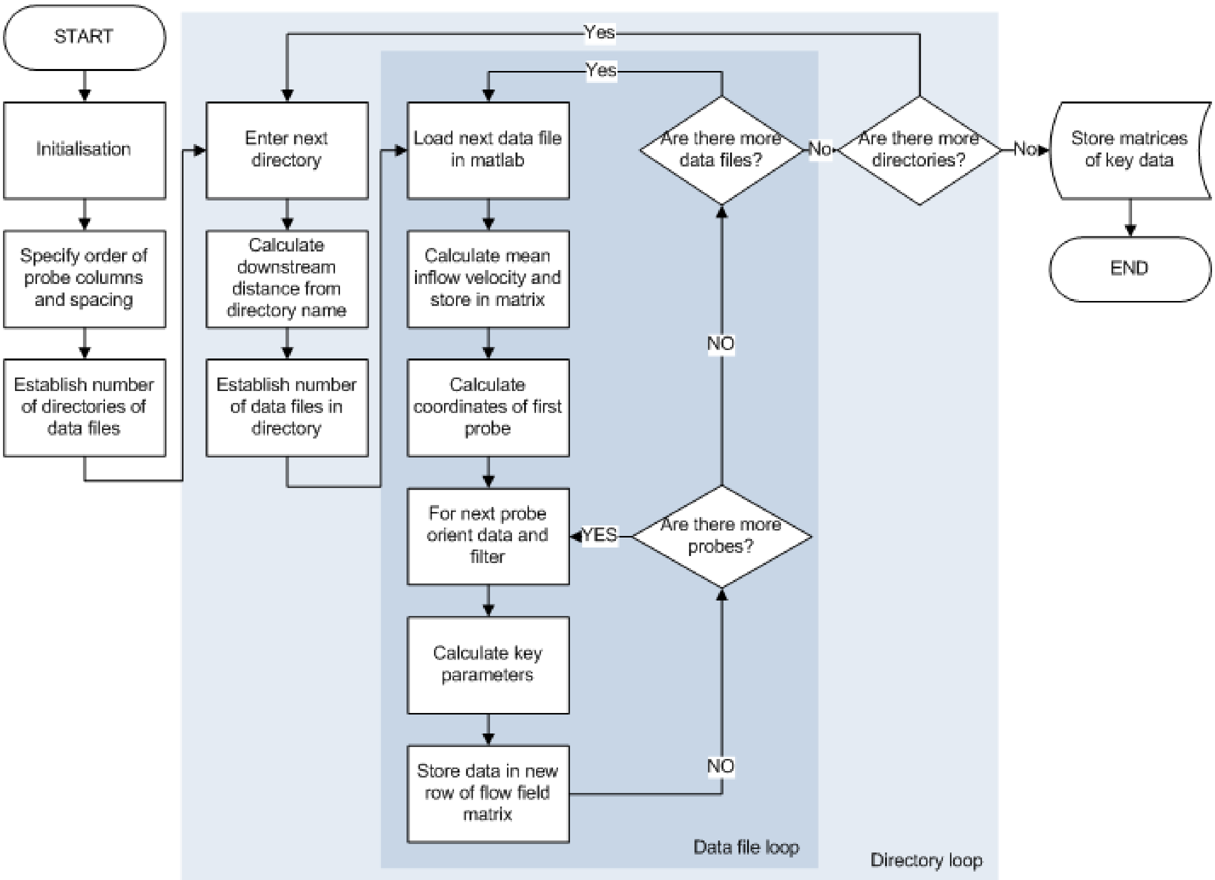

Figure 5-4 Flowchart showing the tasks involved in flow field pre-processing

5.3.1 Initialisation

The first step in the process is to specify the position of the first column of data for each probe. These can be found in the Readme documents for each test. In all experiments, results for each ADV are recorded in 4 adjacent columns with the order Ux, Uy, Uz_1 and Uz_2 respectively. The number of the first column of data for each ADV is therefore sufficient at this stage. The script stores these in vector form, where the first element is the column number of probe 1, the second element the column number of the next probe along and so on. The first column of *inflow* ADV data is specified as a separate variable. Also during initialisation, the spacing between the probes in the array wake is entered in millimetres.

The number of directories of data is then calculated and a loop initialised to go through each in turn, excluding the directory of longitudinal results.

5.3.2 Directory loop

Once in a directory of data files, the downstream distance should be extracted from the name of the directory and stored. The number of data files then needs to be obtained so that a loop can be set up to go through each.

5.3.3 Data file loop

After loading a data file into MATLAB the inflow velocity is calculated by taking the mean average of the inflow ADV axial velocity component. The column of data for corresponding to this is specified during the initialisation. Once found, the value is stored in the new row of an inflow matrix, which will be used during post processing.

The Y and Z coordinates of probe 1 must be found from the file name. These then need to be converted to the global coordinate system. The relationship required to do so can be ascertained from the readme file for each experiment. For the majority of tests, Y and Z in millimetres are found as below.

$$Y = HZ + 271$$
$$Z = 618 - VT$$

A loop is created to go through each probe in turn. With each successive iteration, the Y value is increased by the probe spacing set initially, and the data used is the block of columns specified for the probe at the new position.

The probe data is collected in the Vectrino coordinate system and the components of velocity do not match those in the global coordinate system. The conversion between them is given in each Readme file, and is identical for all tests apart from a small number of early preliminary experiments. Note that there are two versions of one velocity component. The second of these is discarded, leaving three components.

Once the velocity components have been reoriented they are filtered. Firstly, rapid changes in velocity which go significantly far from the mean velocity are deemed non-physical and removed. Secondly, data is resampled to create lower frequency data.

With this complete, the relevant parameters for flow field analysis are calculated for the current probe: mean velocity, standard deviation, Reynolds stresses, turbulent kinetic energy, skewness and kurtosis. The equations for these are given in WG4WP2D4 and repeated in the Definitions section on Page 3 of this report. These results are stored in a new row of a flow-field matrix along with the coordinate position of the probe.

With the data files from all directories analysed, the matrices for inflow velocity and flow field data are saved to the hard disk for use in post-processing.

5.3.4 Flow field post-processing

Post-processing for the flow field is more complicated than for the rotors. The first key step is to load the matrices for the flow field, the inflow probe and the rotor parameters. The axial velocity column of the inflow matrix is averaged and assumed to be the incident velocity on the rotors at hub-height, U0. The rest of the inflow data can then be discarded. For the rotor and flow field matrices, the position coordinates are normalised to rotor diameters. This is simply a case of subtracting from each coordinate the position of the most central rotor in the front row, then dividing by the rotor diameter, 270mm. In some early tests, repeats mean that there may be more than one measurement at a single point. To overcome this, any duplicate flow field points are found, and the values in all columns averaged between them.

From the coordinates in the flow field matrix, a three-dimensional plot of the measurement points can be created. Additionally, rotor positions can be taken from the rotor matrix and included in the same figure.

The select the points required for the majority of plots, the rotor positions are used in conjunction with the downstream positions of traverses. For example, vertical plots exist at every traverse distance and have Y-positions matching those of every rotor in the backmost row. An index of values which satisfy these requirements can be found as shown below:

- i = loop from 1 to number of traverse positions
    - Find index of values at traverse i
    - j = loop from 1 to number of rotor y-positions
        - Find index of values in this traverse at the current y-position
        - Save index in cell array, at location {i,j}
    - End y-position loop
- End traverse position loop

The index of values which make up each horizontal plot can be found by cycling through all traverse distances, and then finding values where Z = 0 (normalised to rotor position).

