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Programme Area: Marine

Project: PerAWAT

Title: Identification of Test Requirements and Physical Model Design

Abstract:

This document describes the scale model experiments required to investigate the performance and the wake of a scale model rotor in order to inform the development and validate numerical models used to predict the performance of a tidal turbine. Section 2 presents the requirements of this work package. The following sections include details of the scaling rationale, the experimental equipment and facilities, and the proposed testing programme. Information regarding the sub-contract to be in place to construct models is also provided.

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.

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PerAWAT WG4 WP1 D1

Identification of test requirements and physical model design

Project	PerAWAT
Work package	WG4
Deliverable	WG4 WP1 D1 Identification of test requirements and physical model design
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V2.0	07/05/2010	Modifications following ETI feedback.
V3.0	14/06/2010	Modifications following ETI feedback.

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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	Blades rotation speed
P	Extracted power
T_d	Drag force
C	Torque

Flow Field

U / 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 height
L	Flume width
PIV	Particle Image Velocimetry
H	Water height

Non-dimensional numbers

Fr	Froude number
Re	Reynolds number
Rec	Reynolds /blade chord
Str	Strouhal
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 Scope of this document

This document describes the scale model experiments required to investigate the performance and the wake of a scale model rotor in order to inform the development and validate numerical models used to predict the performance of a tidal turbine.

Section 2 presents the requirements of this work package. The following sections include details of the scaling rationale, the experimental equipment and facilities, and the proposed testing programme. Information regarding the sub-contract to be in place to construct models is also provided.

1.2 Precautions

Parameters and quantities which are proposed in this document are those deemed to be the most appropriate at this stage. However, the scale model study will take place after the base flow tests (WG4 WP1 D3). Following these first tests the proposed parameter ranges may need to be reconsidered. Given the fact that numerical simulations will not start before the experimental tests are performed, there are no risks associated with these first approximations.

For example the wave height values may need to be modified because of the impact of the current (interaction between waves/current) or because of the presence of devices such as grids (which may increase/decrease the turbulence intensity). For the same reasons, the turbulence intensity range is not defined in this document and will be specified later.

Any changes to the parameters will be submitted to the participants of the work package and to the ETI for approval.

1.3 Purpose of the scaled model testing

The purpose of the scale model experiments described here is to investigate, through physical testing of a single device :

1. the detailed hydrodynamic performance of rotors in turbulent flows,
2. the effect of bounding surfaces on the device performance, and
3. the wake form and structures downstream of a tidal device, as a function of flow profile, depth and ambient turbulence.

As described in the overview table (§ 2) of the PerAWAT WG0 D2 report, the experimental data will contribute to the development of numerical models within the project. They will help calibrate and validate WG3 WP1 (CFD numerical model Ansys Fluent). They will also provide information to WG3 WP4 (GH engineering tool) and WG3 WP5 (CFD numerical model Code_Saturne) and will increase the level of confidence of the models developed in these work packages.

1.4 Specific tasks associated with WG4 WP1

- D1 - Identification of test requirements and physical model design.
- D2 - Construction of a scaled horizontal axis turbine device model and installation of the experimental test platform.
- D3 - Calibration tests without turbine (base flow).
- D4 - Perform tank tests with physical scale model of horizontal axis turbine device installed. Analyse results.

1.5 WG4 WP1 D1 Acceptance criteria

a) Report includes a description of: Test specification requirements, building on from those defined in WG0 D2. This specification will as a minimum include details of the operating points, instrument type, sample frequencies, acceptable error and a proposed experimental programme will be defined in detail.

b) Physical model design specifications include definition of final scale, rotor, instrumentation and support structure and is sufficient to meet the stated test purposes in (a) above. (i.e. range of lateral and longitudinal spacing, flow speed measurement, PIV procedure).

c) Specification, Design drawings and bill of materials sufficient to immediately proceed with procurement of construction subcontractor.

