Programme Area: Marine

Project: PerAWAT

Title: Design of Equipment for Scale Model Experiments

Abstract:

The report explains the data required from experimental study of an array of tidal stream devices. Issues associated with scale of the experiments are discussed and an appropriate facility is identified in the form of the University of Manchester wide flume. This facility allows conduct of experiments at approximately 1:70th geometric scale which will provide the specified data concerning the effect of turbine spacing and ambient flow on wake structure and device loading. 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. Engineering drawings are supplied for the main items of equipment. An explanation is given of how each of the required flow conditions – including steady flow with low turbulence intensity, steady flow with waves and increased levels of turbulence intensity and large scale eddies – will be generated. Although some aspects of equipment design may have been modified following preliminary manufacture and testing the equipment detailed represents the most suitable design choices at the time of writing. Following explanation of
the experimental equipment, a brief outline is given of ongoing work at the time of writing.

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.

PerAWAT WG4 WP2 D2

Design of Equipment for Scale Model Experiments

Project	PerAWAT
Work package	WG4
Deliverable	WG4 WP2 D2 Design of Equipment for Scale Model Experiments
Responsible author	Tim Stallard (UoM)
Second reading	Tong Feng (UoM), Jo Whelan (GH), Peter Stansby (UoM), Mat Thomson (GH)
Circulation	UoM / GH / EDF
To be approved by	Robert Rawlinson-Smith (GH)
Date	04/05/2010
Issue	V0.4

Document revision history

Issue	Date	Summary
V0.1	24/02/2010	First draft
V0.2	04/03/2010	Second draft
V0.3	05/03/2010	Final
V0.4	04/05/2010	Revised in accordance with MRN PWT PM2

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. Issues associated with scale of the experiments are discussed and an appropriate facility is identified in the form of the University of Manchester wide flume. This facility allows conduct of experiment at approximately 1:70th geometric scale which will provide the specified data concerning the effect of turbine spacing and ambient flow on wake structure and device loading. This report, WG4 WP2 D2, details the design of experimental equipment to conduct the 1:70th scale experiments of an array of devices such that the specifications of WG4 WP2 D1 are satisfied. 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.

An explanation is given of how each of the required flow conditions – including steady flow with low turbulence intensity, steady flow with waves and increased levels of turbulence intensity and large scale eddies – will be generated. Velocity measurements will be conducted using NORTEK MicroADV+ Acoustic Doppler Velocimeters mounted on a custom-built traverse table to facilitate accurate spatial mapping of turbine wakes. A dynamometer design is developed which comprises a motor in a sealed nacelle supported on a strain-gauged and force-balanced shaft. A data logging system is described which allows simultaneous measurement of mechanical parameters of 15 tidal stream devices and of multiple velocity field measurements at a sampling frequency of 200 Hz. A 3-bladed rotor is designed for low Reynolds operation which comprises a Goettingen 804 blade with radial distribution of chord length and twist angle selected through application of GH Tidal Bladed to achieve similar thrust coefficient to a generic rotor provided by TGL. Although some aspects of equipment design may be modified following preliminary manufacture and testing the equipment detailed represents the most suitable design choices at the time of writing. Following explanation of the experimental equipment, a brief outline of ongoing work is given.

CONTENTS

SUMMARY OF NOTATION

Turbine characteristics

D	Rotor diameter (m)
R	Rotor radius (m)
C_T	Thrust coefficient
C_P	Power coefficient
TSR	Tip speed ratio
C_{T0}	Thrust coefficient in boundless conditions
C_{P0}	Power coefficient in boundless conditions
C_L	Coefficient of lift
C_D	Coefficient of drag

Flow Field

U(z)	Mean velocity, as a function of depth
$U_{RMS}(z)$	Root mean square of velocity, as a function of depth
TI	Turbulence intensity
T	Wave period
H_s	Significant wave height
T_z, T_p	Zero-crossing period and peak period of irregular wave
X, Y, Z	Streamwise, transverse and vertical ordinates

Abbreviations

ADV	Acoustic Doppler Velocimeter
BEM	Blade Element Momentum
COR	Correlation coefficient
SNR	Signal to noise ratio

1 INTRODUCTION

1.1 Scope of this document

This document constitutes the second deliverable (D2) 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 relationship between each tidal stream work packages is described in WG0 D2. The project partners of this work package are the University of Manchester (UoM) and Garrad Hassan (GH). Building on the objectives and specification of the array-scale experimental work detailed in WG4 WP2 D1, this document provides a description of the design methodology for the main items of experimental equipment. WG4 WP2 D1 explains that array tests will be conducted at approximately 1:70th scale in the University of Manchester wide flume. In this report 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. Finally, an overview is given of the equipment calibration, data collection and data logging procedures that will be implemented. Engineering drawings of several items of equipment are given in the Appendices which are also provided as separate pdf documents.

As per the acceptance criteria this report therefore represents a “Design specification report including a clear definition of reasons for design selection, method for manufacture and assembly of all key components, e.g. rotor (blades, hub, nacelle, generator); instrumentation system and support structure. Specification and system design drawings of sufficient detail and standard to proceed directly to procurement and manufacture.”

The programme and equipment designs presented herein represent the most suitable design choices at the time of writing but UoM reserve the right to make minor modifications to aspects of the design if more appropriate solutions are identified that meet the objectives.

1.2 Specific tasks associated with WG4 WP2

- Test specification of sufficient detail and scope 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] including: Rotor design, Instrumentation system design and support structure design.

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

- Conduct tests (D4) [UoM] including: Set up test facility, Calibrate instrumentation, Conduct test schedule (measuring rotor thrust, power consumption, and the flow field within and around the array).

- Issue database of experimental data (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)

Measurements focus on the effect of lateral blockage on turbine performance and wake structure. Constant depth and similar average flow velocity and velocity profile are therefore maintained across most tests to allow inter-comparison of test data. Regarding the effect of lateral blockage, data is required for relatively close spacings to understand the influence of high blockage. It is expected that devices will be installed at around 2.5 D spacing (EMEC, 2009). A minimum lateral spacing of 1.5 D centre-to-centre spacing will be considered (roughly corresponding to proposed designs for multiple turbines on a single support structure, e.g. Marine Current Turbines Seagen) and blockage is expected to be negligible for centre-to-centre spacing greater than 6 D (see Figure 1, WG4 WP2 D1). For multi-row arrays, longitudinal spacing will be selected based on investigative tests.

As specified in WG4 WP2 D1, two types of experimental study will be conducted – detailed and investigative – which differ in terms of the spatial resolution of velocity measurements. For detailed tests, measurements of the 3-dimensional wake-structure are required. This will comprise the 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 will form a 3-dimensional description of the wake structure. 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. During all tests, 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

The instruments and method used to measure each of these variables are discussed in Sections 3 and 4. The exact sequence of tests will be modified depending on findings from the investigative studies but will be based around the following programme of work. A brief explanation of the use of the data from each series of tests is given to indicate the intended application of the measured data. Based on a water depth of 450 mm and mean velocity U ~ 0.4 m/s the following tests will be included:

- ***1 Device performance study to determine C_T (TSR) curve*** ***(3 tests)***
  - measure C_T, C_P and velocity including downstream wake recovery

  Use of data: provides a baseline dataset for understanding the effect of blockage.

- ***2 Devices at 1.5, 2 and 3D spacing*** ***(3 tests)***
  - measure C_T, C_P and velocity including wake recovery

  Use of data: structure of wake with asymmetric boundary conditions for development and evaluation of wake model and effect of blockage on device loading for development of blockage model

- ***3 Devices at 1.5, 2 and 3D spacing*** ***(4 tests)***
  - measure C_T, C_P and velocity including wake recovery
  - impose waves for 1 configuration

Use of data: structure of wake with symmetric boundary conditions for development and evaluation of wake model and effect of blockage on device loading for development of blockage model. Waves imposed to improve understanding of effect of wave forcing on wake structure.

- ***2 rows of devices: 1 lateral spacing, 5 longitudinal spacings*** ***(5 tests)***
  - measure C_T, C_P and velocity including wake recovery
  - (no velocity measurements between rows)

Use of data: performance curves for the second row of data used for development and evaluation of blockage and wake models.

- impose waves for 1 configuration (2 x long-period irregular) (2 tests)
- modify turbulence for 1 configuration (2 tests)
- large eddy ambient flow for 1 configuration (2 tests)

Use of data: Higher turbulence levels (both bed-generated and large eddy structures) and waves are investigated to understand the effects of these physical phenomena on performance and wake structure. Repetition of a small number of configurations will be of considerably greater value than brief analysis of Multi-row configurations.

- ***3 rows of devices: 1 lateral spacing, 2 longitudinal spacings*** ***(4 tests)***
  - measure C_T, C_P and velocity including wake recovery
  - (no velocity measurements between rows)
  - impose waves for 1 configuration (long period irregular)

Use of data: validation of the array modelling tools accounting for blockage and wake structure.

(approx. 25 tests)

As shown in Section 2.1, practical operating depths for the flume are in the range 0.3 to 0.55 m and so, using a 0.27 m diameter turbine, attainable depths are between 1.5 D and 2.0 D. Thus, whilst the tests outlined above provide measurements suitable for evaluation of array models, these tests provide limited information on the influence of free surface proximity on device performance. However, this parameter is studied in more detail in other work packages (see WG0 D2). A larger range of depths would require either i) tests in a deeper flume or ii) testing of a smaller diameter turbine. Conduct of tests in a deeper flume have not been included in this work package (Schedule 5) but the feasibility of conducting tests in a deeper flume with a 0.27 m diameter turbine will be explored. Alternatively, tests of a 0.2 m diameter turbine would allow consideration of depths between 2.0 D and 2.75 D in the University of Manchester wide flume. Blade geometry for this application will be reviewed following initial physical testing of the 0.27 m turbine.

Detailed wake studies will include measurements at the following locations:

- Longitudinal variation along axis of device - ~ 10 points over 1D to 10D
  - manual repositioning of traverse gantry
- 3 to 5 wake cross sections to understand wake form
  - automated traverse between approx. 80 measurement points (40 y by 40 z)
  - sample duration approx. 2 minutes at each location (see WG4WP2D1)

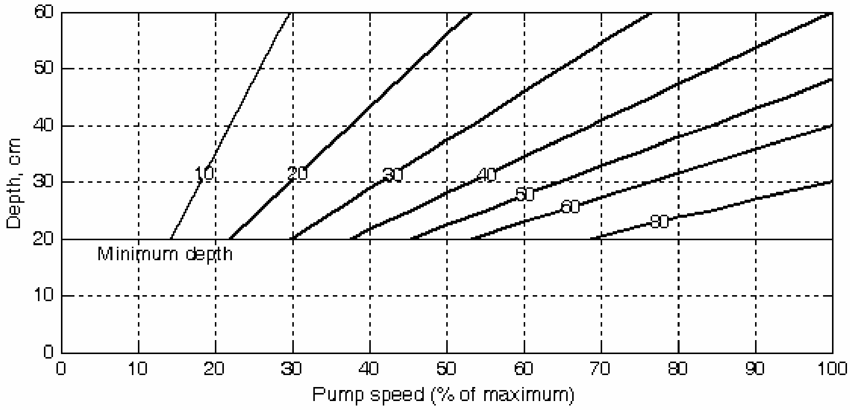
Assuming no problems during the tests, a detailed set of wake measurements requires approximately 1 day for data collection only. Clearly a large number of detailed wake studies are impractical and so investigative studies will be analysed to identify the configurations of most relevance for detailed study.

2 AMBIENT FLOW

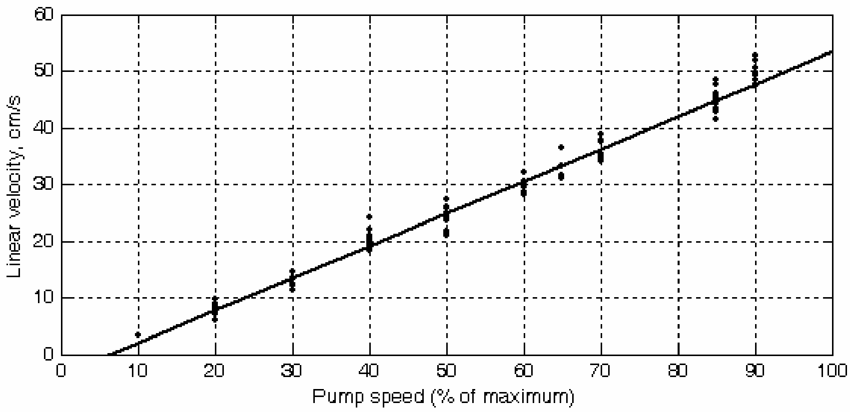
The range of experimental studies required are summarised in Section 4.4 of WG4WP2D1. The majority of tests will be conducted at a comparable mean incident flow velocity but different depth profiles and turbulence characteristics will be studied. A summary of the achievable flow conditions is given in Section 2.1 and flume modifications required to develop particular flow characteristics are described in Sections 2.2 to 2.4.