In the GH code, longitudinal points are separated from those in the traverses. The only filtering required is therefore to create a separate index of points where Y matches that of each back-row rotor.

To allow the calculation of turbulence intensity and normalised flow field quantities, baseflow data is used. The flow-field matrix should be renamed so that it is not overwritten when baseflow data is subsequently loaded.

When dealing with baseflow, the unique number of Z-positions in the data is first obtained and stored. At each Z, all axial velocity and standard deviation values are then averaged and stored as the next elements of vectors. Plotting the depth averaged velocity against the z-positions gives an averaged depth profile of velocity in the baseflow. The point U=0 at the bed of the flume (z = -225/270D) is added, and an 8^{th} degree polynomial is fitted to the points. This polynomial is then shifted such that it is equal to velocity U_0 at hub height, thereby accounting for any small change in flow velocity between the baseflow and test data. The standard deviation also has a polynomial fitted, but is not shifted.

To ease plotting, the wake flow columns are saved as variables matching their names, for example, the axial velocity column is saved as variable ‘U’. Additionally several new values are then calculated, including:

$$U_{norh} = \frac{U}{U_{0,h}}$$

$$U_{defnorh} = 1 - \frac{U}{U_{0,h}}$$

$$\overline{u'v'}_{norh} = \frac{\overline{u'v'}}{U_{0,h}^2}$$

Further parameters are evaluated using the baseflow velocity and standard deviation at each height.

$$U_{nor} = \frac{U}{U_{base}(z)}$$

$$U_{defnor} = 1 - \frac{U}{U_{base}(z)}$$

$$TI_x = 100 \frac{\sigma}{U_{base}(z)}$$

$$TI_{xnor} = 100 \frac{\sigma - \sigma_{base}}{U_{base}(z)}$$

Where σ is standard deviation and σ_{base} is the standard deviation of the baseflow at the current height.

To plot these parameters, another cell array is created containing on each row: the function to be plotted (e.g U_{def}), its name, the axes limits required and measurement unit. Looping through each row of this cell array allows the parameter to be plotted, axes set correctly and the title, axes labels and file save name to be established. Additionally, an index as saved above is applied to each parameter to show only the desired results (e.g only results across the channel at a chosen downstream distance).

5.3.5 Treatment of longitudinal data

Data for longitudinal measurements follows a different file naming convention to that elsewhere, an explanation of which is given in each Readme file. To handle this, a separate pre-process code is used.

In the post-processing code, longitudinal data is used separately from that in the traverse. A method is therefore required to distinguish between the data. GH do so by adding a column to the flow field matrix which is populated with a '1' for transverse results and '2' for longitudinal. However, an equally valid method might be to save separate matrices for longitudinal and traverse data.

Aside from the points made above, treatment of the longitudinal data matches that elsewhere exactly.

5.4 Analysis of signal-noise and correlation files

For every test, there are .cor and .snr files for the calculation of correlation coefficient (COR) and signal-noise ratio (SNR) respectively. Both types of file contain 8 columns, where the first gives the number of the probe, and columns 5-8 are the values of COR or SNR in the coordinate directions Ux, Uy_1, Uy_2 and Uz respectively (in global coordinates). The method for processing both types of file is identical.

First, the top two lines of the file must be removed manually, and the file saved. The file can then be loaded in MATLAB. Here, a separate index is created from column 1 containing the locations of all rows which correspond to each probe.

Two separate figures are then plotted. In the first, time-variation of SNR or COR in every coordinate direction is plotted for each probe. In the second, the probability distribution of the SNR or COR is obtained in each coordinate direction for each probe using the 'histc' function in MATLAB. This calculates the number of values which fall within specified intervals. These are then plotted as a column chart using the 'barh' function.

6 DATA BASE

All data collected during the WG4WP2D2 experiments has been collated into a single database as required by the PerAWaT project. The directory structure of the database follows the numbered ist of experiments described by Table 4. A graphical summary of the rotor locations and measurement locations for each experiment is given in Appendix A. Experiments 1 to 5 of that list have been executed as part of D4 to provide calibration data of the baseflow, rotor characteristics and of a single and dual rotor wake map. The data generated by the experiments has been processed by GH and collated with a database. A description of the available data contained within the database are detailed below:

Input data per experiment

- "Readme" file including
    - Location of each rotor
    - Location and orientation of each ADV provided via ADV.dat file name
    - Calibration parameters for axial force, rotor torque and, if necessary, wave gauges
    - Explanation of column arrangement of raw data files.
- Data recorded prior to test for baseline:
    - COR & SNR for all ADVs in test configuration
    - 'noflowhanging.dat' as per raw data files but measured with zero flow velocity.
- Raw data files. Separate file for each flow-co-ordinate. Data sampled at 200Hz and including the following:
    - ADV velocity measurement (4 components per ADV) for ADVs downstream of rotors
    - ADV velocity measurement at upstream location for evaluation of CT &CP
    - Strain gauges measurements i.e. to obtain axial force per rotor
    - Angular position per rotor i.e. to obtain angular angular velocity per rotor
    - Dynamometer motor current measurement i.e. rotor torque per rotor

Processed data plots per experiment

- Spatial location of data points
- Baseflow profile used to normalise velocity data
- CT vs TSR for each rotor
- COR & SNR time histories
- Flow field plots including:
    - Mean velocity (U,V,W)*
    - Turbulence intensity (U,V,W)*
    - Reynolds Stresses (XY,YZ,ZX planes)
    - Kurtosis
    - Skewness
    - Turbulent Kinetic Energy

  For each of the above parameters the following plots are produced
    - Lateral profiles
    - Vertical profiles
    - Centreline profiles
    - Lateral profiles vs vertical profiles
    - Surf and contour plots if required

*** Suffixes:** X = axial direction, Y = transverse direction, Z = vertical direction
def, nor, norh as defined in Section 5.3

Additional data

- MATLAB (.mat) files containing the predicted coefficients of thrust and power for a given tip-speed ratio

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7 RESULTS

This section presents some of the main findings from the post-processed data. It should be noted that some further analysis of the data will be conducted in WG3WP4 by comparison of numerical models to the experimental data of wake recovery and the effects of blockage. The subsections below present the salient results from the characterisation, blockage, multiple row and ambient flow sensitivity experiments.

7.1 Characterisation investigations

The main aspects of the characterisation experiments are presented in the subsections below. However, a more complete presentation of the ambient flow and the flow with opposing waves is provided in WG4WP2 D4 report. The WG4WP2 D4 report also contains a description of the flow downstream of an immersed conical island for a depth of 460 mm although this differs slightly from the island flow described below (see Section 4.4).

7.1.1 Ambient flow conditions

Figure 7.1 presents the depth profiles of the average longitudinal flow speed for the four different ambient flow conditions. As expected the depth profile of the baseflow (Test 03) and flow with waves (Test 02) is similar because the time varying effect of the waves averages out. The profile differs considerably for the flow downstream of the conical island an over a rough bed. Three depth profiles are shown for the island wake because in this case there is lateral variation of the flow across the width of the array. The profile above a rough bed shows a reduced flow speed in the lower part of the water column. Note that the lowest datapoint for this profile is at z/D = 0.17 since the 45 mm height of the rough bed material precludes measurement below this point.