2 Requirements

2.1 Investigation

The purpose of the PerAWAT tidal subproject is to assess the performance of tidal array systems. Therefore, when looking at the device scale, the first parameter of interest is the device performance.

The array system performance will be significantly affected by the fact that devices in a tidal farm will be relatively close to each other. Any device in an array will be responsible for a wake downstream (velocity deficit and turbulence), which may impact on the performance of any downstream devices. Therefore, the second parameter of interest in this study is the device wake.

2.2 Facility

The purpose of this work package is to investigate the physics of the flow around a horizontal axis tidal turbine via physical testing of a single device at 1/30th scale. Such a scale is a compromise between full scale which would be fully representative but with strong constraints on the experimental programme, and laboratory scale which allows tests to be performed in a monitored environment.

1/30th scale allows detailed, controlled, performance and wake measurements in a laboratory, and as written above, these are fundamental parameters when looking at array effects.

Reynolds numbers based on blade chord at such a scale are lower (around 4.10^4) than at full scale. However, modifying the blade geometry, as discussed in Appendix 2, will substantially increase the Reynolds number (around 8.10^4) and will make the performance of the rotor more representative of a full scale tidal turbine. Indeed, the Reynolds numbers will reach the stabilisation area above the transition area (around 7.10^4) in which the rotor behaves differently.

It is also of importance for the flume to be long enough for the flow profile to stabilize before reaching the turbine, for the waves to form, and for the turbulence characteristics to be controlled, e.g. by roughening the flume bottom. The first tests without turbine will provide information regarding the location of the rotor in order for the flow to be stabilised when it meets the rotor.

2.3 Turbine equipment and instrumentation

In order to investigate the performance and the wake on a turbine, a small scale turbine is to be installed in a turbulent flow, and the flow downstream (wake), the thrust on the device, and the device performance measured.

The turbine equipment and the instrumentation must fulfil these requirements.

2.4 Experimental programme

As this work package is going to inform numerical work packages, the following tests should be performed in several environments (different flow speeds, turbulence intensities, water heights, and waves):

- Performance (Ct and Cp curves) information
- Wake (velocity deficit and turbulence intensity) information at interesting operating points defined by the performance measurements.

An important consideration for the wake study is the requirement for tests which are going to help validate the CFD models. The numerical modellers have requested that six wake studies are performed for the CFD calibration, and four wake studies are performed for the CFD validation in order to provide calibration points (3 TSRs - high, low and approximately optimum thrust loading) and validation points (2 TSRs - at intermediary thrust loadings) at each of two flow conditions. Two flow conditions, one with low and the other with high turbulence intensity (and associated different flow profiles), are to be used to provide calibration and validation data at either end of the expected turbulence intensity range such that the calibrated CFD models can be used with confidence across the range of expected flow conditions, i.e. at intermediary turbulence intensities.

In order to yield information about the physics of the flow around a turbine, the physical process should be as representative of full scale process as possible.

3 Investigation

This section provides some insight on the two key subject areas of investigation: performance and wakes, with different current velocity and turbulence conditions.

3.1 Performance

The performance (both the extracted power and the thrust) of the turbine will depend on the flow conditions. The influence of current velocity, height of water, turbulence intensity as well as wave conditions will be studied.

The following flow conditions will need to be measured in front of the device (about 5 times the diameter away from the turbine, as this is far enough from the pump location for the flow to stabilise as well as far enough from the turbine to obtain a non-disturbed inflow profile – please refer to § 4.2 for the channel characteristics):

- the current velocity: profiles measured by ADV sensors,
- turbulence intensity: extracted from the velocity time response,
- the height of water: resistance gauges usually used for the measurement of wave height,
- wave height: resistance gauges.

The range of variations and the frequency of acquisition for these parameters are described in § 4.5.1.

Both the extracted power and the thrust will need to be measured by sensors :

- Rotor power will be measured by the combination of the rotational speed, the power curve of the motor and measurement of the electrical power.
- The thrust will be measured with a force sensor placed between the support structure and the flume structure.

