Programme Area: Marine

Project: PerAWAT

Title: Experiment Data, Quality Controlled and Delivered

Abstract:

Few experimental scale tests have been conducted to assess the performance of one tidal turbine. However, there is a growing need for scale testing in order to validate numerical models which will predict the effect of the ambient flow conditions on the power performance and the wake shape and intensity of a tidal turbine. The intention of WG4 WP3 is to obtain experimental data describing the wake and performance of ducted device concepts. This document provides an explanation of the test procedure, the format of the collated data and the quality control processes employed during the experiments.

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.

ETI – PerAWaT

WG4 WP3 D2: Experiment data, quality controlled and delivered

Project	PerAWaT
Work package	WG4 WP3
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V0.4	07/03/2013	Feedbacks from project leader
V0.5	08/04/2013	Additional information from UoM

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SUMMARY OF NOTATION

Turbine characteristics

D	Rotor diameter (m)
R	Rotor radius (m)
A	Rotor swept area (πR^2)
C_T	Thrust coefficient (measured)
C_P	Power coefficient (measured)
TSR	Tip speed ratio
C_{T0}	Thrust coefficient in boundless conditions
C_{P0}	Power coefficient in boundless conditions
TSR_0	Tip speed ratio in boundless conditions
c	Blade chord
ω	Blade rotation speed
P	Extracted power
T_d	Drag force
C	Torque

Flow field

U(x,y,z)	Mean velocity profile
U_{RMS}(x,y,z)	Fluctuation of the velocity profile about the mean, as a function of depth
U_0(x,y,z)	Mean velocity profile in boundless conditions
TI	Turbulence intensity
T	Wave period
Hs	Significant wave height
Q	Flow
ν	Kinematic viscosity
g	Gravity acceleration
h	Water depth
L	Flume width

Non-dimensional numbers

Fr	Froude number
Re	Reynolds number
Rec	Reynolds /blade chord
Str	Strouhal number
B_1	Blockage ratio (based on area i.e. A/(hL))
B_2	Blockage ratio (based on diameter i.e. D/L)

1 INTRODUCTION

1.1 Context of the study

In the framework of this project called PerAWaT (**Per**formance **A**ssessment of **Wa**ve and **T**idal Array Systems) which has been commissioned and funded by the **E**nergy **T**echnologies **I**nstitute (ETI) and aims to establish and validate numerical models to predict the hydrodynamic performance of wave and tidal energy converter, the LNHE (**N**ational **L**aboratory for **H**ydraulics and **E**nvironment, part of EDF R&D) performed several tests to study performance and wake of a turbine at $1/30^{th}$ scale in a flume of EDF facilities. Performance and wake are key parameters in developing farms of tidal converters. Converters can be strongly affected by flow conditions like the current velocity, the turbulence of the flow, the distance between the rotor and the free surface or the presence of waves.

Few experimental scale tests have been conducted to assess the performance of one tidal turbine. However, there is a growing need for scale testing in order to validate numerical models which will predict the effect of the ambient flow conditions on the power performance and the wake shape and intensity of a tidal turbine.

The majority of device scale work in PerAWaT addresses the performance and wake of the open-blade type fundamental device concept (FDC). The intention of WG4 WP3 is to obtain experimental data describing the wake and performance of the ducted device concepts. Due to unavailability of a suitable ducted scale model from technology developers, changes to the schedule of WG4 WP1 and numerical simulations of ducted device concepts by UoO, it was agreed in May 2011 that the original scope of work for WG4 WP3 would be abandoned and a revised package of work would be developed.

Within PerAWaT experimental study of rotors has been conducted at two geometric scales: 1:30th approx. at EDF and 1:70th approx. at UoM. Both of these rotors were designed using GH Tidal Bladed assuming unconstrained flow. However, both sets of experiments are at relatively high blockage ratios and the rotor is within close proximity to bounding surfaces of both free surface and flume bed. Simulations conducted in WG3 WP1 show that both blockage and the presence of a sheared onset flow due to bed proximity alter turbine performance and wake structure. Experimental measurements of the WG4 WP2 rotor at low blockage would increase confidence in the higher blockage 1:30th and 1:70th scale experiments conducted to date, and the interpretation of the turbine array results (1:70th) and their use within WG3 WP4. Links to other WP are described in WG4 WP3 D1.