Figure 7.2 illustrates the ambient turbulence intensity due to the different ambient conditions. As expected the base flow conditions show little variation in turbulence intensity through the water column. Wave action causes flow variation longitudinally and vertically and this is shown in the second plot. The effect of surface waves is large with TIx increased by a factor of two and TIz increased by a factor of four. The effect of waves on ambient turbulence is evident throughout the water column with increased ambient turbulence over the upper half of the rotor plane. The flow downstream of the island experiences high turbulence intensities due to the large time varying lateral and longitudinal flow fluctuations. As expected the effect of the rough bed increases the turbulent mixing in the bottom part of the water column and hence increases all three components of turbulence intensity near the seabed.

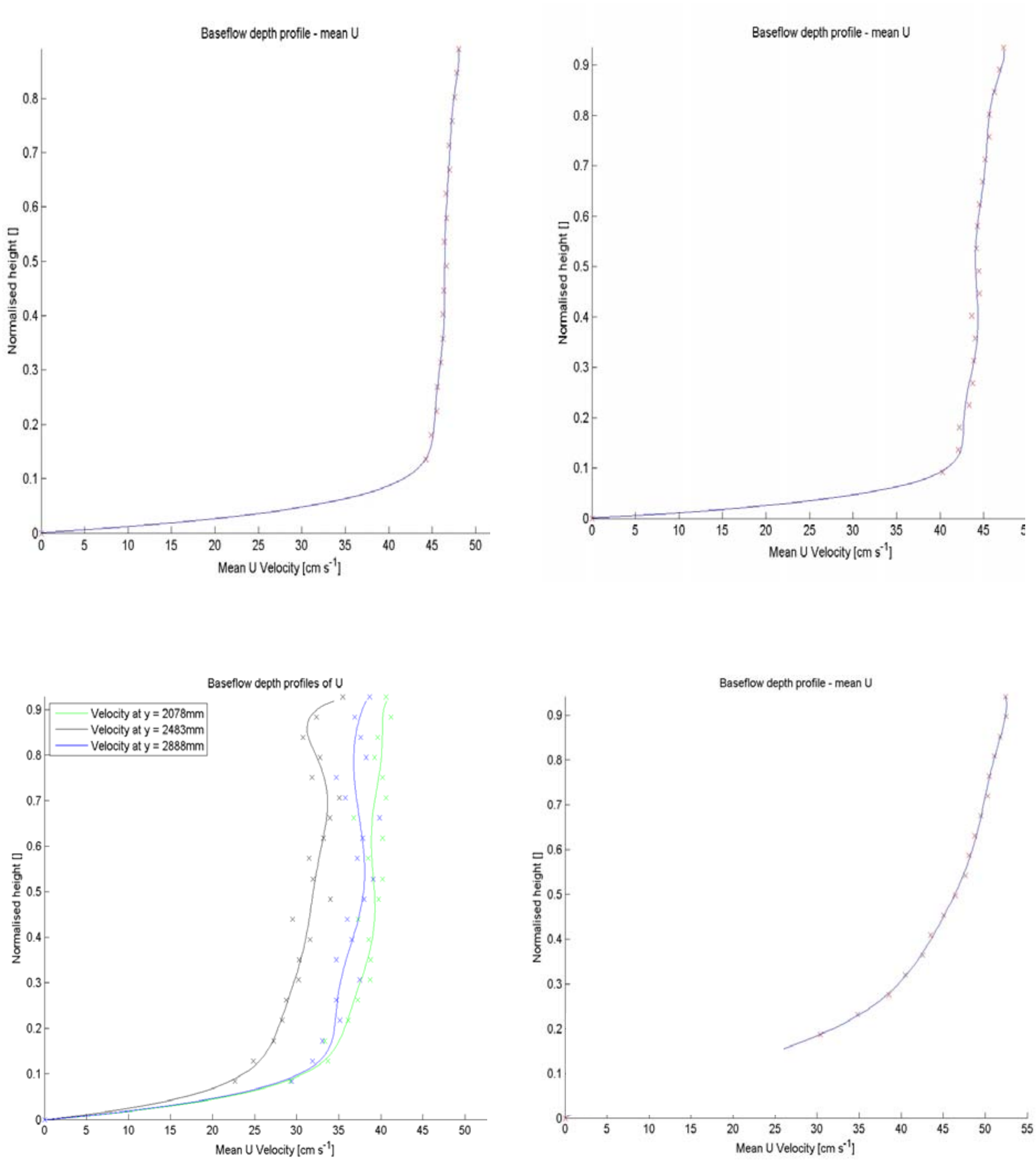


Figure 7-1: Averaged depth profile obtained as mean of all measurements for four different ambient conditions: Baseflow without and with waves, Flow in wake of an island and added roughness bed (see Section 5 for details of analysis).

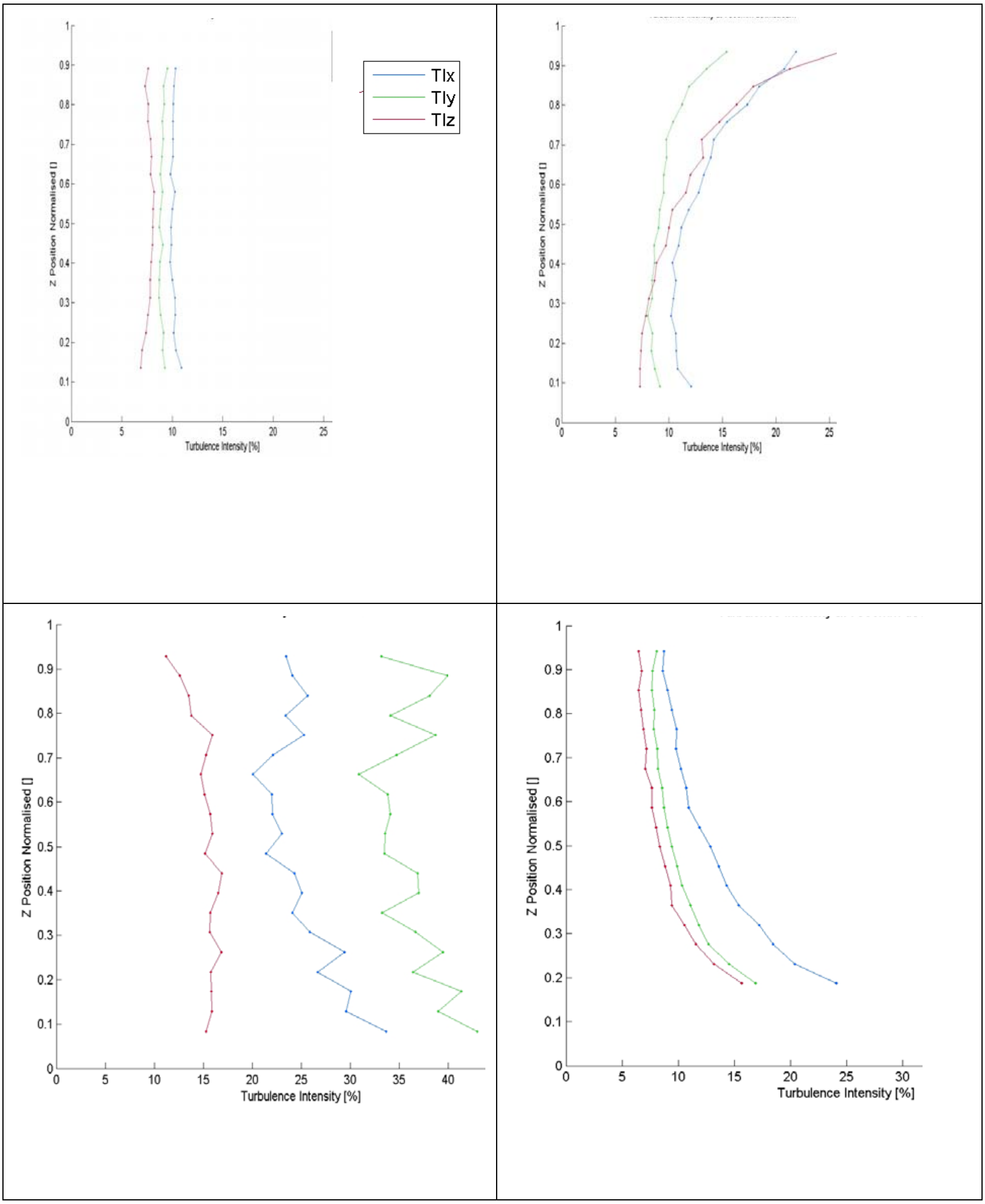
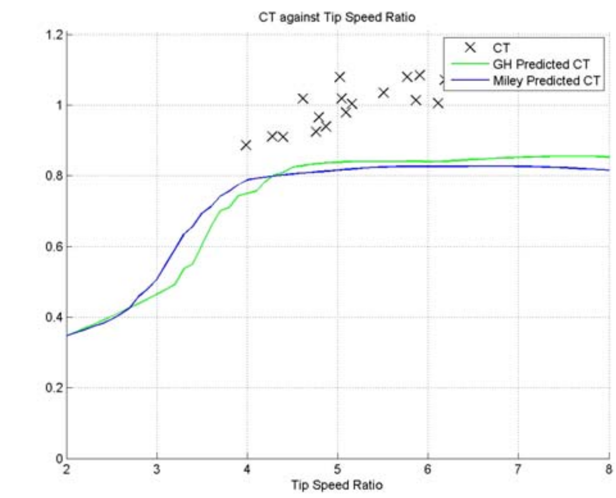