All measurement equipment is detailed in Section 4.5.

3.2 Wakes

Any device that extracts energy from a flow causes a reduction in the axial momentum of the downstream flow. The region of reduced flow velocity and static pressure downstream of the turbine plane (that has passed through the turbine plane) is defined as the wake. The specific form of a wake is likely to be complicated and device specific. As defined in WG4 WP2 D1 (GH document reference 104331/BR/01), the fundamental physics governing the wake structure and its dissipation can be simplified by considering the wake as two distinct regions:

Near wake

Extracting momentum from the flow, whilst conserving mass, drives a wake expansion. This usually occurs within 0 – 1D downstream. The turbines convert the extracted energy into some form of mechanical motion. This may lead to the formation of trailing vortices shed from the blade tips and from the device support structure that will bound the slower moving flow from the free-stream flow. These vortices create a discontinuity in the stream velocity profile. Typically the near wake exists from 0 – 3/4D and, beyond this distance, the ambient turbulence of the free-stream flow breaks down the bounding vortices.

Far wake

Once the initial conditions for the far wake are established by the near wake region there are two main mechanisms that drive the wake structure. These are convection and turbulent mixing. If the fluid were completely inviscid then a volume of slower moving flow would just convect downstream at a slower rate than the free-stream flow. However, turbulent mixing is present and acts to re-energise the wake, breaking it up and increasing the velocity until, at a point far downstream, the mean velocity profile across the wake is similar to the free stream.

The issue of wake interaction within tidal turbine arrays is of key importance due to the relatively small lateral spacing between turbines. This will be investigated in the array tests to be performed under WG4 WP2.

Different ambient flow conditions have varied effects on wake recovery, e.g.

- Higher values of ambient turbulence intensity in a flow can significantly enhance the mixing process and hence speed up the decay of a wake. Ambient turbulence intensity is prominently governed by the seabed roughness.
- Free-surface waves are another source of flow turbulence. Certain wave states and operating depths may significantly impact on the wake recovery process.
- Large scale eddies are another source of turbulence which have the potential to introduce additional flow energy into the wake, aiding recovery.

The following flow conditions will be measured to characterize the upstream flow in front of the device :

- the current velocity: profiles measured by ADV sensors (5 diameters upstream of the turbine),
- turbulence intensity: extracted from the velocity time response,
- the height of water: measured by resistance gauges usually used for wave height measurements.

The influence of waves on the scale model wake will be investigated. However, interactions between current and waves are extremely complex, and distinguishing the effects of these interactions from the turbine wake may prove impossible. Iterations with the University of Oxford (who will model the experiment, with and without waves) will provide information as to whether it is possible to distinguish these effects. The range of variation and the sampling frequency of these parameters are described in paragraph 4.5.

Regarding the wake, the following flow conditions will be measured to characterize the downstream flow behind the device:

- the current velocity: profiles measured by ADV sensors ,
- turbulence intensity: extracted from the velocity time response,
- the height of water: measured by resistance gauges usually used for wave height measurements.

4 Experimental equipment and facility

4.1 Similarity requirements and justification

Two dimensionless scaling parameters should be considered when designing the model rotor tests and choosing appropriate facilities.

- The Froude number represents the ratio between inertial and gravitational forces
- The Reynolds number represents the ratio between inertial and viscous effects.

Even if the Froude scaling is used as the principal scaling criterion, viscous forces cannot be ignored and Reynolds number must also be considered particularly at the rotor blade scale so as to (where possible) avoid ranges where transition may occur.

The EDF facility channel 5 is of sufficient length to allow the flow profile to stabilise before reaching the turbine. It also has the clear advantage of being easily accessible (flume belonging to EDF R&D and staff availability) and hence has been selected as the facility for use in this work package. Table 1 gives the relevant quantities and parameters for different scale rotors operating in EDF channel 5 based on the Froude similarity.