2.1 Flume Characteristics

Flow is developed by 2 No. 20 kW pumps located in 2 No. 500 mm diameter pipes below the test section of the flume. Preliminary measurements have been taken of mean flow velocity over a range of pump speeds (Figure 2.1) and of the depth profile of velocity and turbulence intensity (Figure 2.2). Most tests will be run at 450 mm depth and so flow velocities up to 55 cm/s can be developed.



(a) Variation of mean velocity (cm/s) with water depth and pump speed (by flow-rate)



(b) Velocity measurements taken in water depth of 0.45 m using propeller probe
Figure 2.1 – Indicative range of attainable flow speeds for specified depth and pump speed.

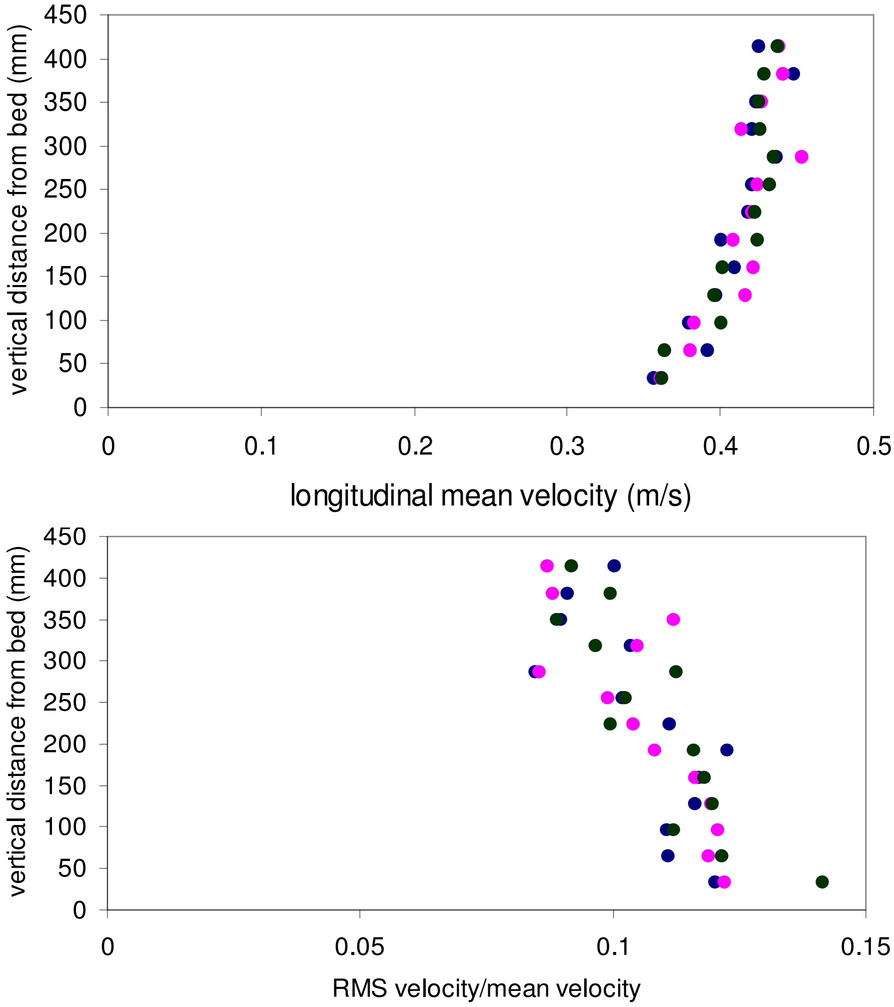


Figure 2.2 Depth profile of mean streamwise velocity and turbulence intensity (RMS velocity / mean velocity) at 7.5 m from inlet. Pumps at 90% capacity. Datapoints from three samples taken at different times under the same flow conditions.

2.2 Steady Flow

The target flow condition is a unidirectional open channel flow with a mean velocity of approximately 0.4 m/s (see WG4 WP2 D1). A target turbulence intensity is U_{rms} =0.04~0.05 m/s i.e. the level of 10~15% for the smooth bed tests. These flow conditions will be used for all tests listed in Section 4.4 of WG4WP2D1 except for the three unsteady conditions listed below. According to the estimated variation of linear speed with pump capacity (Figure 2.1), the required mean flow velocity is developed when the supply pumps operate at 90% capacity. Preliminary ADV measurements of time-varying velocity have been obtained to understand the depth variation of velocity and turbulence intensity (Figure 2.2). This indicates that the flow profile in the UoM flume is a typical pump driven open channel flow. Because of the large width of the flume, 5.0 metres and the smooth Perspex glass boundary of the flume, the flow in the flume will not reach the fully developed uniform open channel flow since this requires 40 hydraulic diameters to develop (~64 metres in this case). Furthermore, the time-varying velocity at mid-depth indicates the existence of continual large eddies formed by upwelling of the flow driven by the recirculating pumps. To satisfy the flow conditions defined in WG4WP2D1, these large oscillations of the "in-flow" have to be suppressed. This can be achieved by accelerating the flow over a solid weir but this option is limited by the flume depth. A porous weir of stainless steel has been designed (Appendix A) for installation at the flume inlet. This consists of a staggered matrix of round holes, 20 mm diameter at 40 mm spacing, such that the size of the eddy around the water turbine models will be less than 5 mm (i.e. 1/50 of the turbine blade diameter). This will eliminate large scale fluctuations from the flow and increased turbulence immediately downstream of the weir will decay over a short distance downstream. The steadiness of the in-flow should be much improved with the weir in place.

2.3 Increased Turbulence Intensity

It is expected that turbulence intensities at typical sites for tidal turbine installation will be in the range 10% - 25%. This range is based on ADCP measurements obtained to date within the industry (e.g. Thomson et al., 2008). However the exact figure and the length scales of the turbulence will be highly site specific, and further research is required to better understand the structure of turbulence at tidal sites. In WG4WP2 the intention is to re-create two different magnitudes of flow fluctuation (i.e the turbulence intensity). The steady flow tests detailed in section 2.2 will contain an ambient level of turbulence, the exact value of which will be evaluated by initial base mapping of the flume in the absence of rotors. A second (higher) turbulence intensity will be simulated in the flume by using artificial roughness techniques. The exact value of this is hard to predict precisely, however there is a body of empirical data that can be used as a guideline and a target value would be 20% (confidential commercial information available to Garrad Hassan). Again, this will be evaluated by initial base mapping of the flume in the absence of rotors. The mean velocity remains as U=0.4 m/s in order to be comparable to the smooth bed case. The target profile of mean velocity is the power of $1/7^{th}$.

Two types of artificial roughness have been used in open channels, namely uniform roughness (typically sand or gravel) and strip roughness. The latter is more suitable for the UoM Perspex bottomed flume. Strip roughness is typically designed based on the literature available for sand or gravel roughness. Figure 4.10 of Nezu and Nakagawa (1993) provides guidance for the strip grid design for the UoM flume. Relevant data from this figure, corresponding to test data from Blinco et al. (1971) and Nezu (1977) is presented in Table 1. For the UoM flume, the (depth) Reynolds number is, $Re = Uh/\nu = 1.8\times10^5$, we use the curves (1) and (2) by Blinco et al (1971), $Re=1.7\times10^4$ as the estimates. At mid-depth, $\zeta = z/h = 0.5$, the use of the uniform sand roughness $k_s/h=9.6\times10^{-2}$ where k_s is the sand size, has increased the turbulence intensity level from u'/U = 0.075 to 0.11, i.e. increase of 47%. Using this as the reference for strip roughness design, a cross-channel strip grid with strip height = 0.045m ($k_s/h=0.1$) and strip space=0.135m ($3\times k_s$), should generally increase the turbulence intensity by more than 50% of that the smooth bed case in the mid-depth region. PVC lattice is a relatively low cost material so trial experiments will be carried out until a satisfactory level of turbulence intensity is obtained.

Source	Reynolds Number (Re)	Relative roughness (k_s/h)	Relative TI (u'/U)	TI increase (%)
Blinco et al. (1971)	1.7×10^4	0 (smooth)	0.075	n/a
		0.096	0.11	47
Nezu (1977)	1×10^4	0 (smooth)	0.073	n/a
		0.016	0.085	16.4
		0.065	0.11	50.8
		0.164	0.123	68.5

Table 2.1: Roughness effect on the relative turbulence intensity u'/U at the mid-depth of an open-channel flow. Data from Figure 4.10, page 61, Nezu and Nakagawa (1993), Blinco et al. (1971) and Nezu (1977)

2.4 Large-scale Turbulent Structures

The effect of large-scale turbulent structures on the performance of the turbine array will be tested using an oscillatory wake produced from an existing submerged conical island model positioned upstream of the turbine or turbine array in the UoM flume. Referring to Lloyd and Stansby (1997a), (1997b), UoM found that the submerged island model is more suitable than the surface piercing island model for the proposed tests. UoM has designed the submerged island model to generate vortex shedding with a frequency of 0.125 Hz i.e. 8 seconds for a full oscillating cycle. The calculation of the dimensions of the conical island model can be found in Appendix B. Preliminary flow visualisation will be performed prior to the proposed tests using $KMnO_4$ dye tracer released at the edge of the island model. These preliminary visualisations will give more details about the real flow structures to identify suitable deployment locations for the turbine models.

2.5 Waves

Waves can be generated by eight position controlled Edinburgh Designs piston-type wave paddles. In the absence of current, the paddles allow generation of regular waves with frequency in the range 0.5 to 2.0 Hz and irregular waves conforming to standard spectra (details are given by Rogers & King, 1997) with peak frequencies in the range 0.5 to 1.5 Hz (roughly equivalent to 5 to 15 s at full-scale). Individual wave heights can be up to 100 mm (approximately 3 m wave height at full-scale). The flume is configured for waves to propagate against the direction of the current only and so the practical range of wave conditions is somewhat smaller than in the absence of current. The range of achievable wave states will first be identified by investigative tests and conditions representative of tidal stream sites will be considered. Based on measurements of conditions at the European Marine Energy Centre (EMEC) roughly half of the irregular sea-states per year are characterised by a zero-crossing period in the range 3.5 to 5.5 s and significant wave heights less than 1.0 m (see Table 2 of Thomson et al., 2008). Assuming a Bretschneider spectrum (for which $T_z \sim 0.78T_p$) these zero-crossing periods correspond to peak periods in the range 5 to 7 s full-scale and 0.8 to 1.2 s at the 1:70th scale of these experiments.

3 FLOW MEASUREMENT

Aside from the velocity measurements, there are some other practical issues associated with the flow measurements and the following are required:

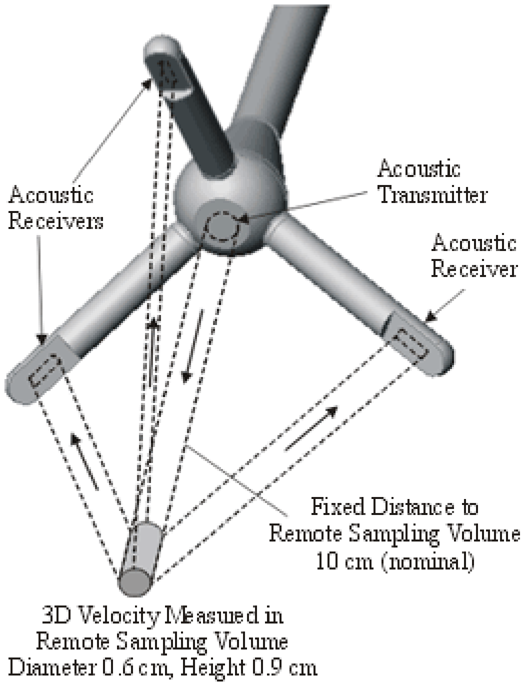
(1) an efficient method for positioning the measurement probes within the flume,
(2) a convenient calibration scheme for various relative measurements and
(3) an efficient method of assessing the quality of the recorded data.

UoM has ordered a two dimensional traverse system from HR Wallingford (Section 3.2) to facilitate positioning of the ADVs within the flume. A few of the proposed measurements such as the speed of rotation of the rotor and the thrust and torque exerted on the water turbine need routine calibration at the beginning and end of the test. Data quality will be checked during acquisition based on Appendix A of WG4WP2D1. All data will be stored as time series for further analysis and backed up to stand-alone hard-disks.

3.1 ADV: NORTEK Vectrino+

Six Vectrino+ ADV probes and the associated software Vectrino Plus, PolySync and ExploreV Lite were delivered to UoM from Nortek AS. UoM has checked each of the six ADV probes along with the associated software and confirm that six velocity measurements can be synchronised and are comparable.

Vectrino+ ADV probe, transmitter cable and case



Sketch of typical ADV probe, acoustic transmitters and receivers, sampling volume

Figure 3.1 Photo of Vecrtrino+ measurement probe on 1 m cable (left) and measuring volume (right).