Figure 7-2: Depth-profile of turbulence intensity for four different ambient conditions: Baseflow without and with waves, Flow in wake of an island and added roughness bed (see Section 5 for details of analysis)

7.1.2 Rotor performance

The details of the 1/70th scale rotor hydrodynamic design are described fully in the D2 report. The method to evaluate the rotor characteristics are detailed in D4 and the data processing method applied to all set of rotor data is presented in Section 5 (access to the values associated with the boundless rotor predictions are also detailed in Section 5). The plots below show that in this case the Ct values are higher than predicted. This could be attributed to local blockage effects. The plot of Cp shows fairly good agreement.



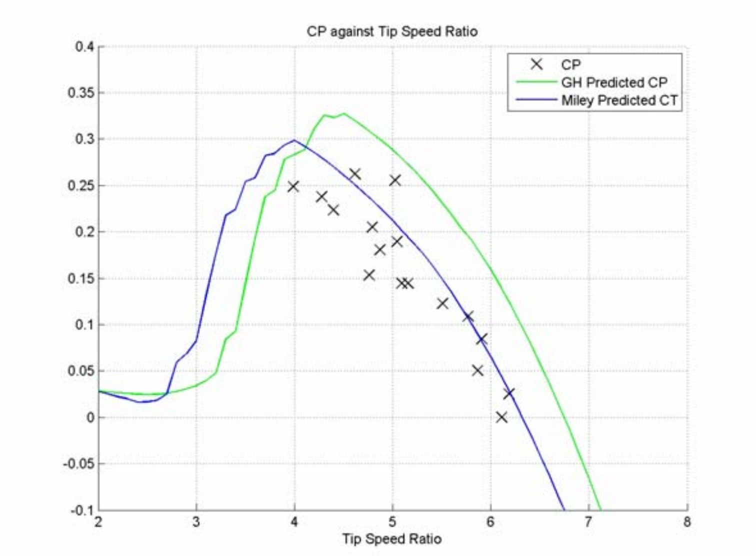
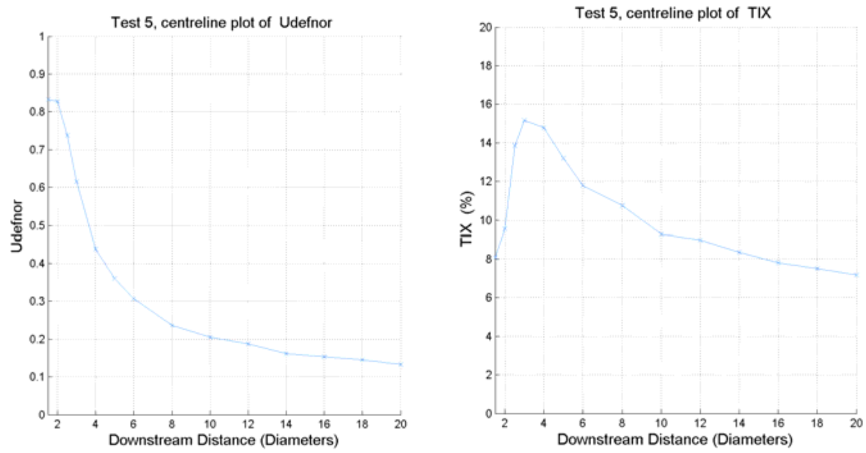


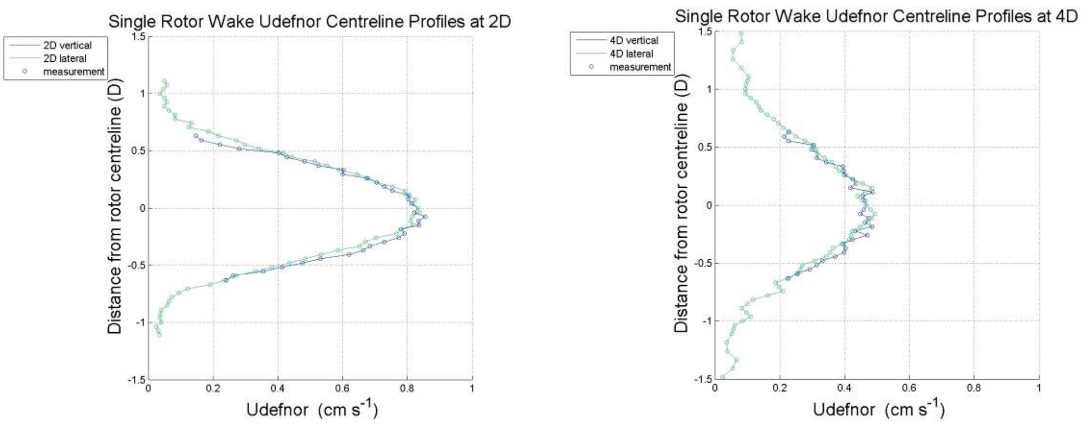
Figure 7-3: Rotor characteristics: Ct vs TSR (top) and Cp vs TSR for experimental rotor (003)