The choice of rotor scale in a controlled facility presents a conflict between Reynolds number and blockage effects i.e. too small a rotor will give a realistic blockage ratio but the blade sections will operate in a low Reynolds number range adversely impacting performance, whilst too large a rotor will present an unrealistically high blockage ratio, but more realistic blade section Reynolds numbers.

A 1:30 scale has been selected for the rotor because this provides a balance between these two effects, i.e.
- The Reynolds number (based on a geometrically scaled blade chord) is 7e4. This Reynolds number is considered satisfactory because it coincides with the critical Reynolds for transition between laminar and turbulent flow (Lissaman 1983). Furthermore this will be the lower bound for operation because it has been agreed within the consortium to modify the blade geometry to increase the Reynolds number. Arguments for modifying the geometry of model rotors of this scale are set out in Appendix 2.
- The blockage ratio (based on area) is 23%. As discussed in Appendix 3 the predictions for unbounded performance of the model scale rotor designed by GH will not be achieved by testing at such a blockage ratio. However a preliminary analysis of the blockage effect on a 1:30 scale experiment, provided in full in Appendix 4, shows that the impact of blockage on performance is within a reasonable bound i.e. the measured power coefficient Cp will be approximately 17% higher and the measured thrust coefficient Ct will be 12% higher than the ones which would have been measured for the case of an isolated turbine in "open water". There is presently no intention to verify the unbounded performance predictions for the rotor design by testing the rotor in a relatively unblocked facility. Instead, the exact blockage configuration of the experiment and an unbounded configuration will both be simulated in the CFD, providing a means of verification of the BEM prediction.

Quantity / parameter	**symbol**	**Full scale**	**Scale : 1/**	**10**	**20**	**25**	**30**	**40**	**50**	**60**
Depth averaged current velocity	U	3	m/s	0,95	0,67	0,60	0,55	0,47	0,42	0,39
Diameter	D	18	m	1,80	0,90	0,72	0,60	0,45	0,36	0,30
Kinematic viscosity	ν	1,00E-06	$m^2.s^{-1}$	1,00E-06	1,00E-06	1,00E-06	1,00E-06	1,00E-06	1,00E-06	1,00E-06
Gravity acc.	G	9,81	$m.s^{-2}$	9,81	9,81	9,81	9,81	9,81	9,81	9,81
Water heigth	H	25	m	2,50	1,25	1,00	0,83	0,63	0,50	0,42
Flume width	L	60	m	1,50	1,50	1,50	1,50	1,50	1,50	1,50
Blades rotation speed	ω_{ref}	15	rpm	47,43	67,08	75,00	82,16	94,87	106,07	116,19
		1,57	$rad.s^{-1}$	4,97	7,02	7,85	8,60	9,93	11,11	12,17
Blades chord	c	1,10	m	0,11	0,06	0,04	0,04	0,03	0,02	0,02
Needed flow Q=U.L.h			m^3/s	3,56	1,26	0,90	0,68	0,44	0,32	0,24
(Pump 250 l/s or 1000 l/s)			l/s	3558	1258	900	685	445	318	242
Intersection between wake and flume borders[1]			Nb of D		1,1	1,4	1,6	1,9	2,0	2,1
Extracted power[2]	$P=1/2\rho CpSU^3$		W	489	43	20	10	4	2	0,9
Drag force[3]	$T_d=1/2\rho CtSU^2$		N	973	122	62	36	15	8	5
Torque	$C=P/\omega_{ref}$		N.m	98	6	2,5	1,2	0,4	0,2	0,1
TSRref	$TSRref=\omega_{ref}R/U$	4,7		4,7	4,7	4,7	4,7	4,7	4,7	4,7
	TSR=3,5	1,2	ω (rad/s)	3,7	5,2	5,8	6,4	7,4	8,2	9,0
RPM range		11,1	ω (rpm)	35,2	49,8	55,7	61,0	70,5	78,8	86,3
(TSR from 3.5 to 6)	TSR=6	2,0	ω (rad/s)	6,3	8,9	10,0	11,0	12,6	14,1	15,5
		19,1	ω (rpm)	60,4	85,4	95,5	104,6	120,8	135,0	147,9
Non-dimensional numbers :										
Blockage ratio based on diameter (B2)			-	120%	60%	48%	40%	30%	24%	20%
Blockage ratio based on area (B1)			-	68%	34%	27%	23%	17%	14%	11%
Froude (Fr)		0,19	-	0,19	0,19	0,19	0,19	0,19	0,19	0,19
Reynolds (Re)		5,40E+07	-	1,7E+06	6,0E+05	4,3E+05	3,3E+05	2,1E+05	1,5E+05	1,2E+05
Re/bl. Chord		1,11E+07	-	3,5E+05	1,2E+05	8,9E+04	6,7E+04	4,4E+04	3,1E+04	2,4E+04
Strouhal (Str)		9,42	-	9,42	9,42	9,42	9,42	9,42	9,42	9,42