The Vectrino+ is the revised version of Nortek Acoustic Doppler Velocimetry system, which enables the measurement of three components of water particle velocity at data rate of 1~200 samples per second. As the turbulent fluctuations in open channel flow are in a frequency range of 10~100 Hz, the revised Vectrino+ is suitable for the turbulent velocity measurement in the surface bounded wake behind the turbine array.

The Relevant Specifications of Vectrino+ ADV System are given below:

Water velocity measurement

Range:	±1, 2 m/s
Accuracy:	± 0.5% of measured value (NORTEK documentation)
Sampling rate (output):	1 to 200 Hz

Sampling volume

Distance from probe:	50 mm
Diameter:	6 mm
Height (user selectable):	3~15 mm

Doppler uncertainty (noise):

Typical uncertainty at 25Hz:	1% of velocity range (approx.)

Echo intensity:

Acoustic frequency:	10 MHz
Resolution:	0.45 dB
Dynamic range:	60 dB

Data communication

I/O:	RS232
Baud rate:	300~115200
User control:	Via Vectrino WIN32 Software, ActiveX function calls, or direct commands
Analogue output:	3 channels standard, one per velocity component. Output range is 0~5 V, scaling is user selectable.
Synchronization:	SynchIn and SynchOut.

The specifications provide both the technical details of the velocity measurement and an indication of the logging instruments required to synchronize velocity measurements with other variables. A description of the data acquisition system is given in Section 5.

UoM has examined the capability of the ADV Vectrino+ system in term of sample rate and sample population on the basics of theory of turbulent flows. The choice of device for turbulence measurements in laboratory open channel flow has been described in detail by Nezu and Nakagawa (1993). Usually the dimensionless wave-number $L_x k_{max}$ should be at 100 in order for the experimentalist to analyze the spectral distribution down to the viscous subrange. The maximum response frequency f_{max} of the turbulence of the open channel flow can be estimated as follows:

$$f_{max} = \frac{k_{max} U}{U} \geq \frac{100U}{2\pi L_x} \approx \left(\frac{50}{\pi}\right)\left(\frac{U}{h}\right)$$

where U is the bulk velocity and h is the depth of the open channel flow. For the proposed measurement at UoM, $U = 0.45$ m/s and $h = 0.45$ m ans so $f_{max} \sim 16$ Hz. The sampling frequency f of data processing should be chosen so as to satisfy the Nyquist criterion $f \geq 2f_{max} = 32$ Hz in order to allow for the elimination of data aliasing. By sampling at 200 Hz, the Nyquist criterion is satisfied in that this will provide accurate digitisation of the measured parameter to 100 Hz, considerably greater than the expected maximum frequency of turbulence.

The sample population for the proposed measurement should contain at least 100 coherent cycles of the turbulence produced by the rotor movement. As the slowest rotational speed of the proposed rotor is $\omega_{min} = 14$ rad/s , the sample population at the sample rate $f = 200$ Hz can be calculated as $N = 2\pi/\omega_{min}(100)f = 9000$ samples. With this sample rate and sample population, the auto- and cross-correlations of the velocity fluctuations i.e. the RMS velocities and Reynolds shear stresses as well as the mean velocity should be correctly measured for all the proposed scenarios. For investigative measurements which do not require Reynolds stress, UoM will allow a relatively small population of 5000 samples to fulfil the requirement of mean velocity measurement.

The ADV Vectrino+ system offers an "initial preparation" scheme in its data acquisition software: Vectrino Plus. (see Vectrino Velocimeter, User Guide) The "initial preparation" scheme allows one to check the performance of the Vectrino+ probe including the Signal-to-Noise-Ratio (SNR) defined as:

$$SNR = 20\log_{10}\left(\frac{Amplitude_{signal}}{Amplitude_{noise}}\right)$$

In a laboratory environment the SNR of Vectrino+ can be improved by the use of seeding particles in filtered clean tap water. Initial measurements using Vectrino+ indicate SNR of 20~25 dB in the open channel flow in the UoM flume. By optimising the use of seeding particles and improving the water quality, the SNR could be increased further but this satisfies the raw data accuracy of 15 dB SNR specified in WG4 WP2 D1.

3.2 Traverse Table

Flow measurements are required at several points upstream, within and downstream of the array. WG4 WP2 D1 states that the measurement positioning system should allow measurements to be conducted within the following range: 0 – 4 m lateral (Y: across the flow) and 0 – 10 m longitudinal (X: streamwise). The detailed tests require measurements of the 3D wake structure thus multiple points must be measured in the lateral-vertical plane (Y-Z). To facilitate accurate positioning of the probes, the Vectrino+ ADV probes will be mounted on a custom-built two-dimensional traverse table manufactured by HR Wallingford (Appendix C), who have a track record in producing high-quality instrumentation for hydraulic experiments. The table is designed to support up to 4 Vectrinos and is designed to give a position accuracy of ±1mm in both vertical (Z) and transverse (Y) directions. The transverse position (Y) is measured relative to a set-point which will be defined either by a contact switch located on a calibrated rail at one side of the flume or by an optical switch aligned with streamwise axis (X) of the flume. The position of the traverse table in the streamwise (X) direction will be adjusted manually and a low powered laser pointer used to measure the X-ordinate to an accuracy of ±1mm.

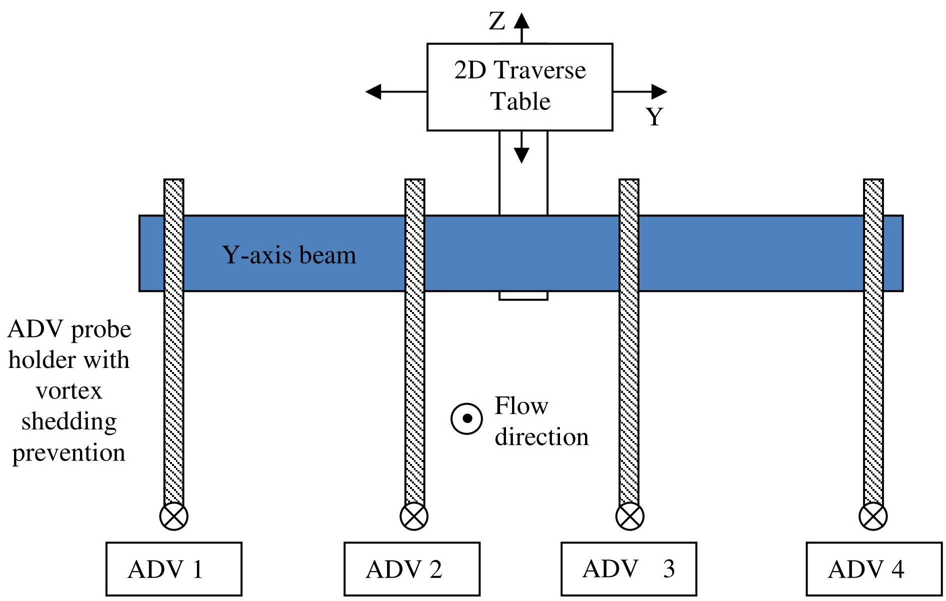


Figure 3.2 ADV support structure (forward facing)

3.3 ADV Support Structure

Each ADV comprises a lightweight 4-pronged measurement probe (main body 2 cm diameter cylinder) connected to the main case (10 cm diameter cylinder). The ADV case is supported on either a fixed gantry or the traverse table (horizontal part) with base 400 mm above water line (at 450 mm depth) so only the probe is supported within the water column. Probe holders extending from the gantry or traverse table to the probe comprise a small diameter rod of 1 m (approx.) length and 10 mm diameter. The immersed part (lower 500 mm) of the support structure is enclosed by a streamlined outer casing formed from folded plastic or aluminium, in order to minimise excess flow disturbance. Alternative passive techniques for experimental scale vortex control are reviewed by Kumar et al (2008), Figure 3.3. All the devices as shown below are rather simple and low cost but a streamlined section seems to offer the simplest solution for both the ADV supports and for the dynamometer support structure (Section 4.2).

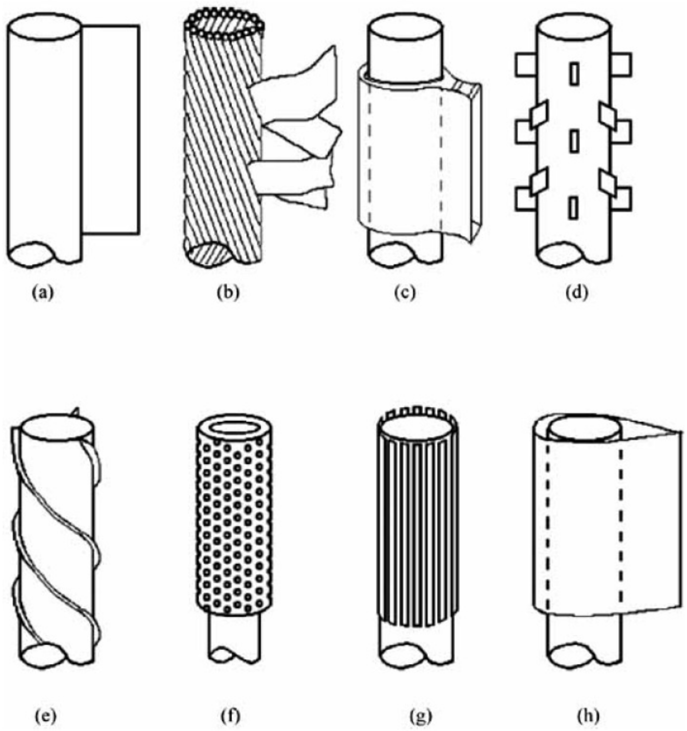


Figure 3.3 Passive control devices for suppressing vortex induced vibrations
(Figure 4 of Kumar et al, 2008)

4 TURBINE & SUPPORT STRUCTURE DESIGN

A design of a suitable experimental model of a tidal stream turbine has been developed by UoM. Manufacture of the design has been discussed with Cussons Technology Ltd who previously supplied UoM with a dynamometer for an experimental study of wind turbines with a similar rotor diameter (300 mm). The proposed design is illustrated in Figure 4.1 and comprises a small diameter motor housed in a cylindrical nacelle which is in turn supported on a vertical shaft (a dimensioned arrangement drawing is given in Appendix D).

Cussons have designed the nacelle to incorporate several seals in order to prevent damage to the motor by water seepage into the nacelle. Clearly the seal around the mechanical drive shaft is important and a motor with small diameter shaft has been selected to minimise the seal area. Rotor diameter is 270 mm and the nacelle diameter 40 mm or less. The support shaft profile will be cylindrical with a streamlined faring below waterline. The cylindrical section is clamped to one of the supporting gantries which span the width of the flume. Design of the rotor is detailed in Chapter 7.

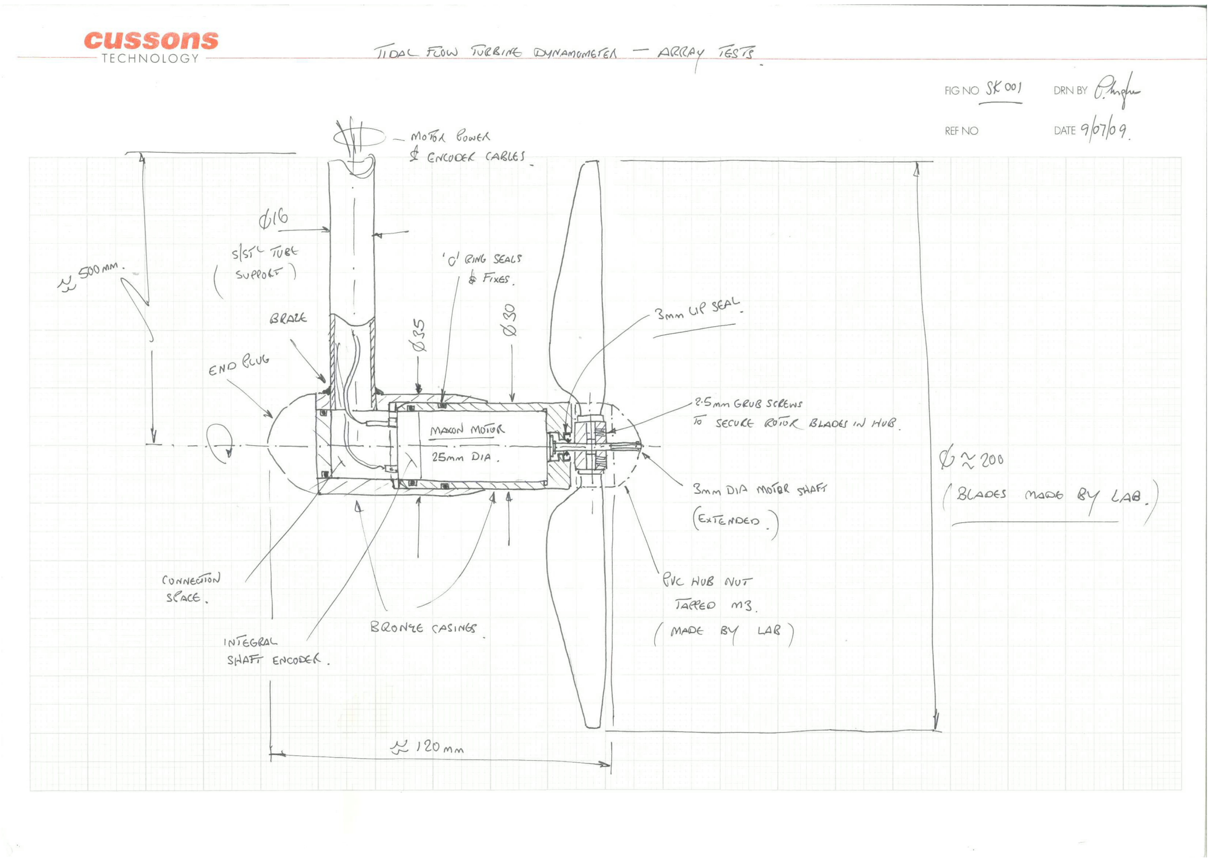


Figure 4.1 General arrangement of tidal stream turbine dynamometer
(Provided by Cussons Technology Ltd. Image is not to scale and dimensions are indicative only. An engineering drawing of this sketch is given in Appendix D which is also provided as a separate A3 pdf file.)