7.1.3 Baseline single wake

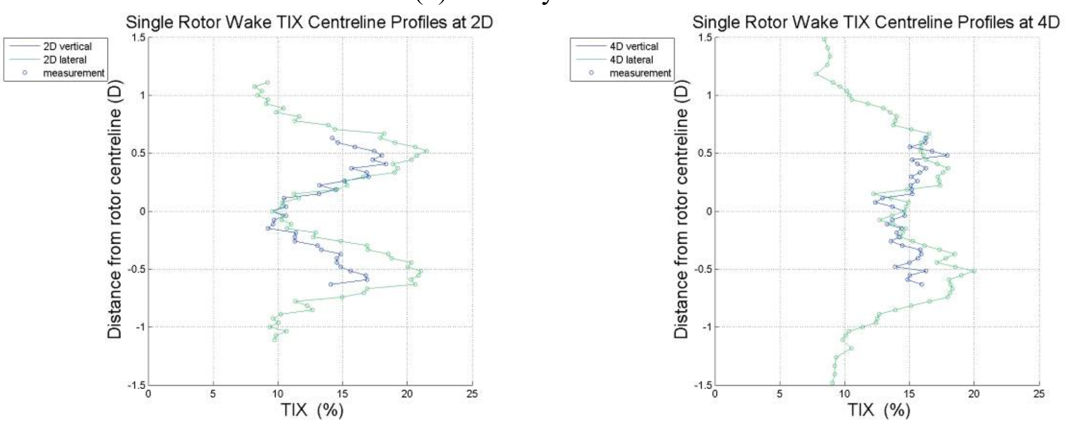
Figure 7.4 presents the centreline recovery of the single wake test and the vertical and lateral velocity deficit profiles of the near wake structure. As stated in D4, the structure of these wakes is as expected and so provide confidence that the array wakes will be representative of large scale rotor wakes.



(a) Centreline recovery downstream



(b) Velocity deficit



(c) Longitudinal turbulence intensity

Figure 7.4: Vertical and lateral profile of velocity deficit (top) and turbulence intensity at 2D (left) and 4D (right) downstream of a single rotor.

7.2 Blockage effects

The figure below presents the rotor thrust coefficient relative to the free stream flow speed of individual rotors subject to different local blockage effects. This indicates that the rotor thrust does increase with reduced lateral spacing. The Figure 7.5 shows an increase in rotor thrust for the series of 3 rotors tests at varying lateral spacing compared to the single rotor case (dotted red line). At a 3D lateral spacing the rotor Ct values are close to the single rotor cases, but increases at the lateral spacing is reduced. The effect on the near wake profiles is shown in Figure 7.6 below.

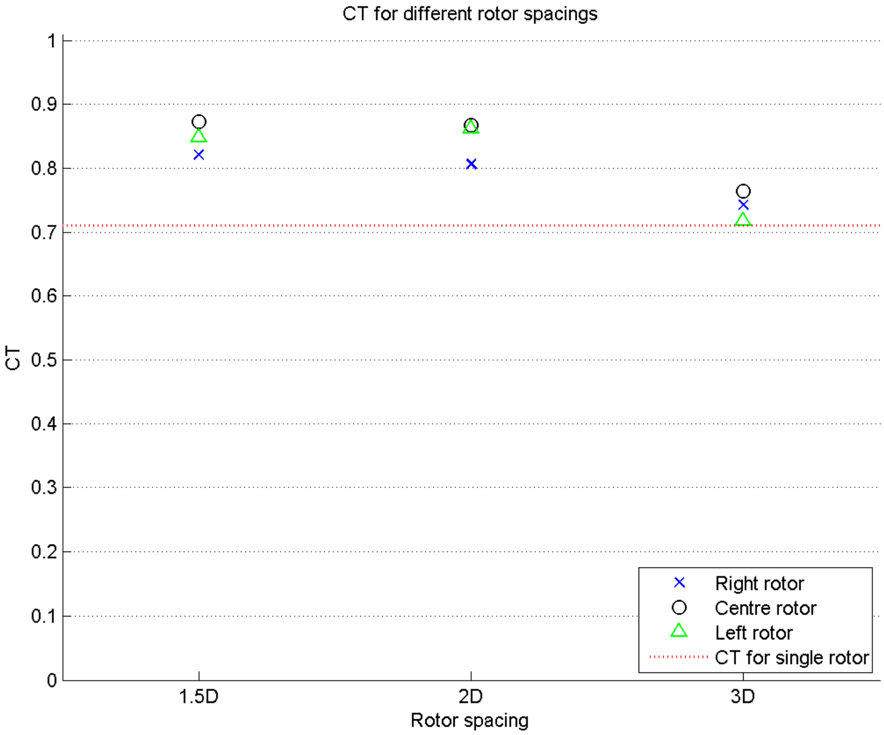


Figure 7-5: Effect of lateral spacing on rotor thrust (single row of 3 rotors)

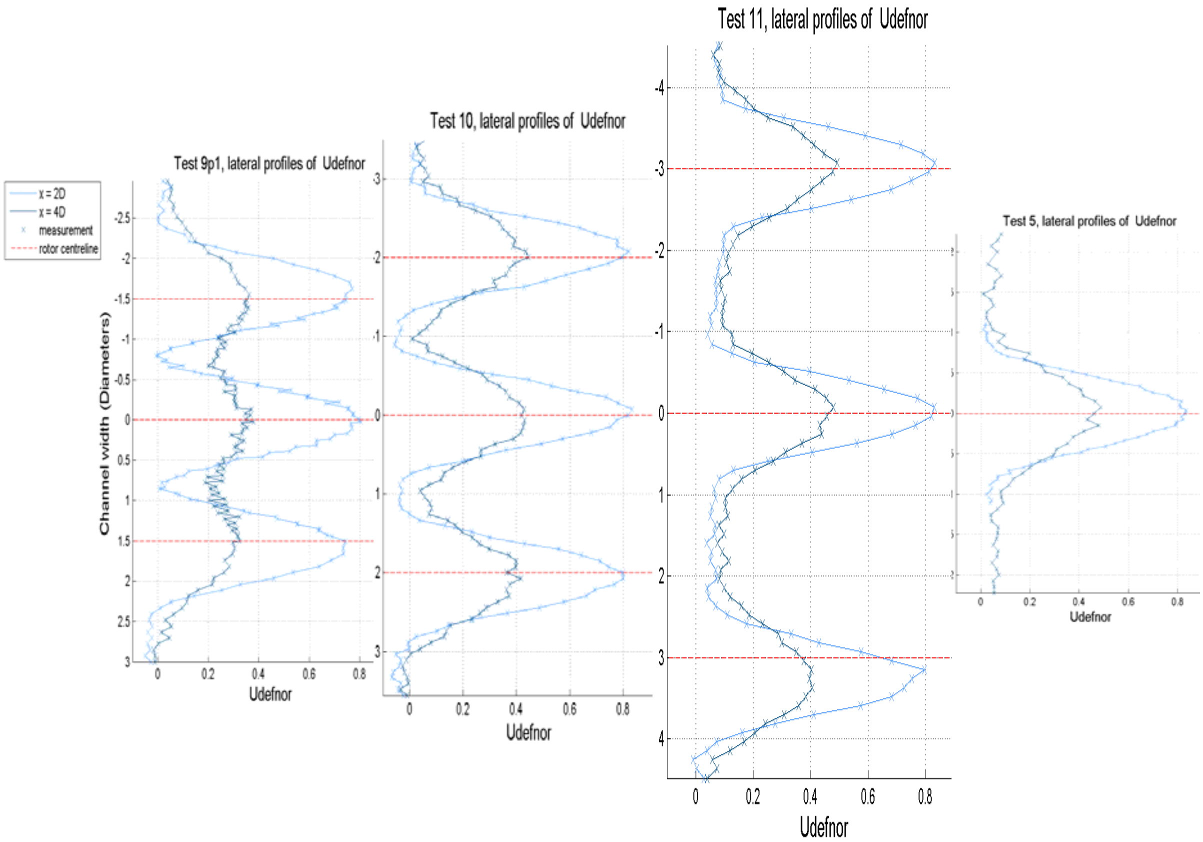
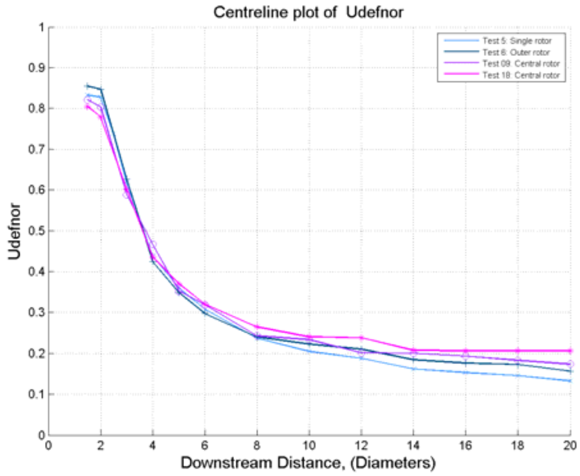