Table 1 - Quantities and parameters for different scales (green cells represent input data, grey cells represent technical impossibility or scientific inappropriate conditions)

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[1] Strong approximation

[2] Cp is supposed to be equal to 0.45 as a first approximation, as provided in “20100225-104330BT02.doc”.

[3] Ct is supposed to be equal to 0.85 as a first approximation, as provided in “20100225-104330BT02.doc”.

A summary of the advantages and disadvantages (and associated mitigation measures to be taken) of the chosen scale is provided in Table 2.

	Disadvantages	Mitigation	Advantages
Scale: 1/30th	As mentioned in § 2.2, the Reynolds number range will be low.	The blade geometry will be modified to increase the Reynolds number and to make the performance of the rotor more representative of a full scale tidal turbine.	Laboratory study in controlled environment
Flume: EDF Channel 5	Relatively high blockage ratio	Regarding the primary objective of this work package, which is to help calibrate and validate the CFD numerical model Ansys Fluent, the blockage ratio is not an issue since the experiment is going to be replicated in the numerical model. Regarding the other objectives (to provide information to GH engineering tool and to the CFD numerical model Code_Saturne), corrections will be attempted to investigate the blockage effects.	Long flume which allows the turbulence to develop correctly. Current and wave flume. Located on the same site as the work package leader (highly beneficial in experimental testing)

Table 2 – Disadvantages and advantages of the chosen scale and flume.

4.2 General description of the experimental facilities

Below are the channel 5 features :
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 and 0 to 1000 l/s (depending of the pump)
Paddle : Piston-type, regular and irregular waves

Figure 1: channel 5 in LNHE halls

The following table gives the theoretical maximum current velocity for different water heights for the 1000 l/s pump and does not take the pressure losses into account. These figures will be verified during the base flow tests.

H (m)	U (m/s)
1	0,67
1,1	0,61
1,2	0,56

Table 3 - Theoretical maximum current speed for different heights of water and the 1000 l/s pump.

4.3 Flow scale model

The minimum water height is calculated from the full scale turbine diameter (18m) and considering approximately 3 metres of clearance with the seabed and 3 metres of clearance with the free-surface.

The maximum water height will be calculated from the maximum pump flows and the required current velocity (see Table 3).

4.4 Turbine and support structure scale model

The task of constructing the turbine and support structure scale model has been sub-contracted. An EngD student sponsored by TGL, Jeremy King, has been identified as being available to conduct this task. He is experienced in the design, construction and tank testing of instrumented model tidal turbines of similar scale, having successfully built two such models which were tested in the flume at Ifremer[4]. Given the significant overlap between the requirements for the construction of the model turbine for WG4WP1 and those for the TGL model turbines (and hence his relevant experience), Jeremy King has been selected as the preferred subcontractor for the manufacture of the turbine and support structure scale model. The overall dimensions of the turbine that has been suggested by Jeremy King are provided in Appendix 1. As part of an on-going consultation process between Jeremy King, EDF and GH the existing design will be adapted, where necessary, to meet the specific requirements of WG4WP1.