4.1 Speed and Torque

Further to the discussion in WG4WP2D1 on the options for rotor control, it has been decided to adopt a constant torque strategy. Using a constant torque approach means that in unsteady flow the rotor speed will fluctuate, but provided the losses are small, the rotor should maintain an approximately constant TSR. Constant torque will be maintained using a control system developed at UoM for experimental study of a wave energy device in which power take off is via a unidirectional generator driven by a flywheel. The torque control system has been described by Stallard et al. (2008) and Brown (2009).

Torque on the rotor shaft is considered as the sum of the electromagnetic torque (τ_{load}) developed by the motor and any mechanical friction on the shaft (τ_{Fric}). Mechanical friction is quantified by calibration and may be dependent on rotor speed, whereas electromagnetic torque is proportional to the product of the motor torque constant (kT) and the applied current (I_{Load}), $\tau_{load} = I_{Load}kT$. Custom hardware and firmware has been developed by UoM to continuously adjust the applied current to modify the net torque on the rotor shaft. For these tests the UoM control system will be used to maintain constant torque. A schematic of the system is given in Figure 4.2. During each pass of the slow loop, angular speed (ω) is obtained as the difference between successive position measurements. A quadrature encoder reading a 1000 count per revolution optical code-wheel is specified such that position is to an accuracy of π/150 (WG4 WP2 D1 states minimum resolution of π/50) and angular speed is given to an accuracy of 1.5% when sampled at 20 Hz.

For this application, the user will specify a simple torque-speed curve in terms of a minimum speed only such that the starting torque is reduced. Above a minimum speed, constant torque is applied whereas at lower speeds, torque is reduced and reversed to compensate for friction in the system. This reduction of torque at low speed is only used to start the rotation of the turbine, test data will be recorded whilst constant torque is applied. Within the seek-current loop, the measured bridge current (I_{Load}) is adjusted to match the target current (I_{Assist}). A simple comparator algorithm is employed which operates at a rate of 20 kHz and to an accuracy of 1 mA thus satisfying the specification of less than 2 mA (WG4 WP2 D1).

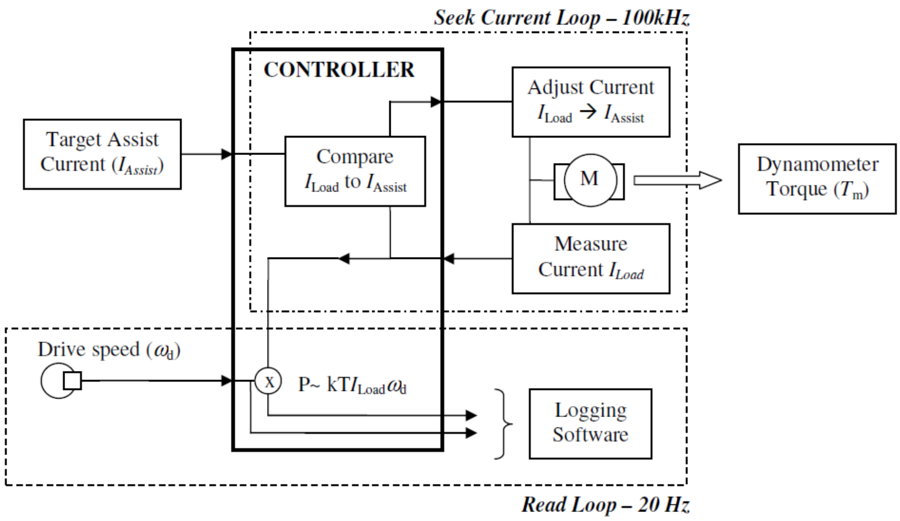


Figure 4.2 Schematic of torque control system.

The motor selection has been made to satisfy two considerations: minimum physical size and provision of suitable level of torque (τ_{Load}). Options include the CROUZET 82-800 Series (42 mm diameter) or the MAXON 118 Series (25 mm diameter). These differ in dimension and the range of operating current and torque. Torque on the rotor shaft is the sum of the electromagnetic torque (τ_{load}) developed by the motor and any mechanical friction on the shaft (τ_{Fric}) so knowledge of friction in the system affects motor specification. Earlier experiments suggest mechanical friction in the range $20 < \tau_{Fric} < 30$ mNm and this has been used to inform motor selection. The mechanical power developed by the rotor is expected to be small; a nominal rotor radius of 0.135 m operating within a uniform flow of 0.4 m/s would develop 1 W only if operating with a power coefficient of 0.55. When operating at a TSR in the range 5 – 7 (see Section 7) rotational speed is 14 – 20 rad/s and so the mechanical torque will be in the range 50 – 80 mNm. Based on this operating range of speed and torque a MAXON 118-743 motor has been specified. The operating range will be confirmed by testing of a single motor prior to installation within a nacelle.

4.2 Dynamometer Support Structure

An arrangement drawing for the nacelle and support structure assembly is given in Appendix D. Horizontal load on the supporting gantry will be due to horizontal thrust on the swept area of the rotor ($F_{Rotor} \sim ½C_T\rho A_D U^2$) and drag on the supporting shaft ($F_{Drag} \sim ½C_D\rho BLU^2$ where shaft width B ~ 1 cm and immersed length L ~ 20 cm). For a flow speed of 0.5 m/s rotor thrust is approximately an order of magnitude larger than the drag on the supporting shaft (F_{Rotor} ~ 3N, F_{Drag} ~ 0.3N). Force measurement in this range is not trivial and the two principal options are: a) measurement of strain at the top and the bottom of supporting shaft such that resolved moments yield total force and b) measurement of horizontal force between support structure and gantry using a load cell. Both options will be investigated for the first unit to determine the most suitable method for the array of 15 devices. In both cases, total horizontal force ($F_{Rotor} + F_{Drag}$) will be measured.

5 DATA LOGGING

The following variables will be recorded directly to file for post-processing:

Four velocity signals (U_x, U_y, U_z, $U_{z'}$) from each of N_{ADV} probes (RS232 or USB)
Angular speed from each of the tidal stream devices (digital counter)
Applied current from each of the tidal stream devices (analogue)

As summarised in Table 5.1, this requires the following inputs:

Analog inputs:	38 (or 62)
Digital counters:	15
Serial ports:	6 (or 0)

It is convenient to use a single software interface to both co-ordinate control of the traverse carriage and synchronise data collection from all ADVs and dynamometers and so the logging interface must allow specification of:

N_{yz} velocity sample co-ordinates (in the *y-z* plane perpendicular to the flow)
Duration of each sample
N_{MEC} devices

The interface requires the following outputs:

Analog outputs:	2

National Instruments hardware has been ordered for this purpose and a Labview software interface is presently in development as detailed in Sections 5.1 and 5.2.

Table 5.1: List of all time-varying signals and I/O type

	Variable	Analog	Counter	Serial
Velocities	U_x	*6*		6
	U_y	*6*		
	U_z	*6*		
	$U_{z'}$	*6*		
Surface elevation	η	6		
Angular Position	ϕ	n/a	15	*15*
Current (Torque)	I	15		
Thrust	F_x	15		
Carriage Position	Y	1		
	Z	1		
Total		38	15	6

Values in *small italics* denote alternative input method and are not included in totals

5.1 Hardware

National Instruments hardware has been ordered to allow simultaneous monitoring of all variables listed in Table 5.1. The system comprises a basic chassis with windows operating system and National Instruments Labview installed and several modules for particular inputs. The main components are listed in Table 5.2 against the corresponding input and output.

Table 5.2 Components of National Instruments data logging system

Chassis & operating system	18-Slot 3U Chassis & AC PSU	NI PXI-1045
	Core 2 Duo 2.53 GHz Vista	NI PXI-8108
	250 GB (or Greater) 2.5 in SATA HDD	
	2 GB DDR2 RAM	
Current input	16 Port RS232 Interface	NI PXI-8430/16
ADV inputs	8 Port RS232 Interface	NI PXI-8430/8
	Cable 68-D to VHDCI Offset 2 m	SHC68-68

Position inputs	PXI Terminal Block for Digital I/O	TB-2715
Position reader	Counter/Timer	NI PXI-6602
Torque, Thrust, Carriage, Surface Elevation	32 Analog Inputs, 48 Digital I/O	NI PXI-6224
	Noise Rejecting Shielded Terminal Block	SCB-68

5.2 Software

A Labview interface used for similar experimental studies is described in Appendix E. This interface will be modified for the variables listed in the previous sections. For post-processing, it is convenient for all data to be sampled at the same rate. For velocity field measurements, the control factor is the ADV sample rate. Nortek Vectrinos+ will be employed which allow sampling at up to 200 Hz (Section 3.1). For tests which do not require velocity measurement, the sample rate can be even faster but to simplify data analysis, all data will be recorded at 200 Hz as specified in WG4 WP2 D1. For quality control, the interface incorporates a graphical display of key variables during data collection (from at least one user-selected dynamometer and one user-selected ADV). In addition, the traverse carriage position (in y-z plane, see Appendix C) is reported.

6 EQUIPMENT CALIBRATION

6.1 NORTEK Vectrino+

Since published studies demonstrate good agreement between ADV and Laser Doppler Anemometer (LDA) measurements in an open channel (Voulgaris & Trowbridge, 1998) it is known that ADVs provide an accurate method of measuring velocities within an open channel flow. All six of the Vectrino+ devices to be used in these tests were delivered in January 2010 and are supplied calibrated so will conform to the manufacturer specification as listed in Section 3.1. Cross comparison of measurement volume (MV) has been conducted by UoM by selecting the MV height for Vectrino+ ADV probe configuration, the minimum height 3 mm to the maximum height 15 mm. No significant difference in the mean velocity was found in the main stream of open channel. Mean velocity measurements will be confirmed by measurement of a known flow and an inter-comparison of the six probes will be conducted by measurement of the same fluid point using pairs of devices.

6.2 Dynamometer

Calibration of the angular position encoder consists of measuring and recording the decoder scalar quantities reported before and after a complete revolution. The motor torque constant is specified by the manufacturer but variation of ±2.5% was observed between Crouzet motors used in an earlier study (Stallard et al., 2008 and Brown, 2009) and so each motor constant will be checked. The motor torque constant stated by the supplier will therefore be compared to the motor torque constant calculated from measurements of the DC voltage induced in the machine whilst driven at a constant, measured speed by a second motor. A non contacting speed sensor will be used. To quantify the mechanical friction retarding rotation of the rotor shaft, deceleration of a known inertia is considered. A flywheel of inertia J is mounted on the shaft and accelerated to greater than the operating speed. Time variation of angular position, $\phi(t)$, is then recorded as the flywheel decelerates due to retarding friction (τ_{Fric}) only and differentiated to obtain the rate of deceleration (a_D). Friction torque is then $\tau_{Fric} = a_D(J + J_{Gen})$ where the motor inertia (J_{Gen}) is estimated from the suppliers' data sheet.

6.3 Thrust

As discussed in Section 4.2, the thrust measurement device used for the turbines in the array tests will be either be a one-dimensional force-cell located between the supporting shaft and gantry or two strain gauge pairs located on the supporting shaft. An inter-comparison of both approaches is planned. In both cases, dry calibration will be conducted in which the rotor shaft is loaded with a series of calibrated masses. This will provide a calibration constant for the load cell (or each strain gauge) defined in terms of mV/N. Using either method, the force measured will be the total of both rotor thrust and support shaft drag. Support shaft drag is expected to be an order of magnitude smaller than rotor thrust but two tests will be conducted to quantify support shaft drag. Firstly, the drag on the bare structure (i.e. without rotor) will be recorded over a small range of flow velocities (e.g. 0.3 to 0.4 m/s). Secondly, force during operation (i.e. with the rotor installed) will be measured after installation of a streamlined cover that is separate to the dynamometer support structure and rigidly connected to the gantry. Drag on the streamlined cover will not be measured but total force will then represent rotor force only.