Figure 7-6: Effect of lateral spacing on near wake structure

An analysis of varying both the number of rotors and the lateral spacing between rotors is presented and discussed in a EWTEC paper. To avoid direct repetition of all of the contents of the paper in this report, the paper is presented in Appendix B. Figure 7.6 shows that at a lateral spacing of 2D and 3D the near wakes of adjacent rotors (e.g. 2D downstream) are not significantly affected by adjacent rotors. However, interactions are observed by 4D downstream for the rotors at 2D lateral spacing. At a lateral spacing of 1.5D the near wakes (2D downstream) are interacting at the wake edges and the wake centrelines are offset outwards from the rotor.

7.3 Multi-row wakes

In addition to the results presented in the EWTEC paper, the following figures present the effect of increasing the array size laterally and with additional rows. Figure 7.7 illustrates the effect on the central wake recovery when increasing the number of surrounding wakes. Far downstream the effect of two rotors either side of the central rotor is to increase the wake deficit by approximately 50%. The corresponding far wake turbulence intensity (longitudinal) is lower than for the single wake case. This is because the turbulence intensity is calculated using the free stream flow rather than the local (wake) flow speed (see definition in Section 5). In the near wake the multiple rotor rows show additional mixing but little different in the wake region between 2D and 6D.



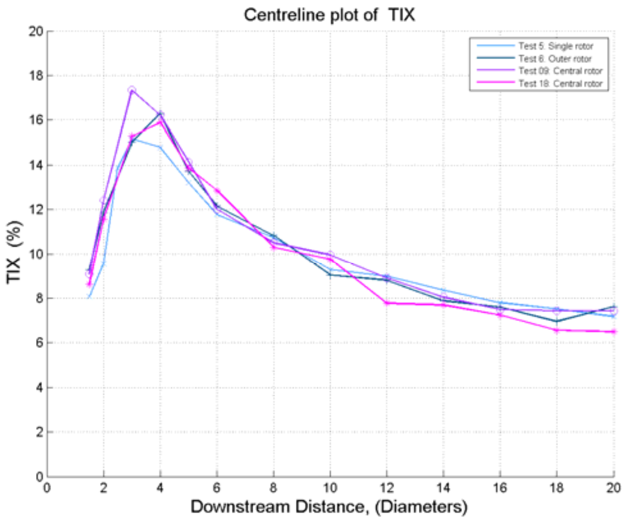
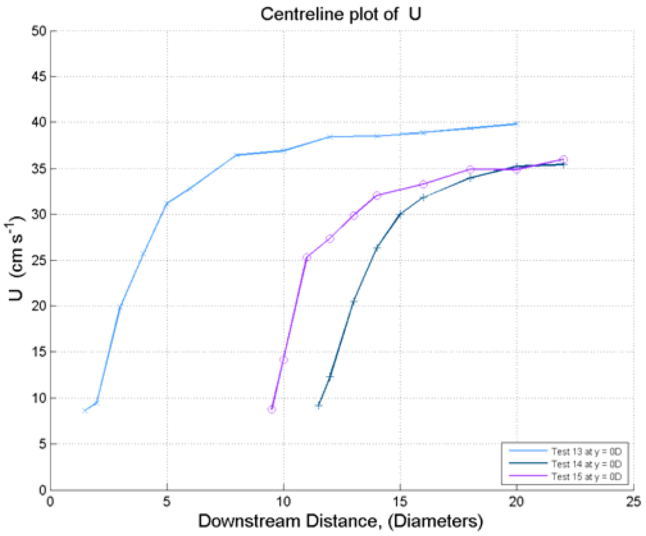


Figure 7-7 Centreline wake recovery in arrays with increasing rotors in a row



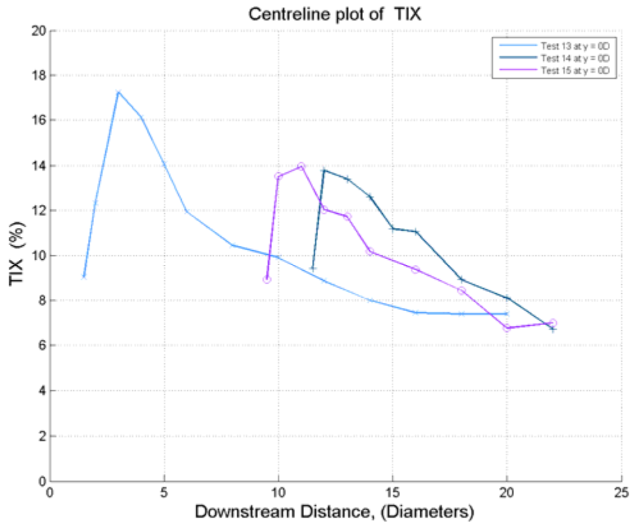
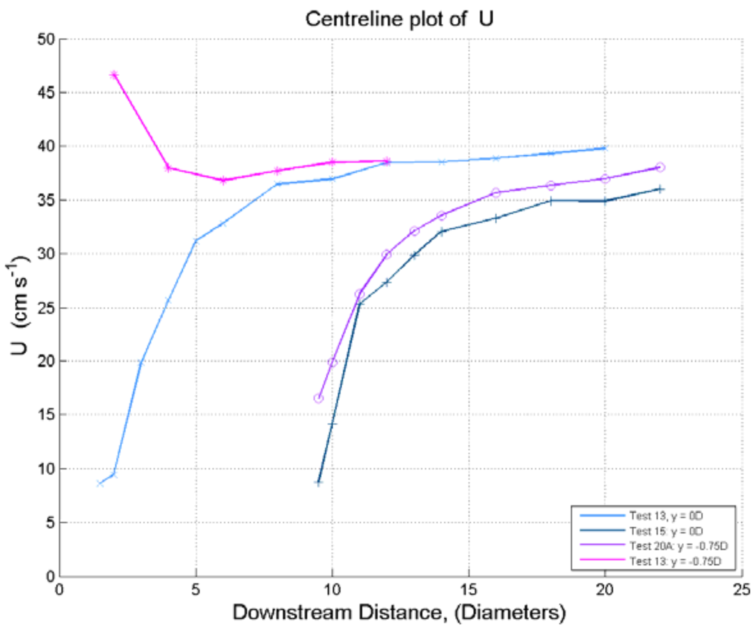