It has been agreed with the ETI and the PerAWAT consortium including the project manager (GH) that the third party EDF are proposing to use for the scale model will provide a set of concept drawings to the ETI and to the PerAWAT consortium (please refer to § 7 - Appendix 1 and § 12 - Appendix 6 for the quote) but not a set of full, detailed drawings. However, EDF as the purchaser of the scale model will get a set of full, detailed drawings from the third party.

As EDF will hold the detailed drawings, maintenance operations and/or modifications if required will be handled by EDF or EDF subcontractors. EDF reserve the right to make minor modifications to the design if necessary to meet the objectives.

The three parts of the device (rotor, nacelle, support structure) will be bought from TGL suppliers.

4.4.1 Rotor, gearbox, motor

Blade shape

Two options were investigated to choose the blade shape:

- Geometrically similar case. The scale model blade would be exactly scaled down from the full scale blades.
- Modified geometry case. The geometry to be designed to match the thrust coefficient curve of the full-scale device (the modification away from geometric similarity being required due to low Reynolds number for the 1/30th scale model).

The purpose of the experimental work is to study the physics of the flow around a turbine. With the wake being a significant area of interest, the wake form is driven by the thrust on the device. A

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[4] "Maganga, F. Germain, G. King, J. Pinon, G. Rivoalen, E. Experimental study to determine flow characteristic effects on marine current turbine behaviour. Proceedings of European Wave and Tidal Energy Conference, 2009, Uppsala, Sweden."

similarity of the thrust coefficient curve (and a modified blade shape) is therefore preferred to geometrical similarity. A detailed technical justification is provided in Appendix 2 (cf. § 8).

At this stage, there are still two possible designs based on two different NACA profiles. Please refer to Appendix 3 (§ 9) for the blade profiles provided by GH.

The CAD models which correspond to these profiles are shown below. The hydrodynamic properties of these two blades are very similar (Appendix 3, § 9).

The thicker blade (NACA 4415) will be selected for various reasons regarding the manufacturing process, mechanical strength, and root – hub assembly. Even in that case, the root profile may need to be modified to fit the required strength and the root – hub assembly.