7 ROTOR DESIGN

A 3-bladed rotor of 0.27 m diameter has been designed using GH Tidal Bladed, a rotor design tool based on a blade element momentum method and described in further detail in Bossanyi (2007). The following sections detail the considerations and procedure adopted in the design of the model scale rotor.

7.1 Design Requirements

As discussed in WG4WP1D1, the purpose of the scale experiments 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. Hence the models should provide power and thrust extraction representative of a full scale tidal turbine design. A “generic tidal turbine” design has been supplied to the PerAWaT project by TGL (Thake, 2010).

The Reynolds number, based on blade chord, at the scale of these experiments is considerably reduced compared with a full-scale turbine (Re = 1e4 – 4e4). The blade lift and drag characteristic is highly dependent on Reynolds number. As a result of the reduced Reynolds number, using a turbine design that has been geometrically scaled from the proposed full scale turbine design will lead to considerably reduced power and thrust. It is unrealistic to expect to be able to match power at the model scale (due to increased drag at low Reynolds number), however the power can be maximised and the thrust characteristic of a full-scale rotor can be better represented by both employing a different blade section, which demonstrates improved performance in the Reynolds number range appropriate to the experiment, and increasing the blade chord lengths to increase the Reynolds number. Further background on the motivation for modifying the geometry can be found in the technical note by Whelan (2010). Note that the Reynolds number of these experiments is less than those of WG4 WP1 (Re ~ 7e4) and so a different rotor designs are required for WG4 WP1 and WG4 WP2.

7.2 Rotor Manufacture

The rotor will be manufactured using a rapid prototyping technique in which the geometry specified by a 3D CAD model is built up from 0.1 mm layers of material. This allows construction of features of 0.1 mm thickness although only features thinner than 0.5 mm may not be fully built-up. Specification of the entire rotor in one complete piece (3 blades and a hub) allows accurate setting of the chord variation and twist distribution. A finishing process is then applied to seal the material and smooth the surfaces. After completion of the rapid prototyping and finishing process the rotor is impregnated with resin as a means of waterproofing. This fills the voids in the material but does not alter the finished geometry and has the positive side-effect of increasing the stiffness of the rotor assembly.

7.3 Blade Section for High Lift in Low Reynolds Number Flow

In order to accurately predict the performance of a proposed blade geometry using a blade element momentum (BEM) code it is necessary to have an accurate source of blade section performance characteristics (lift and drag as a function of angle of attack). An extensive review of the available data for blade section performance at the Reynolds number range of interest has concluded that there is a limited amount of data available and that the reliability of the available data is variable. This is to be expected given both:

- the lack of commercial applications with a requirement for blade section performance at this range (e.g. aircraft and wind turbine generally operate at much higher Reynolds number).
- the proximity to transition between laminar and turbulent flow, which is sensitive to many parameters including surface roughness and ambient turbulence.

The most extensive data set available that is considered to be reliable, over the Reynolds number range of interest, can be found in Miley (1982). This catalogue of data was collated from experiments conducted in a variety of wind tunnel facilities, with differing ambient conditions, such as turbulence intensity. Since lift and drag coefficients are sensitive to the ambient conditions, a minimum uncertainty bound should be taken when using these data for performance prediction. Another source of blade section data that has been considered to be reliable has come from an experimental study on wind turbine wakes, which was performed at the same scale as those planned for WG4WP1 and detailed in Hassan (1993). This study included wind tunnel tests to evaluate the performance of a variety of blade sections over the Reynolds number range of interest. The blade section adopted for the final wind-turbine rotor design was based on the section which demonstrated the highest lift to drag ratio and minimum performance variation over the Reynolds number range of interest. The blade section adopted by Hassan is similar in profile and demonstrated good agreement with the Miley data for a Goettingen 804 section at Re = 2e4.

For the purposes of this study, the geometry of a Goettingen 804 section will be adopted where possible. Due to manufacturing limitations (Section 7.2) it will not be possible to replicate this geometry precisely at the blade trailing edge since very thin features may not be accurately built-up. However, the resolution of the rapid prototyping method is such that it is expected to reasonably replicate the remainder of the profile and the trailing edge will be refined in the finishing process. Given the uncertainty levels in the blade section datasets available and the range of Reynolds numbers that will be achieved during the planned experiments, initial performance predictions have been produced using both the average of the Hassan dataset (Re = 1.5e4 – 4e4) and the Miley dataset (Re = 2e2) to provide an indication of the dependence of the BEM method on the input dataset. These are summarised in Appendix F.

7.4 Final Rotor Geometry

An iterative design procedure has been followed using for the design of the blade profile (twist and chord distribution) in which GH Tidal Bladed has been used to predict the rotor performance. The prediction for the performance characteristic of the final design is shown in Figure 7.1, based on the assumed performance characteristics of a Goettingen 804 section. Due to uncertainties associated with the blade section data it is unlikely that the performance at model scale will exactly match the predictions in Figure 7.1. It should also be noted that these predictions have been made assuming unbounded flow, which will lead to a further discrepancy with the measured data. A correction for blockage could be attempted according to Whelan et al. (2009). In the first instance one rotor will be manufactured and preliminary tests will be performed in the UoM flume. If necessary the results from initial testing will be used to refine the rotor geometry following a similar iterative design procedure.

The rotor will be assembled from 3 identical blades attached to a central cylindrical hub. A nose cone has been added to the front of the hub to minimise adverse drag effects. A model of the rotor blades has been constructed using 3D CAD software (Figure 7.2), this is the format required for manufacture of the rotor using the rapid prototyping technique. The final twist and chord distribution at 10 blade sections along the radial span, and an engineering drawing of the rotor assembly are provided in Appendix F.

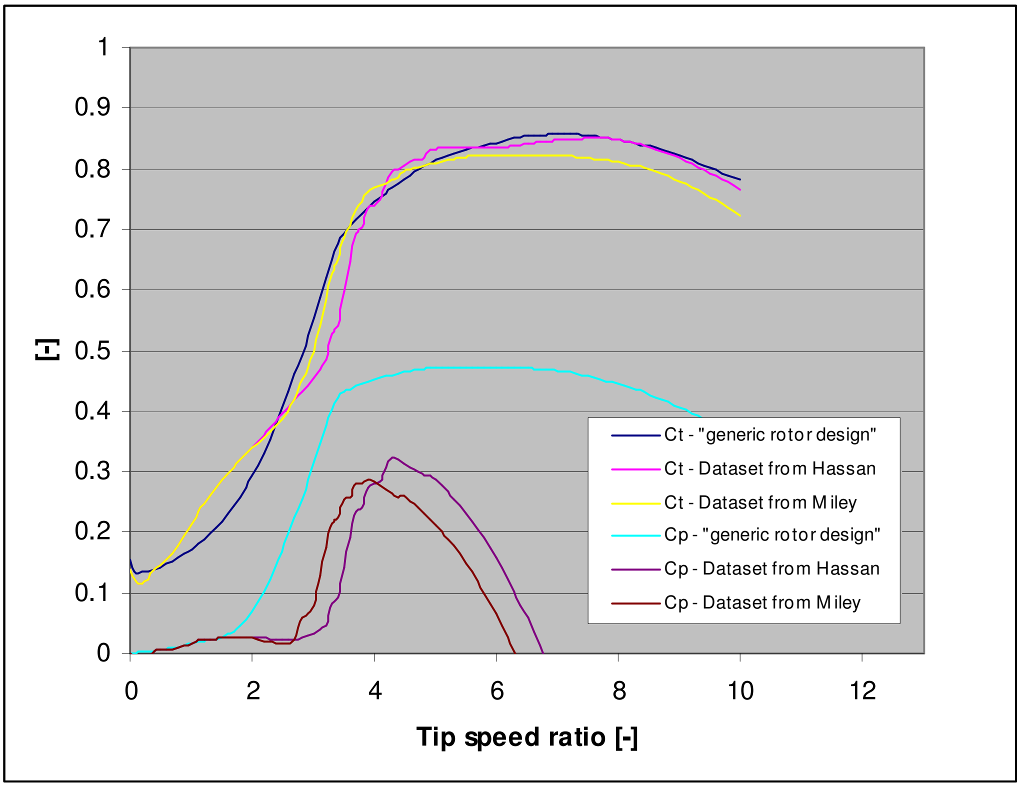


Figure 7.1: Performance prediction for modified geometry.

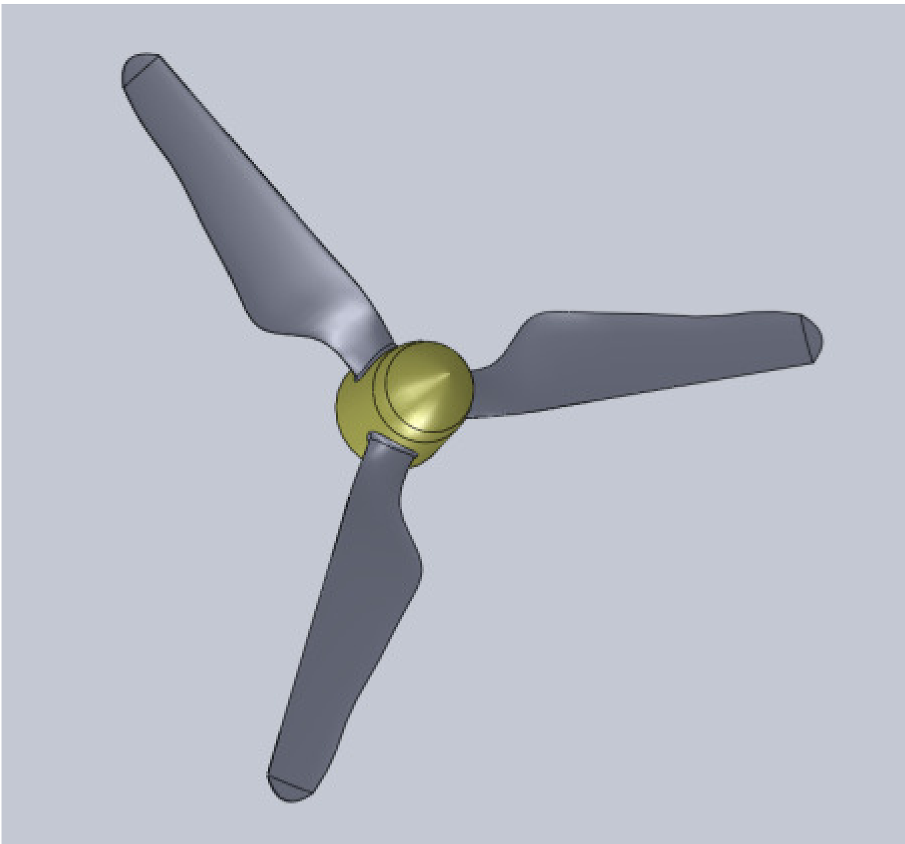


Figure 7.2: 3D CAD model of rotor assembly.

8 SUMMARY

This report explains the design of equipment for conducting small-scale experimental measurements of an array of tidal stream devices to satisfy the experimental specification detailed in WG4 WP2 D1. An explanation is given of how each of the required flow conditions – including steady flow with low turbulence intensity, steady flow with waves and increased levels of turbulence intensity and large scale eddies – will be generated. Selection of velocity measurement instrumentation is shown to satisfy the specified requirements and a traverse table has been designed to facilitate measurement at the required spatial positions. The generator of each turbine will be modelled using a dynamometer that comprises a small diameter electric motor with a bridge-current controller to allow operation with constant torque. The dynamometer is supported on a strain-gauged structure for measurement of horizontal thrust on the rotor. Hardware required for synchronisation of data logging is described and work continues on development of a software interface. The specification report WG4 WP2 D1 highlighted the need to design the rotor to operate at a similar thrust coefficient and tip speed ratio to a full-scale turbine despite the much reduced Reynolds number (order of $3x10^4$ in these experiments versus 10^7 at full-scale). This has been addressed by design of a rotor to achieve operating points similar to those of the generic rotor. Low Reynolds number lift and drag curves have been reviewed and a Goettingen 804 blade has been selected for the basis of design. The radial distribution of chord length and twist angle has been selected through application of GH Tidal Bladed to achieve similar thrust coefficient to the generic rotor. This design may be modified following preliminary manufacture and testing. Note that, although the same blade design process has been employed in WG4 WP1 for experiments at 1:30th scale (as discussed by Whelan, 2009), different rotor designs are used for WG4 WP1 and WG4 WP2 due to the lower Reynolds number of the 1:70th scale experiments.