The motivation for this WP is to provide experimental data quantifying:

1. Influence of turbine augmentation with duct on turbine performance and wake structure. This will improve confidence in the findings of numerical simulations and the application of derived wake models to ducted devices.

2. Effect of vertical positioning and bounding surface proximity on wake form. This will improve confidence in the range of application of wake models.

This work also complements WG4 WP2 by quantifying:

3. Performance and wake of the UoM rotor in unconstrained flow.

This allows direct comparison of GH Tidal Bladed predictions to measurements with UoM rotor and increases confidence in quantifying the effect of blockage measured in WG4 WP2. WG4 WP3 D1 details the specification of the experimental data required to both assess the influencing of duct augmentation on a porous disc and to assess the effect of bounding surfaces on the wake of the $1:70^{th}$ scale rotor. WG4 WP3 D2 describes the quality control process of the experimental data and format before delivery to interested parties.

1.2 Scope of this document

Details of the planned experiments are given in WG4 WP3 D1. This document provides an explanation of the test procedure, the format of the collated data and the quality control processes employed during the experiments. Finally, the format and location of archived data is briefly described. It should also be noted that the University of Manchester, GH and EDF were in communication throughout the duration of the tests.

1.3 WG4 WP3 D2 acceptance criteria

Acceptance criteria: Summary report explaining data format and QC process. Data uploaded to ftp.

Data files were uploaded to the UoO FTP site as soon as they became available and remain available to all project members.

Data were verified after every test by UoM. When data was of insufficient quality, tests have been repeated until quality criteria were met.

2 BRIEF DESCRIPTION OF THE TEST FACILITIES

EDF's Flume 5 was selected as the most suitable facility for the purposes of this work package (as defined in WG4WP3D1).

Figure 1: Channel 5 at EDF LNHE facilities

The main features of the flume relevant to these experiments are:

- Cross section of 1.5 m width and up to 1.2 m depth, 0.8 m depth employed for the present series of tests.
- A flat, smooth bed of length 70 m allowing production of a fully developed turbulent profile upstream of the turbine and sufficient distance downstream for wake recovery.
- Flow developed by means of a diverter valve and two pumps providing mean velocity of up to 0.6 m/s at 0.8 m depth.
- A motor driven support carriage that facilitates automated positioning of instrumentation in the streamwise (x-) direction and vertical (z-) direction.

The characteristics of flume 5 are summarised below:

Dimensions:	80 m long (72 m effective length) x 1.50 m wide
Maximum water height:	1.20 m
Flow:	0 to 250 l/s or 0 to 1000 l/s (depending on the pump)
Wave paddle:	Piston-type, regular and irregular waves

3 INSTRUMENTATION AND OTHER EQUIPMENT

An Acoustic Doppler Velocimeter (ADV) is used to measure the current velocity in three dimensions. PC-run, specialised data-logging software is used to capture the flow measurements. The instrument employed is a Nortek Vectrino+ identical to the equipment used in WG4WP2. Specifications in terms of the principal measurement parameters are given WG4 WP3 D1 and WG4 WP2 D4.

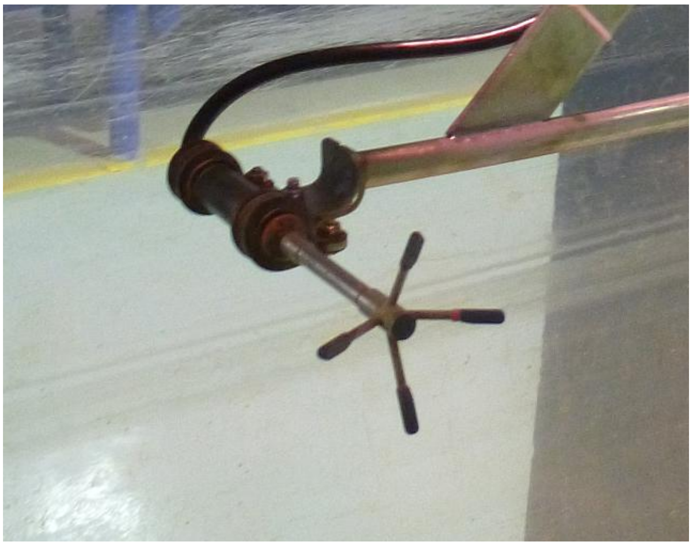

Figure 2: 3D ADV sensor head

Measurements were taken over different sampling durations. Each acquisition has a 2-minute sampling duration at 200 Hz