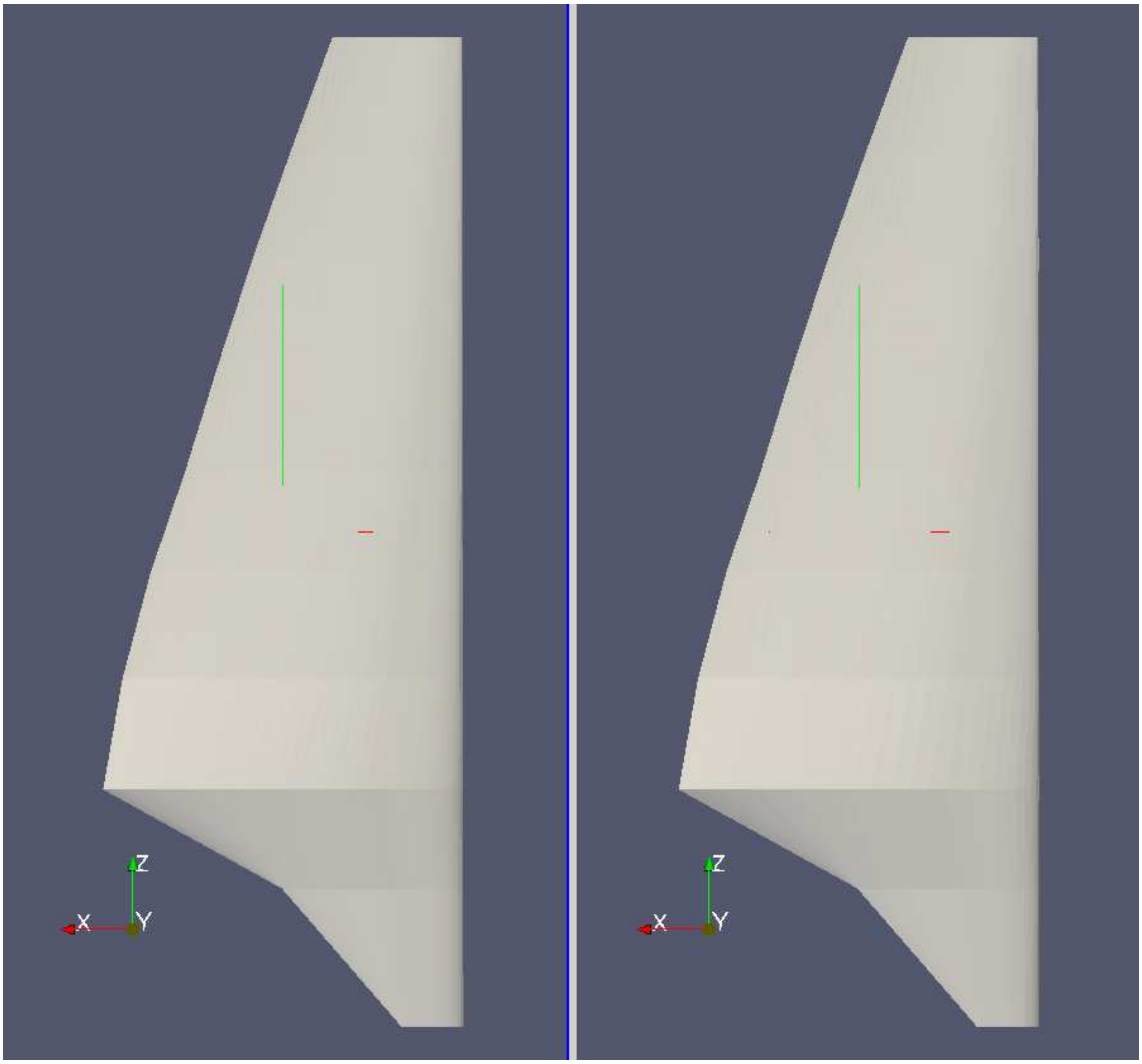


Figure 2 – Blade CAD model (NACA 4415 –left- and NACA 6412 –right-). These pictures illustrate that the chord distribution remains the same between both models (both views are identical).