Figure 7-8 Centreline wake recovery in arrays with varying longitudinal spacing

Figure 7.8 shows that the row at 10D longitudinal spacing recovers more quickly than that at 8D. However, for both the 2nd row wakes, the recovery is slower than the upstream wake recovery. The plot of turbulence intensity shows lower values for the 2nd rows, but again this is due to the turbulence intensity being referenced to the free stream flow rather than the local flow speed.

Figure 7.9 illustrates the effect of placing rotors in the second row at a staggered location to avoid the operating directly in the centre of the upstream wake. However, as show in the plot of longitudinal flow speed, the incident flow upon the second row rotors located at 8D is similar if the upstream row is directly inline or staggered. In contrast the longitudinal turbulence intensity is greater in front of the second staggered row. This is because there is increased mixing at the edge wakes. If the lateral spacing of the upstream row increased then the difference between the incident flow upon the second row of rotors would increase, but there would still be an increased level of flow mixing.



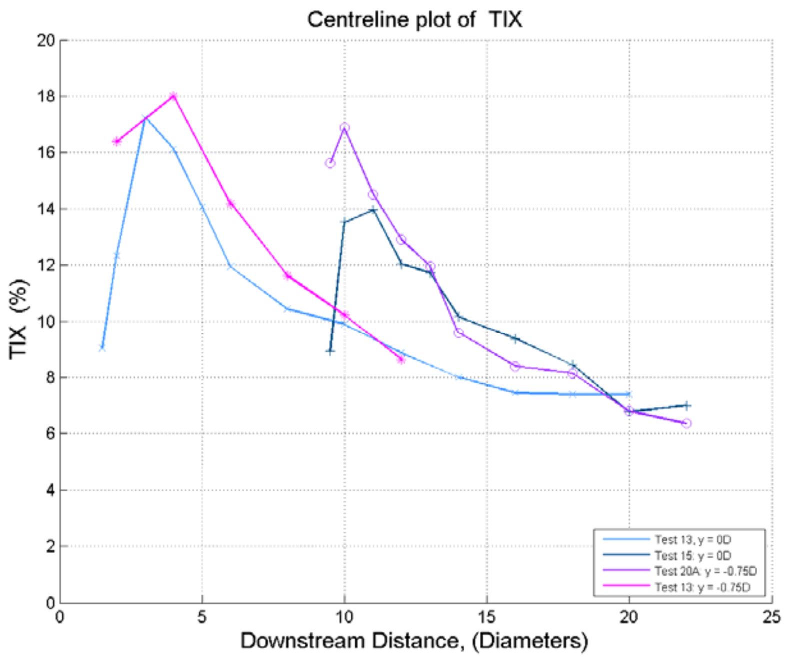
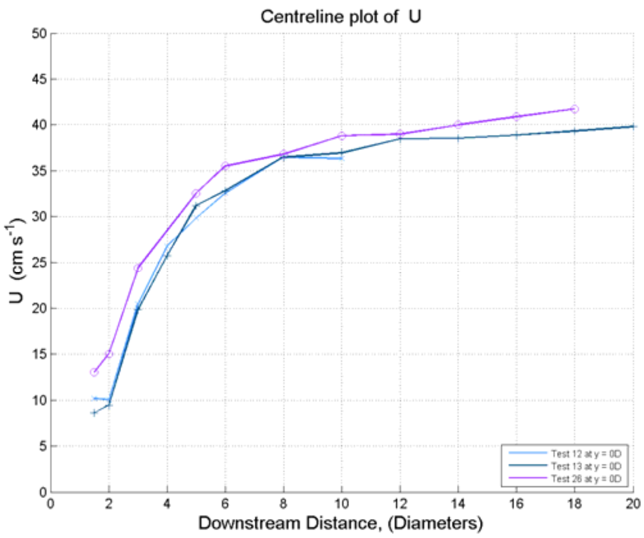


Figure 7-9 Centreline wake recovery in arrays with staggered row spacing

7.4 Ambient flow sensitivity

It was expected that the effect of increased ambient turbulence intensity would be to increase wake mixing and hence aid far wake recovery. The effect of added seabed roughness does improve recovery by more than 10%. However, changes to wake recovery are less obvious due to opposing waves. Centreline measurements with opposing waves were limited to less than 10D due to practical constraints on ADV and wave gauge support. However, the middle part of the wake does not show any deviations from the baseline flow, suggesting that the imposed wave kinematics do not aid wake mixing. This finding is also observed in Figure 7.11. Initial results showing the wakes of the rotors operating within the wake of the conical island detailed in WG4WP2D4 indicated that large amplitude fluctuations of lateral velocity caused frequent intervals of rotor stall. Since this directly affected the wake measurements, a subsequent set of tests have been undertaken. These results were not available for inclusion in this report, but will be post processed and appended to the database.



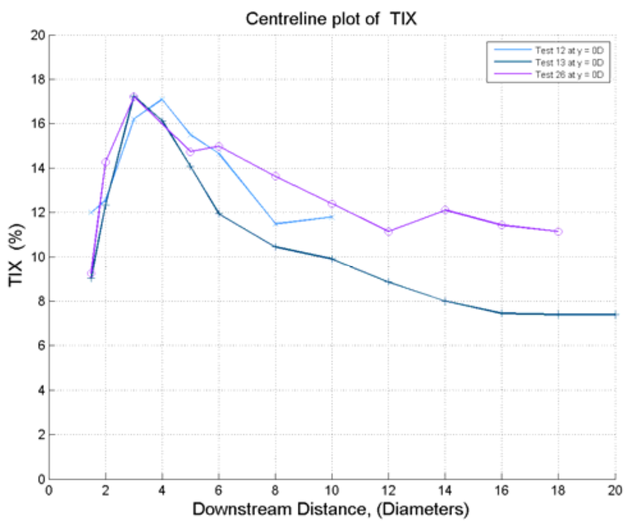
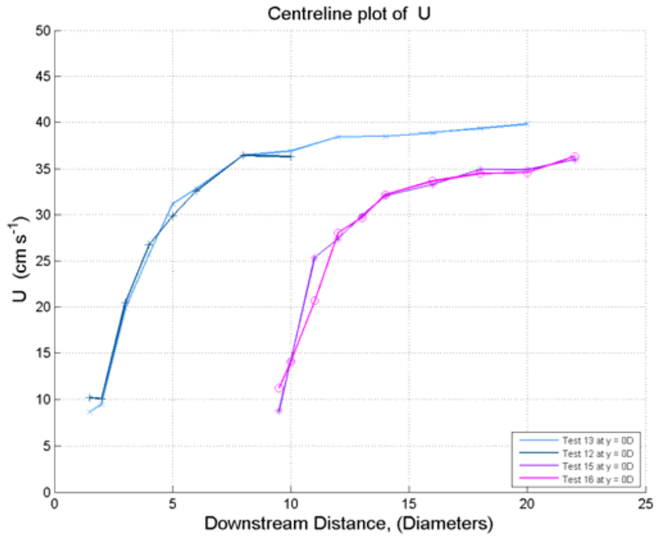


Figure 7-10 Centreline wake recovery in arrays with varying ambient conditions

Figure 7.11 shows the wake recovery of the first and second row of an array of 3 rotors longitudinally spaced apart by 10D for ambient flow with and without waves. It is apparent that the wave field does not noticeably affect the wakes at hub-height in the region of 2D-12D downstream, despite the wave kinematics acting within the wake region.