Following design of the experiments, UoM has commenced procurement of several items including the ADVs, data logging equipment and traverse table. The next stages of work include the following:

- Installation and commissioning of traverse table (Delivery due Apr 2010)
- Inter-comparison of ADV probes (Mar 2010)
- Installation of inflow weir and measurement of baseline flow (Installation due Apr 2010)
- Development of data logging interface to synchronise data collection as detailed in Section 5. (by end Mar 2010)
- Manufacture of rotor design detailed in Section 7 to confirm structural suitability. Revision of design if necessary. (Jun 2010)
- Calibration of motor to confirm torque constant, position reading and constant torque control method (dry-testing prior to installation in nacelle). (Jun/Jul 2010)
- Manufacture of dynamometer and support structure as detailed in Section 4. Inter comparison of horizontal force measurement by strain gauges and force balance (dry-testing). Calibration of mechanical friction on rotor shaft (dry-testing). (Jul/Aug 2010)
- Performance testing of rotor for evaluation of operating points. (Jul-Sep 2010)

The foregoing items of work represent the main stages of work required to satisfy Milestone 3: delivery and installation of the test equipment.

In addition, the feasibility of conducting tests on a single turbine with increased depth ratio will be evaluated. Two options are i) tests using a 0.27 m diameter turbine in a facility with water depth greater than 0.6 m or ii) tests using a diameter of turbine less than 0.27 m in the University of Manchester facility. Both options will be explored during Apr – Sep 2010.

REFERENCES

Bossanyi, E. A. (2009). GH Tidal Bladed - Theory Manual. Technical Report 282/BR/009, Garrad Hassan and Partners Ltd.

Blinco, P.H. and Partheniades, E. (1971). Turbulence characteristics in free surface flows over smooth and rough boundaries. Journal of Hydraulic Research, IAHR, 9:43-69.

Brown R.J. (2009) Design and construction of a dynamometer system for testing an array of wave energy point absorbers. MPhil Thesis, School of Mechanical, Aerospace and Civil Engineering, University of Manchester.

EMEC (2009) Assessment of tidal energy resource. Marine Renewable Energy Guides, The European Marine Energy Centre Ltd.

Hassan, U. (1993) A wind tunnel investigation of the wake structure within small wind turbine farms. Technical Report ETSU WN 5113. Garrad Hassan and Partners Ltd.

Kumar, A. Chan-Hyun Sohn and Bangalore H.L. Gowda (2008) Passive Control of Vortex-Induced Vibrations: An Overview, Recent Patents on Mechanical Engineering 2008, 1, 1-11

Lloyd, P.M and Stansby, P.K. (1997a) Shallow-water flow around model conical islands of small side slope. I: surface piercing, pp.1057-67, Journal of Hydraulic Engineering, December

Lloyd, P.M and Stansby, P.K. (1997b) Shallow-water flow around model conical islands of small side slope. II: submerged, pp.1068-77, Journal of Hydraulic Engineering, December

Miley, S.J (1982). A catalog of low Reynolds number airfoil data for wind turbine applications. DE82-021712. NTIS.

Nezu, I. (1977) Turbulence intensities in open-channel flows, Proc of Japan Soc. Civil Engineers, 261: 67-76 (in Japanese).

Nezu, I and Nakagawa, H. (1993) Turbulence in Open-Channel Flows, IAHR/AIRH, A.A.Balkema/ Rotterdam/ Brookfield

Rogers, D. and Bolton King, G. (1997) Wave generation using Ocean and Wave. Edinburgh Designs Manual version 3.62, March 1997.

Stallard, T.J., Stansby, P.K. and Williamson, A.C. (2008) An experimental study of closely spaced point absorber arrays. Proceedings of 18th International Offshore and Polar Engineering Conference, July 6-11 2008, Vancouver, BC.

Thake, J. (2010) Email to EdF and GH 20th Jan 2010.

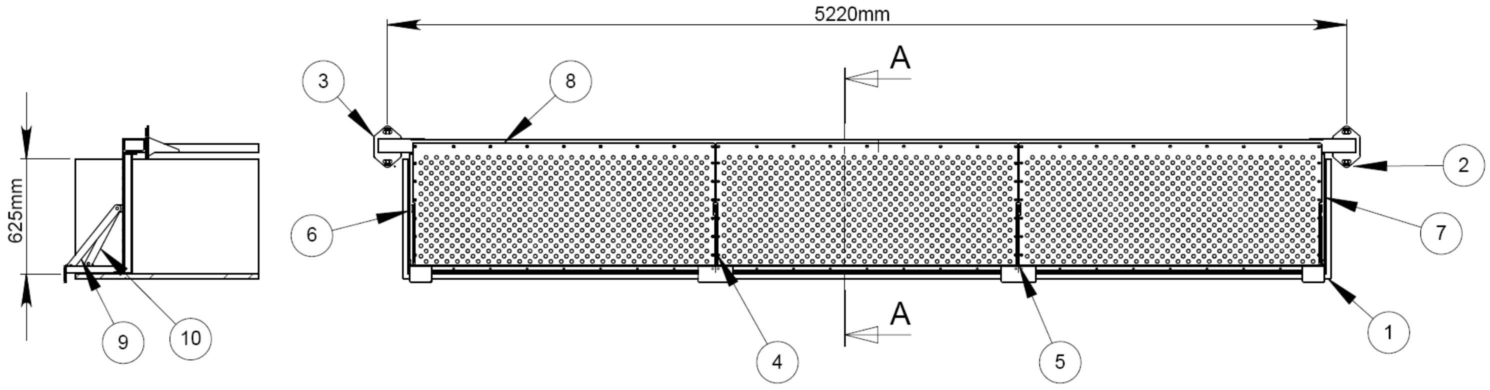
Thomson, M., McCann, G. and Hitchcock, S. (2008) Implications of site-specific conditions on the prediction of loading and power performance of a tidal stream device. Proceedings of 2nd International Conference on Ocean Energy, 15th – 17th October 2008, Breast, France.

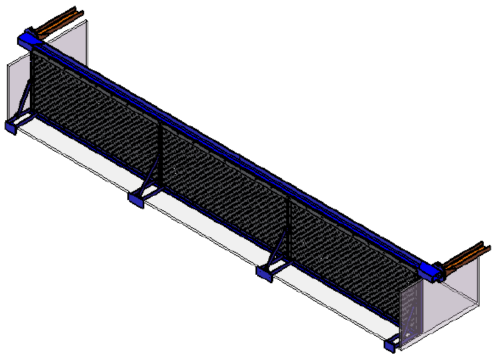
Voulgaris, G. and Trowbridge, J.H. (1998) Evaluation of the Acoustic Doppler Velocimeter (ADV) for Turbulence Measurements. Journal of Atmospheric and Oceanic Technology 15. pp272 – 289.

Whelan, J. I., Graham, J. M. R., & Peiró, J. (2009). A free-surface and blockage correction for tidal turbines. Journal of Fluid Mechanics 624, 281-291.

Whelan, J. I. (2010) Arguments for modifying model scale rotor geometry. Garrad Hassan Technical note No. 104330/BT/01.

APPENDIX A: INFLOW WEIR DRAWING





ITEM NO.	PART	DESCRIPTION	QTY.
1	Perspex bed	Existing	1
2	Side rail	Existing with added lasercut flange & gusset	2
3	Cross beam	65x125 channel with lasercut flanges and cleats	1
4	Vert brace	50x50x6 tee with lasercut flange & lug	2
5	Bottom brace	Fabrication. 40x40x5 angle, lasercut profiles	1
6	LH side brace	50x50x6 angle with lasercut flange & lug	1
7	RH Side brace	50x50x6 angle with lasercut flange & lug	1
8	Diffuser	St Steel lasercut profile	3
9	Centre spar	10x40 flat	2
10	End spar	10x40 flat	2

	NAME	SIGNATURE	DATE	MATERIAL:	TITLE: Weir	A4
DRAWN	R Wroe		Feb 2010			
CHK'D				WEIGHT:	SCALE:1:50	SHEET 1 OF 1

See **“WG4WP2D2_AppendixA - Weir Arrangement Drawing.pdf”** for A4 version of this drawing.

APPENDIX B: LARGE EDDIES

A structure is required to generate large-scale turbulence. The requirements are: an oscillatory wake with swiping [shedding] frequency, f = 0.125 ~ 0.15 Hz (i.e. the wake completes a full oscillation cycle in 8 seconds approx.), and the large scale turbulence should cover the water turbine diameter in the near wake area. The oscillatory wake generated by conical island models has been investigated experimentally and computationally by previous researchers including Jirka and Chen (1997), Lloyd and Stansby (1997a), Lloyd and Stansby (1997b). Following the studies by Lloyd and Stansby, UoM has chosen a submerged conical island model for the required large-scale turbulence tests.

For a water depth h = 0.45 m and in-flow speed U = 0.4 m/s, the calculation of the conical island dimension is as follows:

The design Strouhal number is assigned as S = 0.3 for which vigorous vortex shedding are found in the near wake of the submerged conical island models (Lloyd and Stansby, 1997b), $S = fD_a/U$, where f = measured vortex shedding frequency and D_a = island diameter at its midheight. For the vortex shedding frequency at f = 0.125 Hz, D_a = 0.3(0.4) / 0.125 = 0.96 m. Following Lloyd and Stansby (1997b), using the side slope angle $\theta = 33.1^o$ and the depth/height ratio h/h_i=1.10, the island height h_i = 0.41m and the island diameter at its base D = 1.59 m, the diameter of the island at its flat top d = 0.34m. Since the width of the existing flume is 5.0 m, the flume side walls should not affect the development of the wake especially in the near island region.

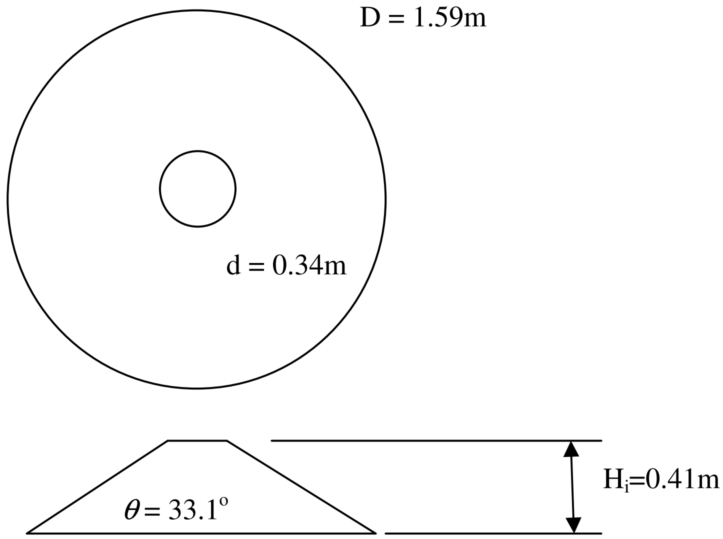
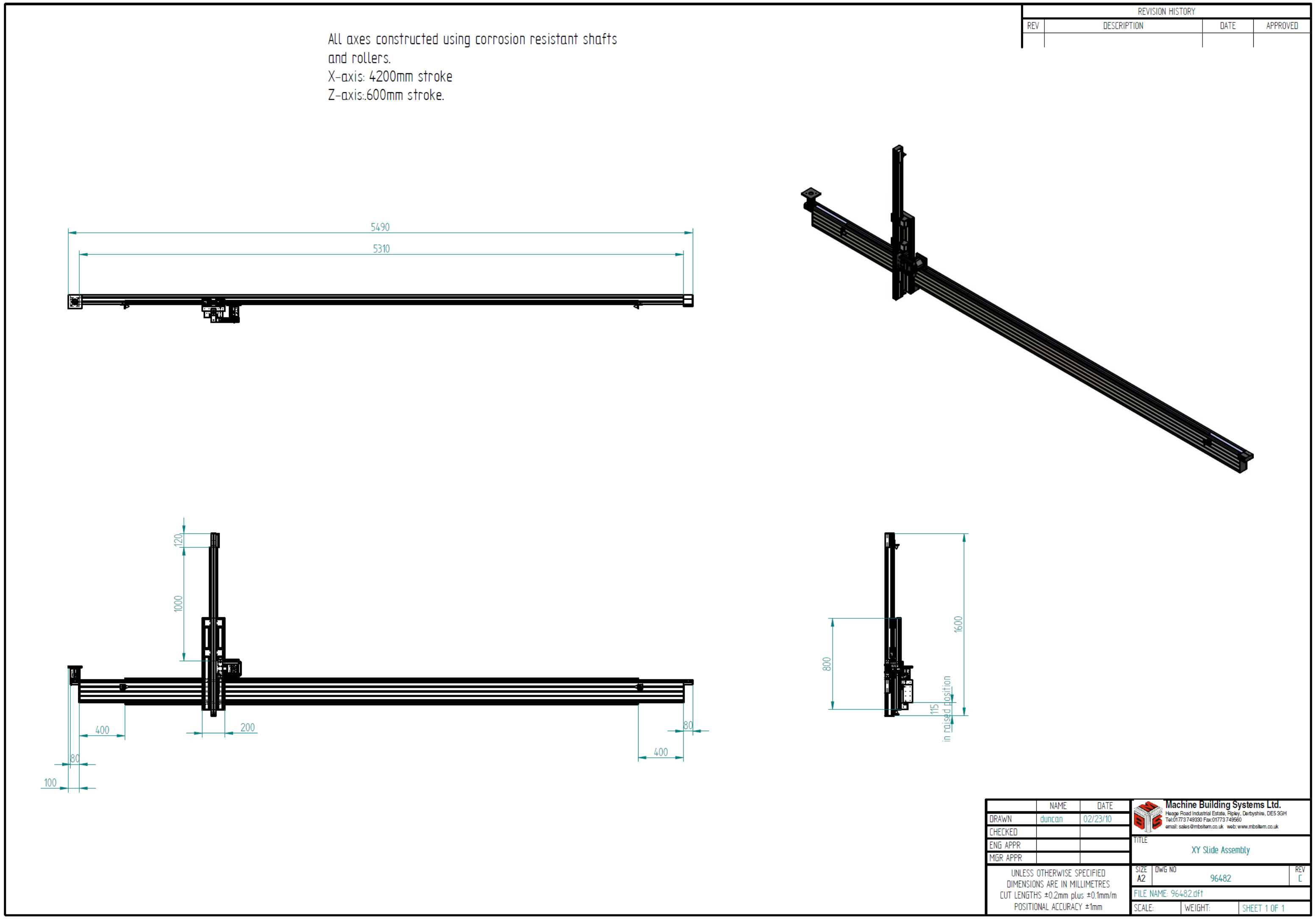