- ADV support

The ADV sensor is held on a support that is wheeled along the rails located on the upper part of the two longitudinal walls of the flume (Figure 3). This allows translation along the X axis (lengthwise along the flume). Translation along the other two axes (Y – width- and Z – depth) is realised by moving the sensor along the runners incorporated on the support. The precision of the ADV location is about 1 mm. The ADV was supplied by UoM and the support tower manufactured by EDF (Figure 4).

Figure 3: ADV support

Figure 4: ADV tower support

- Turbine support

The turbine support is a combination of the systems used in WG4 WP1 (EDF) and WG4 WP2 (UoM). The turbine nacelle and supporting tower are identical to the system used in WG4 WP2. This comprises a 40 mm square 90° bevel gearbox supported on a vertical rod of 15 mm outer diameter and 800 mm length. The top of this rod is strain gauged and affixed to a rectangular mounting plate, which also supports a dynamometer in the case of rotor experiments. An intermediate part is used to fasten the top plate of the UoM tower to the support structure used for the WG4WP1 experiments (Figure 5).

Figure 5: tower of UoM fastened to the EDF support.

With this configuration, one keeps the possibility to remove the tower from the water when tests are not performed or when maintenance is needed.

Figure 6: Rotation of the central support to place the turbine in the water

- Acquisition system

The acquisition system (Figure 7) is described in WG4WP2.

Figure 7: UoM's acquisition system on canal 5 footbridge

4 CALIBRATION AND MEASUREMENTS REFERENCES

- Water height: when the pump is turned on, after a stabilisation of the flow, the level of water is readjusted.
- The flow is controlled with an electromagnetic flow meter and the velocity is verified with a measurement far from the device upstream (but after flow fully developed). The control point is at z=400 mm from the flume floor. This calibration and reference measurement section is the same as in WG4 WP1.
- No calibration is required for the ADV sensor
- ADV volume control positioning:

  A small plastic nozzle can be fastened to the ADV sensor head to position the point of measurement of the velocity (position of the control volume). This point has been located in the canal 5 rulers.

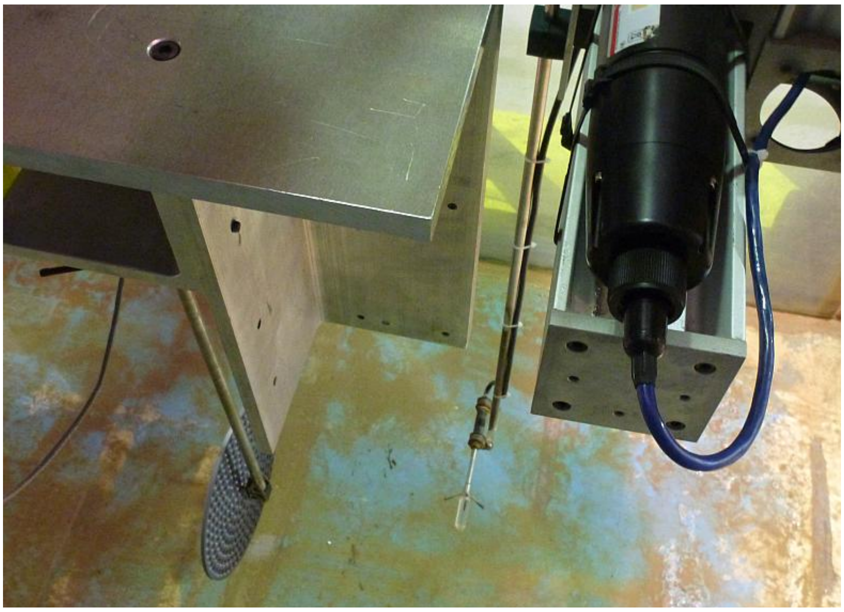

Figure 8: ADV sensor with its plastic nozzle to position the point of measurement

- Strain gages for thrust measurement: before every test a calibration is performed with the tower in a horizontal position and small weights put on the axis.