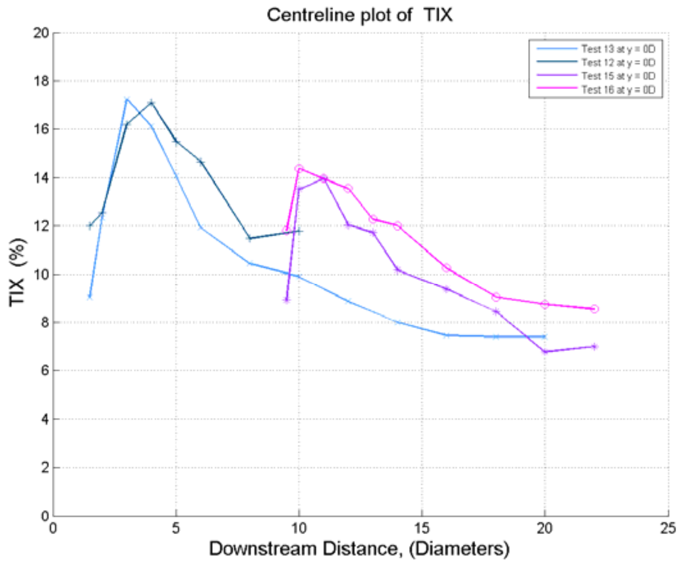


Figure 7-11 Centreline wake recovery in multi-row arrays with varying longitudinal spacing

8 SUMMARY

The purpose of the experiments of work package WG4WP2 is to investigate the hydrodynamic interactions of rotors when operating within arrays. Specifically the objectives of WG4WP2 were: to investigate the influence of bounding surfaces (free surface, seabed and other devices) on device performance and loading; to analysis the effect of the bounding surfaces, ambient flow field and device performance characteristics on the far wake form; and, to investigate wake interactions within an array under varying ambient conditions (seabed, waves and large eddies).

To achieve the set objectives a series of small-scale experiments of arrays of tidal stream turbine rotors were conducted in a wide channel. The tests were conducted at approximately 1:70th geometric scale using rotors that are specifically designed to produce similar momentum extraction to a generic full-scale rotor design. The experimental facility used enables the layout of various array configurations to be investigated along with different ambient flow conditions including surface waves, added seabed roughness and a large upstream island.

The preceding four deliverables included, a test specification report (D1) which defined the details of rotor operating points (speeds/torques), instrument types, sample frequencies, acceptable error and programme of investigations. Report D2 described the design of test equipment, including dimensions and component specification of the turbine model. Report D3 detailed construction of test equipment, including flume, rotors, support structures, and instrumentation and D4 presented the calibration tests and the characterisation experiments.

All time-varying data, quality control data and explanatory files have been collated into a single database. The database also contains summary plots of the time-averaged loading of each rotor and of the time-averaged velocity and turbulence characteristics of each ambient flow and each wake.

The array scale experiments were designed to provide four different areas of investigation. The characterisation experiments included detailed measurements of velocity field for four different ambient flows. The results show that the expected characteristics in terms of mean flow profiles and turbulence intensities were achieved. The rotor characteristics for a number rotors used in the experiments were evaluated by running at various tip speed ratios. The results have been compared to the boundless prediction and show good general agreement. The single wake baseline test showed that the 1/70th scale wake had the expected characteristics (in terms of velocity deficit added turbulence intensity and Reynolds Stresses) providing confidence that the array tests are representative of larger full-scale rotors.

Measurements of tower load, and rotor torque and speed enabled the effects of blockage to be investigated. Loading and wake measurements have been obtained for a line of 2, 3 and 5 rotors at lateral spacing of between 1.5 and 3.0D to assess the effect of blockage on rotor performance and wake structure. The results show that at a lateral spacing of 1.5D the adjacent wakes start to interact within 2D downstream of the rotor plane changing the applied thrust of the row of rotors and the near wake profiles.

The multi-row wakes investigations included eight multi-row rotor configurations. These tests provide evidence on the effect of lateral and longitudinal spacing on far wake recovery.

Ambient flow sensitivity investigations included the measurements of a row of three rotors operating in four ambient flows. Single wake measurements were taken for the added roughness test to evaluate three dimensional effect of added mixing without the added complexity of multiple wakes. The island wake test was repeated to avoid the issue of prolonged rotor stalling. This data although not processed at the time of writing this report will be included in the database.

For all array tests, the water depth to rotor diameter is the same (depth ~ 1.67D) and the average operating point of each rotor is the same. Investigative studies have not been conducted for different depth ratios or operating points due to constraints on flume-dimensions and rotor scale discussed in WG4WP2D2. Since all tests were conducted at the same depth ratio, the unbounded rotor characteristic has not been measured. However, inter-comparison between tests is straightforward. Further experiments are planned to measure the rotor characteristic in a 0.8 m deep test facility. The same facility will also be used to investigate the sensitivity of loading and wake structure to free-surface proximity. The sensitivity of wake structure to operating point and free surface proximity are also the subject of detailed numerical studies in WG3WP1 and WG3WP5.

A large body of data has been collected and processed and is collated in an accessible database which constitutes part (a) of WG4WP2D5. This report constitutes the test report WG4WP2D5 part (b). The main work package objectives have been fulfilled and all planned investigations have been completed. Some planned tests were not executed but these tests have either been replaced by alternative configurations or repeated in a modified form. The missing tests have not compromised the validity of the experimental programme, and were excluded on the grounds of unforeseen practical constraints (e.g. rotor stalling, measurement accuracy) or in view of the benefits that would be obtained by conducting extended or additional investigations of particular aspects. .

Preliminary analysis of the effect of blockage on wake structure has been conducted and summarised in a peer-reviewed conference paper. Further analysis of the effect of blockage on device performance and the effect on the local flow field will be reported in WG3WP4 D11 where the GH blockage model will be compared to the relevant experimental data. Additional analysis of the far wake interactions will be undertaken as part of a comparison study with the GH far wake model and will be report in WG3WP4 D14.

This report provides a summary of the experimental scope and the various experimental tests undertaken to investigate the physical processes of interest. The experimental and calibration processes are summarised and reference to existing documentation is provided. The method of data collection and documentation is described and reference to the database of test data is made. The post-processing method used to analysis the data is also described in detail. Finally the salient findings from initial analysis of the experimental measurements are presented and discussed. Both comparison of the test programme to the specification and the summary of findings demonstrate that the main objectives of the work package have been satisfied.

APPENDIX A – FIGURE OF ALL DATA POINTS

APPENDIX B – EWTEC PAPER