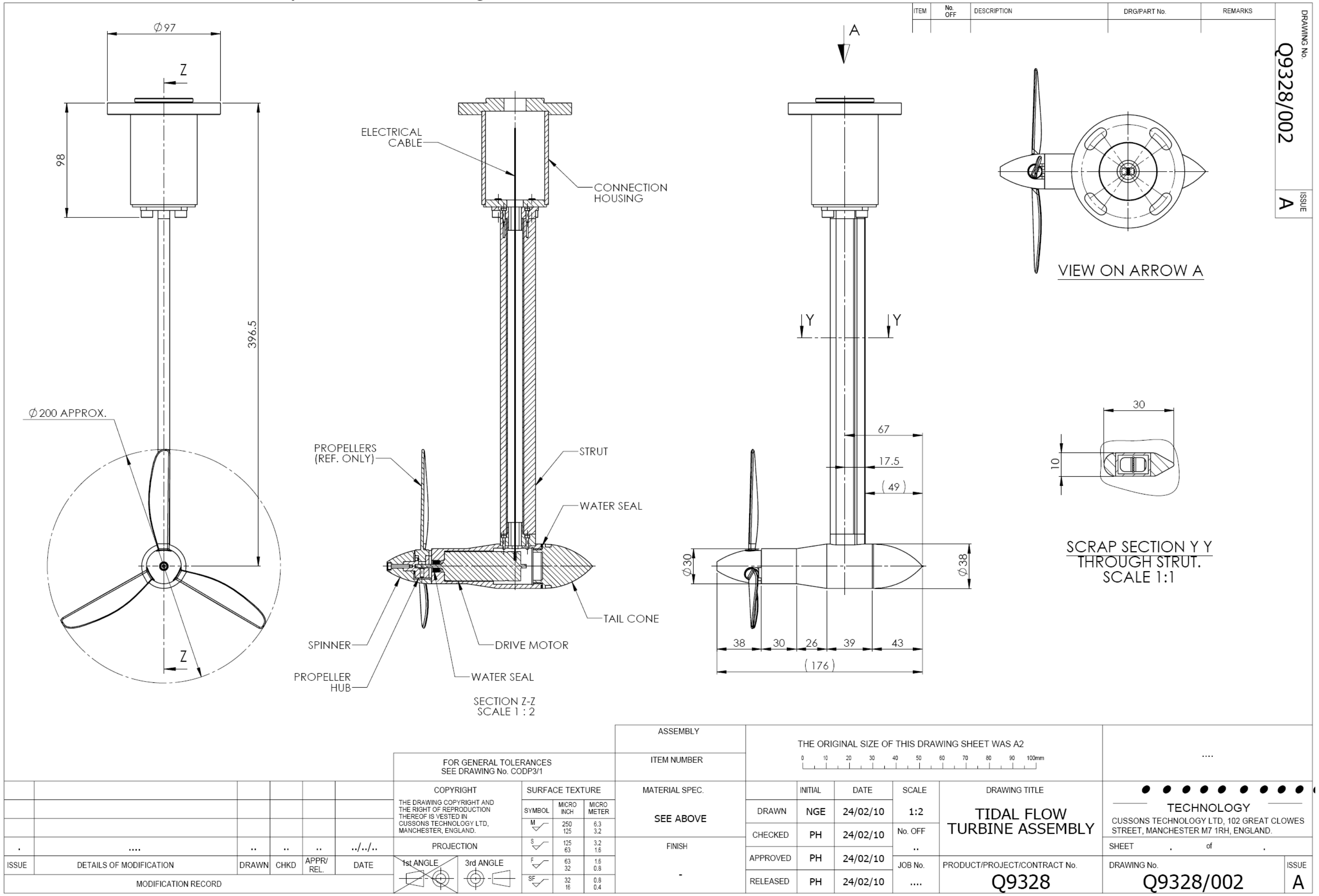
Figure B.1 Sketch indicating dimensions of submerged conical island model for development of large eddies

APPENDIX C: TRAVERSE TABLE DRAWING



See "WG4WP2D2_AppendixC - Traverse Table - HRWallingford Drawing 96482c.pdf" for A2 version of this drawing..

APPENDIX D: Tidal Flow Dynamometer Arrangement



See **"WG4WP2D2_AppendixD - Tidal Flow Dynamometer (Cussons Technology Ltd Drawing Q9328-002).pdf"** for A3 version of this drawing.

APPENDIX E: SOFTWARE INTERFACE

A block diagram of the basic components of the Labview logging system is given in Figure E1. This system is designed for synchronised logging of a number of digital counters (N_{CTR}) and analog inputs (N_A). Samples are synchronised via an external clock which is referenced by block A (Figure E1(a)) and recorded in Block D (Figure E1 (d)). All analog channels (up to 64) are recorded via a single command within Block D. However, Labview requires that digital counters are recorded independently and so the counters defined in Block B (Figure E1(b)) are recorded via a subloop in Block D. Modifications are required for the present application to allow recording of R232 serial inputs which will be implemented in a similar manner to the digital counters. A separate block will be developed for control of the traverse gantry and position co-ordinates saved to output file.

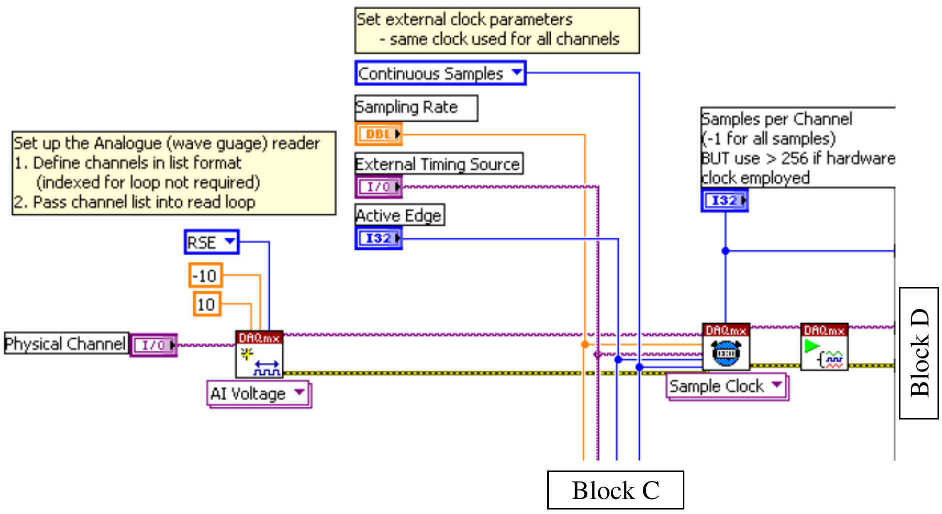


Figure E1(a): Block A – defines analog (voltage) inputs as used for wave gauges, ADVs and dynamometer torque. Characteristics of external sample clock also defined.

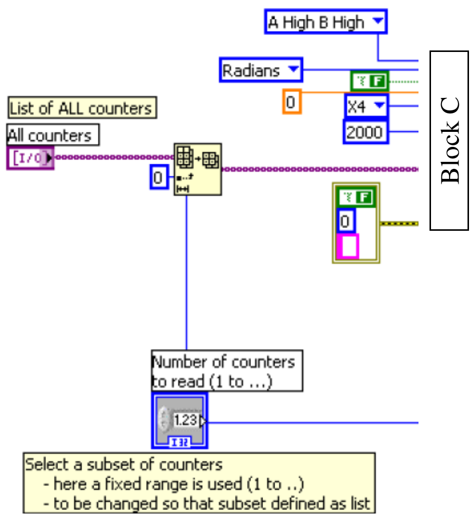


Figure E1(b): Block B – defines number and type of counter inputs used to read from angular position encoders.

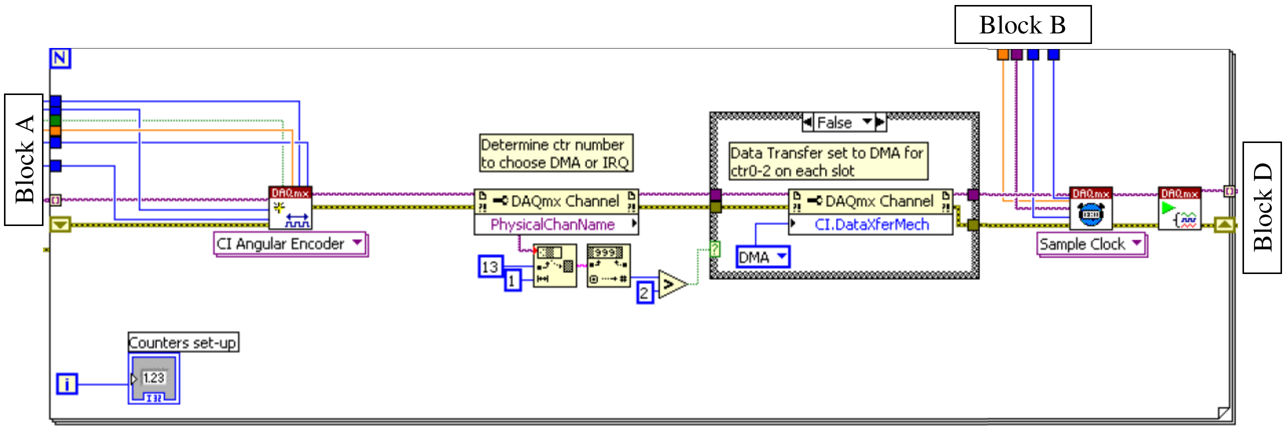


Figure E1(b): Block B – defines characteristics of counter inputs (CI Angular Encoder) including the physical location of each channel (DMA or IRQ) and specifies use of an external clock.

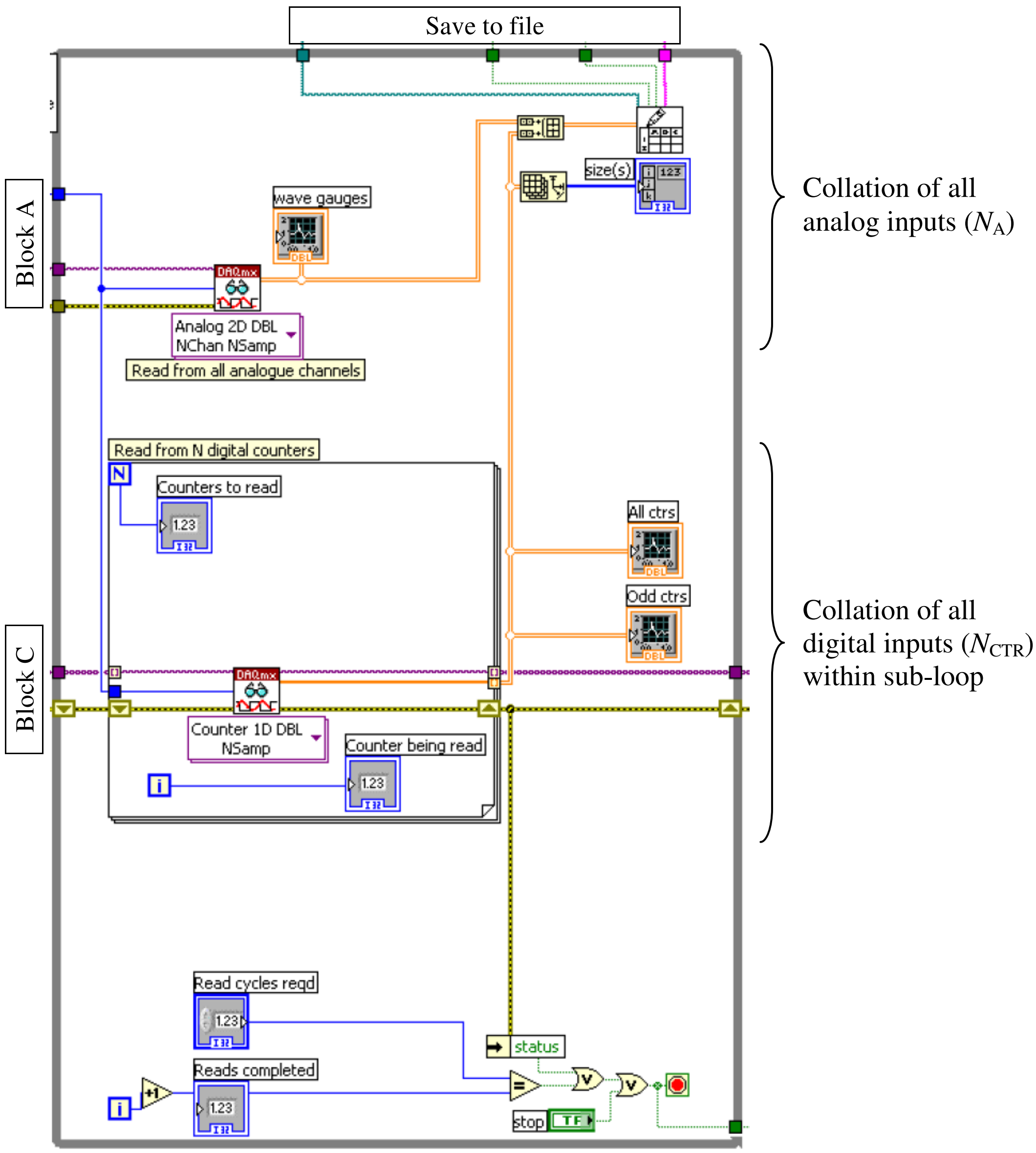


Figure E1(d): Block D - loop structure to conduct simultaneous read of all analog channels defined in Block A and all digital counters defined in Block C. Data is displayed graphically and saved to file.