5 PROCEDURES FOR TESTINGS

The following procedure was employed:

- Calibration (without weight and with 1, 2, …7 weights, “2012-AA-BB-CCCCC.dat” files, 2012-AA-BB representing the date and CCCCC the weight)

- Record without rotor nor disk, with flow (“flow_TSR.dat” file),

- Record with rotor or disk, without flow (“noflowhanging_Ax” file),

- Record of the "waves" when the pump is switched on (“power_ON” file),

- Performing TESTS when the velocity is stabilised

- Record when the pump is switch off (“power_OFF” file),

- Record of no flow after stabilization (“noflowhanging_Zx”, velocity smaller than 1 cm/s)

- Second record of no flow (“noflowhanging_ZZx”) 10 minutes after the previous

The calibration is done every day or between tests if the tower is touched (for example when a disk is changed) or moved.

When the pump is switched on or off, the sudden change in the flow velocity generated a strong wave that was found to damage the strain gauges on the turbine support tower. Therefore a porous disk attached to a tower is held, manually, just in front the rotor or disk to decrease the drag force of the waves propagating in the flume on the rotor or a disk and the strain experienced by the equipment is recorded to verify that it does not exceed a critical value. This is why we have noflowhanging_A, power_ON, tests, power_OFF and noflowhanging_Z files.

Figure 9: Porous disk fixed on a tower that is placed in front on the instrumented tower (with disk or rotor) to limit the drag force when the pump is switched on.

Another step was added, between the second and third steps, for tests with the duct because its weight does not allow moving the tower when the duct is fixed without creating damages on the strain gauges: the flume is drained to allow changing the disk and a record is then performed to verify that strain gauges remain operational (“noflowhanging_Zxdry.dat” file).

6 TESTS

Descriptions of the equipment used for each test and the test programme are given in WG4 WP3 D1. Tests performed with porous disks (Figure 10) or a rotor (Figure 11) are mostly as listed in Table 2.1, 2.2 and 2.3 of WG4 WP3 D1. The following small variations were made during the testing programme:

- Tests 3.3x – measurement of the wake of a rotor with centreline 200 mm below mean water: these tests were intended to provide information on the influence of free surface proximity on wake structure. This test series was omitted since it was agreed that there would be greater value to additional measurement points within Tests 3.1x with centreline 400 mm below mean water line. These extra data points were selected to improve understanding of the wake with relatively low influence from bounding surfaces.

- Test 3.1x – measurement of the wake of a rotor with centreline 400 m below mean water line: wake measurement points expanded to include:

  - ZptsB amended to include points at z = +210 mm and z = -210 mm (note: ZptsB and ZptsA are tables of wake measurement co-ordinates, see Appendix 3 of WG4 WP3 D1):

    - Edit to Series 3.14: changed from ZptsA to ZptsB

    - NEW Series 3.18: ZptsB at 3D

    - NEW Series 3.19: ZptsB at 5D

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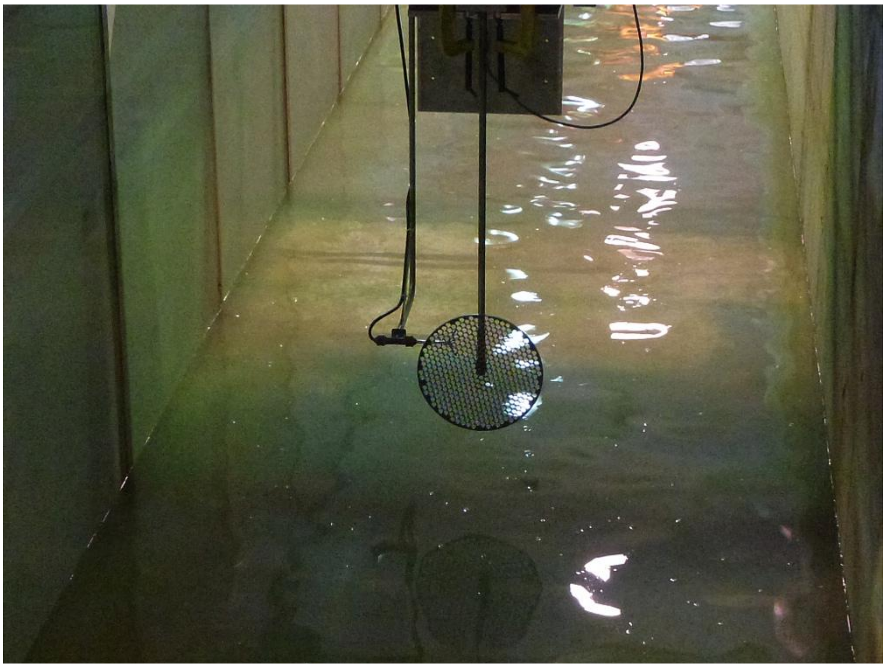

Figure 10: disk fixed on the UoM's tower

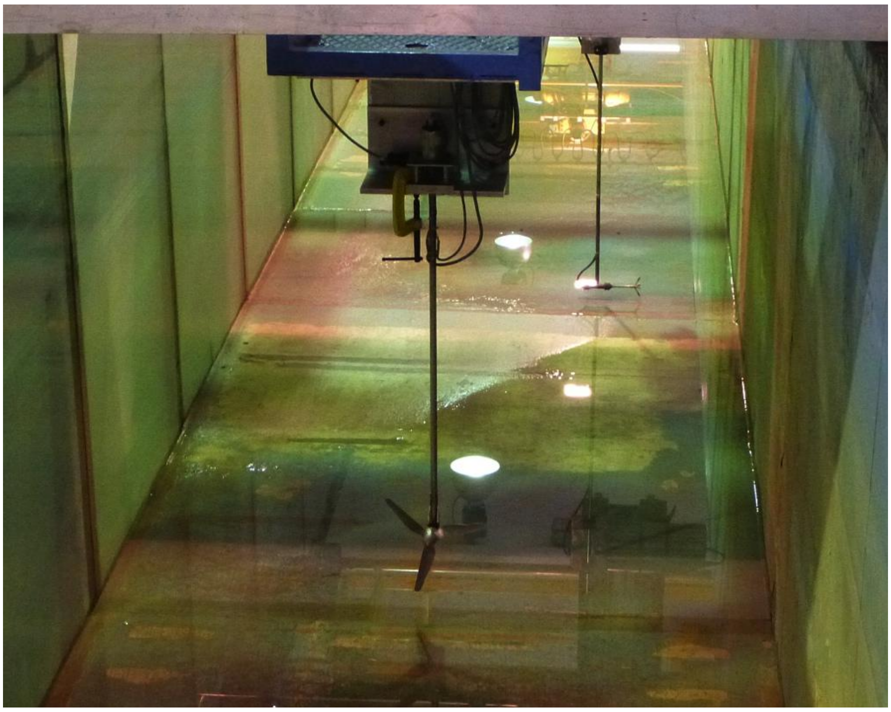

Figure 11: rotor fixed on the UoM's tower

7 DATA

The equipment employed for measurement of mechanical parameters (thrust, torque, speed) and flow velocity is identical to the equipment employed for WG4WP2. Differences concern the duct and porous discs, both of which are detailed in WG4WP3D1.

7.1 Time varying data

The logging system employed for these experiments is an amended form of the Labview data logger described in WG4WP2D3. For all WG4WP3 experiments exactly the same logging interface and file structure are employed. A sample rate of 200 samples per second and a sample population of 12,000 samples were used for all tests. Data files do not contain a time stamp since all data recorded at fixed sampling rate. Each data file contains 7 columns:

Column 1	Ux velocity component (cm/s),
Column 2	Uz (cm/s),
Column 3	Uy1 (cm/s),
Column 4	Uy2 (cm/s),
Column 5	Torque volts (V),
Column 6	Strain gauge volts (V)
Column 7	Angular displacement (rad).