APPENDIX F: ROTOR DESIGN USING BLADED V3.82

Project Name	UoM
Date	23.02.2010
Engineer	JIW
Notes	Final design for UoM
Version	3.82
Project file	u:\marine\perawat\104331_wg4wp2\generic rotor design\bladed model\uom\final geometry\uom.prj

GENERAL CHARACTERISTICS OF ROTOR AND TURBINE

Rotor diameter	0.27	m
Number of blades	3	
Teeter hinge	No	
Cone angle of rotor	0	deg
Blade set angle	0	deg
Rotational sense of rotor, viewed from upstream	Clockwise	
Position of rotor relative to tower	Upstream	
Hydrodynamic control surfaces	None	
Fixed / Variable speed	Fixed	
Diameter of spinner	0.02	m
Radial position of root station	0.015	m

BLADE GEOMETRY

Blade length	0.12	m
Pre-bend at tip	0	m
Pitch control	None	

Distance from root (m)	Chord (m)	Twist (deg)	
0	0.015	38.3667	The following parameters are constant with radius:
0.0175	0.02	22.8758	
0.03	0.03	16	Twist axis = 0% of chord
0.044	0.0275	11.3441	Thickness = 8% of chord
0.0575	0.025	8.96169	Pitch axis = 0% of chord
0.07	0.022326	7.4854	Pre-bend = 0 m
0.084	0.019486	5.77244	Hydro-dynamic control = Fixed
0.0975	0.0175	4.12977	Hydrofoil Section Reference = 1
0.11	0.015454	3.08001	Cross sectional area = 0 m^2
0.12	0.013	2.57973	

AEROFOIL DATA

Aerofoil dataset: Hassan (1993)

Percentage thickness	8	%
Reynolds number	30000	
Chordwise origin for pitch moments	0	%
Aileron deployment angle	0	deg

Angle of Attack (deg)	Lift coefficient	Drag coefficient	Pitch moment coefficient
-180	0.01	0.05	0
-179.5	0.01	0.05	0
-80	0.7	0.8	0
-30	-0.7	0.48	0
-20	-0.5	0.25	0
-10	-0.3	0.13	0
-7	-0.4	0.12	0
-6	-0.45	0.11	0
-5	-0.4	0.1	0
-4	-0.35	0.09	0
-3	-0.15	0.08	0
-2	0	0.07	0
-1	0.15	0.06	0
0	0.3	0.058	0
1	0.4	0.055	0
2	0.5	0.052	0
3	0.65	0.05	0
4	0.8	0.05	0
5	0.9	0.05	0
6	1	0.06	0
7	1.15	0.08	0
7.5	1.2	0.09	0
8	1.2	0.11	0
9	1.15	0.14	0
10	0.9	0.17	0
10.5	0.82	0.18	0
11	0.82	0.2	0
12	0.82	0.23	0
13	0.84	0.26	0
14	0.86	0.29	0
15	0.88	0.32	0
16	0.9	0.35	0
17	0.92	0.38	0
18	0.94	0.41	0
19	0.96	0.44	0
21	0.98	0.47	0
22	1	0.5	0
23	1.02	0.53	0
24	1.04	0.56	0
25	1.06	0.59	0

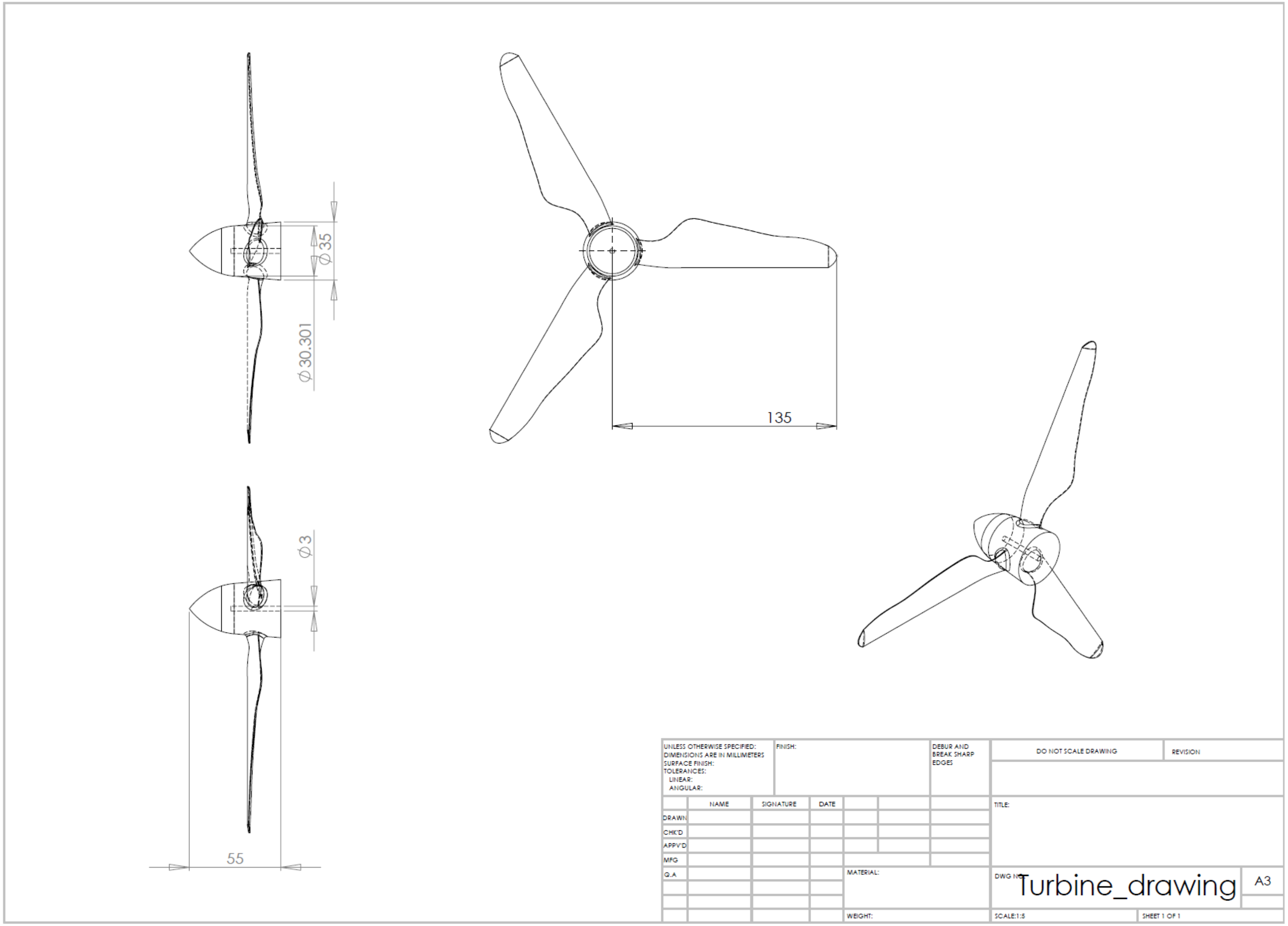
26	1.08	0.62	0
27	1.1	0.65	0
28	1.12	0.68	0
29	1.14	0.71	0
30	1.16	0.74	0
31	1.17	0.77	0
32	1.18	0.8	0
33	1.19	0.83	0
34	1.2	0.86	0
35	1.2	0.89	0
36	1.19	0.92	0
37	1.18	0.95	0
38	1.17	0.98	0
40	1.16	1.01	0
41	1.15	1.04	0
42	1.14	1.07	0
43	1.13	1.07	0
45	1.12	1.07	0
46	1.11	1.07	0
48	1.1	1.07	0
49	1.09	1.07	0
51	0.747	1.07	0
52	0.733	1.07	0
53	0.719	1.07	0
55	0.687	1.07	0
56	0.671	1.07	0
57	0.654	1.07	0
59	0.618	1.07	0
60	0.6	1.07	0
61	0.581	1.07	0
63	0.543	1.07	0
64	0.523	1.07	0
65	0.503	1.07	0
66	0.483	1.07	0
68	0.442	1.07	0
69	0.422	1.07	0
70	-0.8	1.07	0
80	-0.8	1.07	0
180	0.01	0.05	0

Aerofoil dataset: Goe804

Percentage thickness	8	%
Reynolds number	20000	
Chordwise origin for pitch moments	0	%
Aileron deployment angle	0	deg

Angle of Attack (deg)	Lift coefficient	Drag coefficient	Pitch moment coefficient
-180	0.01	0.05	0
-179.5	0.01	0.05	0
-80	0.7	0.8	0
-30	-0.7	0.48	0
-20	-0.5	0.25	0
-10	-0.3	0.13	0
-7	-0.4	0.12	0
-6	-0.45	0.11	0
-5	-0.4	0.1	0
-4	-0.25	0.0745	0
-3	-0.18	0.0648	0
-2	-0.06	0.0624	0
-1	0.11	0.0628	0
0	0.25	0.0638	0
1	0.36	0.0648	0
2	0.47	0.066	0
3	0.6	0.068	0
4	0.72	0.0714	0
5	0.85	0.0754	0
6	0.98	0.0793	0
7	1.11	0.0846	0
8	1.21	0.0923	0
9	1.25	0.0994	0
10	1.27	0.1	0
11	1.27	0.1124	0
12	1.1	0.23	0
13	1.03	0.26	0
14	0.97	0.29	0
15	0.93	0.32	0
16	0.89	0.35	0
17	0.87	0.38	0
18	0.85	0.41	0
19	0.84	0.44	0
21	0.98	0.47	0
22	1	0.5	0
23	1.02	0.53	0
24	1.04	0.56	0
25	1.06	0.59	0

26	1.08	0.62	0
27	1.1	0.65	0
28	1.12	0.68	0
29	1.14	0.71	0
30	1.16	0.74	0
31	1.17	0.77	0
32	1.18	0.8	0
33	1.19	0.83	0
34	1.2	0.86	0
35	1.2	0.89	0
36	1.19	0.92	0
37	1.18	0.95	0
38	1.17	0.98	0
40	1.16	1.01	0
41	1.15	1.04	0
42	1.14	1.07	0
43	1.13	1.07	0
45	1.12	1.07	0
46	1.11	1.07	0
48	1.1	1.07	0
49	1.09	1.07	0
51	0.747	1.07	0
52	0.733	1.07	0
53	0.719	1.07	0
55	0.687	1.07	0
56	0.671	1.07	0
57	0.654	1.07	0
59	0.618	1.07	0
60	0.6	1.07	0
61	0.581	1.07	0
63	0.543	1.07	0
64	0.523	1.07	0
65	0.503	1.07	0
66	0.483	1.07	0
68	0.442	1.07	0
69	0.422	1.07	0
70	-0.8	1.07	0
80	-0.8	1.07	0
180	0.01	0.05	0



∅35
∅30.301
135
∅3
55
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:
FINISH:
DEBUR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
REVISION
NAME
SIGNATURE
DATE
DRAWN
CHK'D
APPV'D
MFG
Q.A
TITLE:
MATERIAL:
DWG NO.
Turbine_drawing
A3
WEIGHT:
SCALE:1:5
SHEET 1 OF 1