The foregoing velocities are given relative to the flume co-ordinate system with x- in streamwise direction, y- transverse to the flow, z- vertical. The ADV Vectrino+ x-axis is aligned with the flume x-axis. Converting the Ux, Uz, Uy1 and Uy2 velocity obtained with ADV vectrino to the conventional hydraulic velocity, the longitudinal velocity U=Ux, the transverse velocity V=-(Uy1+Uy2)/2 and the vertical velocity W=-Uz.

Four categories of data file are recorded for

(1) Thrust measurement
(2) Rotor performance
(3) Wake measurements

The filename convention and application of each file type are briefly explained:

(1) Thrust measurement

The strain gauge record data has 3 classes.

Class 1: Calibration of Strain Gauge.

Data file: All the same for the name of all tests.
For example: 2012_12_19_10853.dat denotes the test date 19/12/2012 and the calibration weight added on the tower structure 108.7 grams and so on.

Note: for these files 7 columns of data are recorded but only col6 (Voltage, Thrust) is relevant.

Class 2: Quality Control analysis (QC analysis)

Data files: noflowhanging_A1.dat, noflowhanging_Z1.dat, noflowhanging_ZZ1.dat etc. noflowhanging_A1 and noflowhanging_Z* are the strain gauge records before and after the flow test assuring the strain gauge in stable condition through the period of flow test. The consistence of noflowhanging load before and after the test i.e. noflowhanging A1 and noflowhanging Z confirms that the strain gauge remains operational during the test. The average of noflowhanging Z1 and Z2 is used as the noflowhanging load.

Note: for these files 7 columns of data are recorded but only col6 (Voltage, Thrust) is relevant.

Class 3: Calculation of tower weight and tower drag

The average load evaluated from of noflowhanging_Z1 and Z2 are used for calculation of the noflowhanging load for the strain gauge.

The file flow_TSR.dat contains the strain gauge records of the “naked” stem of tower structure hanging in flow. noflowhanging_TSR.dat contains the strain gauge records of the “naked” tower structure hanging in air. Hence the difference of the two gives the load due to the tower only. Finally the actual thrust on the disc or rotor is obtained as:

Thrust = total load due to flow – noflowhanging load – tower load.

(2) Rotor performance data

The name of rotor performance data file contains the dynamometer setting of the igen and ifric for the particular test. For example, igen000_ifri_-230_FX_T_w.dat denotes that igen=0 and ifric=-230 mA were set up for the test.

Note: for these files, Cols 1-4 (velocity components) are measured but are irrelevant.

(3) Flow measurement data

The name of flow measurement data file contains the location where the measurement was taken in flow relative to the center of the rotor plane. For example, U_X0155_Y000_Z0000_FX.dat denotes that the measurement was at the location of (x=155mm, y=0, z=0) in the flow.

7.2 Quality Control and analysis of time-series

Three data checks were conducted:

1. Confirmation of strain gauge linearity
2. Confirmation that strain gauge within-range throughout test period
3. Confirmation of rotor operation (rotor tests only)
4. Confirmation of mean values

These are briefly summarised:

(1) Strain Gauge linearity: The QC analysis on the stability and linearity of the strain gauge were carried out through the tests. For all tests the strain gauge calibration is linear with $R^2 > 0.99$.

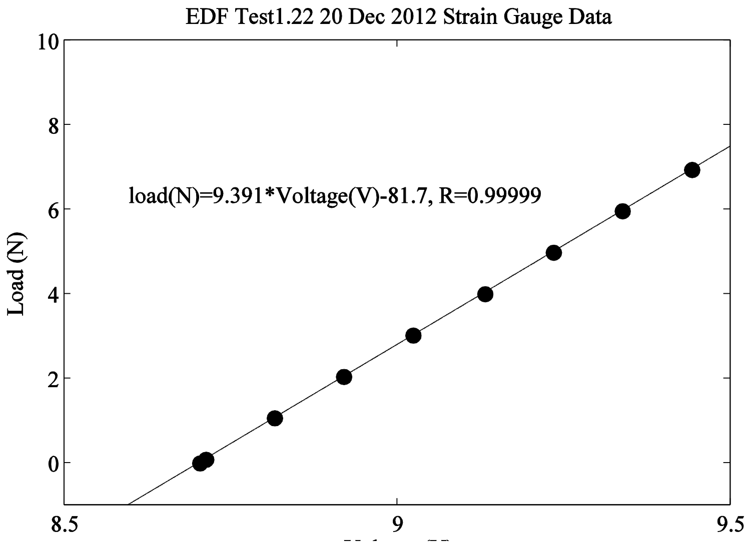

Figure 12: QC analysis 2: Linearity of Strain Gauge

(2) Thrust within range: The identical of the strain gauge output before (noflowhanging$_A$1) and after the flow measurement (noflowhanging$_Z$1) shows the consistency of the strain gauge during the test. Despite the rapid surge load produced by switching on and off pump, the strain gauge kept perfectly stable. Hence the calibration as shown as below can be used with confidence for the particular test.

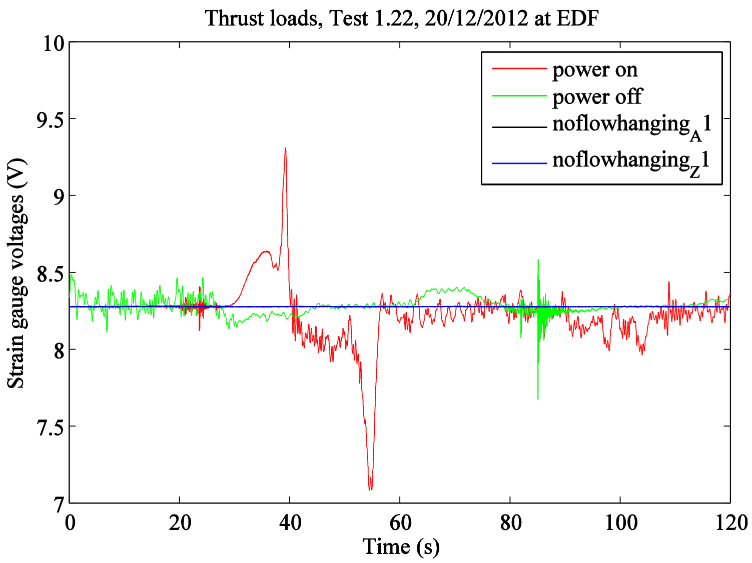

Figure 13: QC analysis 1: Stability of Strain Gauge before and after flow measurement

(3) Rotor rotation: The angular displacement was monitored during data process and no stalling was observed.

(4) Sample average: Average thrust coefficient, and where available TSR and CP, are obtained for each 1 minute sample. An example of the variation of C_T during the eight measurement points of a single wake traverse is shown in Figure 14. Where large variation of the mean value of CT was observed, tests were repeated.

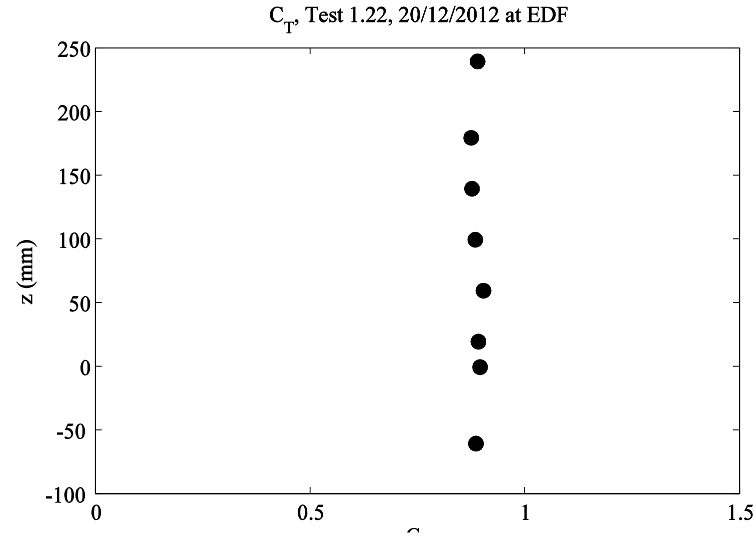

Figure 14: QC analysis 3: C_T values

7.3 Time averaged (processed) data

Following test completion, data has been processed by UoM to obtain a summary of time-averaged velocities and mechanical parameters for each test. The summary data files are organized in the formation as shown as in Table 1: UoM Processed Data File Configuration.

Table 1: UoM Processed Data File Configuration

Test	Traverse	Col1	Col2	Col3	Col4	Col5	Col6	Col7
Porous Disc Wake And Ducted Disc Wake	Longitudinal (Test1.16, 1.17; Test 1.26, 1.27)	x (mm)	y=z=0 (mm)	Ux (m/s)	Ux,rms (m/s)	C_T	N/A	N/A
	Transverse (Test 1.12, 1.14 Test 1.22, 1.24)		y (mm)					
	Vertical (Test 1.11, 1.15 Test 1.21, 1.25)		z (mm)					
Rotor Wake	Longitudinal (Test 3.11, 3.21)	x (mm)	y=z=0 (mm)	Ux (m/s)	Urms (m/s)	C_T	TSR	C_p
	Transverse (Test 3.15 – 19; Test 3.25 – 27)		y (mm)					
	Vertical (Test 3.12 – 14; Test 3.22 – 24)		z (mm)					
Rotor Performance	Fixed Point (Test 2.1 – 2.3)	Iinst[1] (mA)	ω[2] (rad/s)	TSR	C_T	C_p	N/A	N/A

Note: [1] Iinst = Igen + Ifric, [2] ω = rotor angular speed.

*The type of test and the type of traverse are as listed in WG4WP2D1 report.

Brief explanation of the names of the data file:

The data files were named after the Test. For example: “Test112vertical.dat” contains the data obtained during the vertical traverse of Test 1.12, “Test112Transverse.dat” contains the data obtained during the transverse traverse, and so on.

7.4 Data Storage

All time series datafiles as described in Section 7.1 are available on the UoO FTP site with the directory structure as shown in Figure 15. Summary data files as described in Section 7.3 are also available in the direction “UoM time average data”.

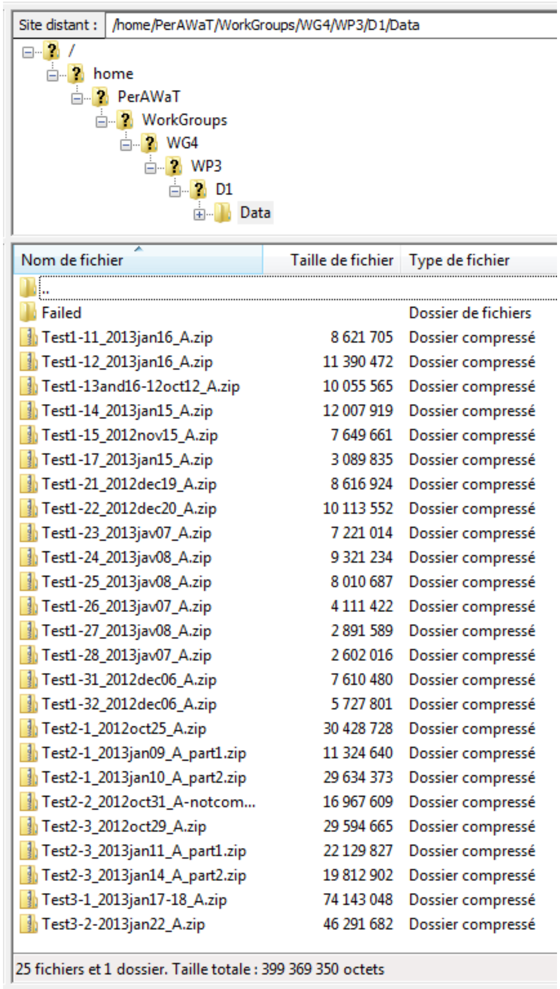

Figure 15: Screen copy of the directory of WG4 WP3 D1 on UoO’s FTP site.