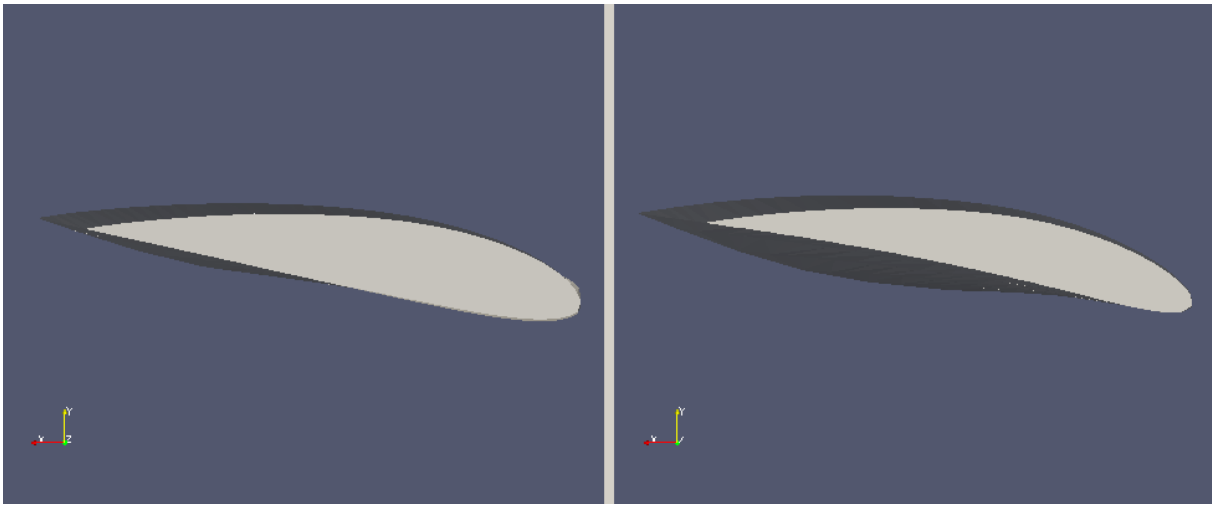


Figure 3 – Blade CAD model slices (NACA 4415 –left- and NACA 6412 –right-). These pictures show how different the blade sections are between both models.

Blade manufacturing process

First, a master model is made using stereo-lithography which is a process by which a complex 3D model can be made from a CAD file by ‘printing’ successive layers with a laser. Second, a female silicon mould is made using the master model. A tapered stainless steel spar is machined from bar, incorporating appropriate end fittings and pull-out features. The spar is held in the mould and the blade is cast permanently around it. The material used is a hard polymer with glass powder in the matrix. This material has high strength and very high stiffness. The finished blades are removed from the mould and finished by hand.

The blade roughness should be scaled down from the full scale equivalent device. However, because the equivalent blade will not present high roughness, it is very likely that the smoother the small scale blade surface condition, the better.

Nose and hub

The nose and hub dimensions shall be approximately scaled down from the full scale hub (the nose is missing on purpose in the overall design drawing in Appendix 1 (§ 7), in order to show the hub assembly details).

Drive train

A Maxon motor and gearbox will be used.

- The generator is rated at 150W. The maximum continuous current is around 7A, with a peak value of 10A for short duration.
- The control system for the drive train allows operation in two control modes – constant current (i.e. constant torque) and constant speed. Constant speed will be used for the test in order to validate the numerical models. The drive train is controlled with a voltage ‘demand’ signal in the range +/-10V.
- Current and speed can be monitored in real time from the control system.

4.4.2 Nacelle

The nacelle shape will be as close as possible to an existing nacelle to ensure the wake is representative (the nacelle design will be close to the TGL design).

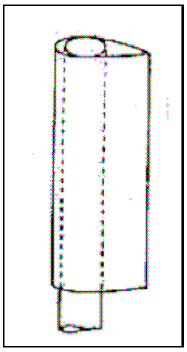
The material used is black anodised aluminium.

4.4.3 Support structure

The device will be held from the top. A load cell or a specific device will be placed between the support structure and the flume structure. The sensor detailed characteristics will be provided when the overall weight of the manufactured turbine is known.

The attachment flange on the support structure will be provided by Jeremy King.

The support structure effects on the flow will be minimized probably through the use of a streamlined fairing, such as the one below.



4.5 Experimental equipment

This section presents the characteristics of the experimental equipment. All real time data series shall be collected using a data logging system. Ideally the signals will be processed in real time to allow statically useful parameters to be evaluated in real time during experiments. But all data will be recorded and stored in a coherent and useful manner.

EDF reserve the right to make minor modifications to the choice of sensors, data sampling, etc… if the following specifications are found not to meet the work package objectives.

The objective for the overall acceptable error relating to test measurements is 5%. This is reasonable considering the type of measurement campaign and the sensors which will be used (however, some sensors will give more accurate information, e.g. the water height gauge precision is 1%).

4.5.1 Instrumentation

An Acoustic Doppler Velocimeter (ADV) will be used to measure the current velocity in the three dimensions. PC run, specialised data logging software is used to capture the flow measurements. The instruments used for measuring the principal parameters are :

Measurement parameter	Device	Measurement range	Raw data sampling frequency/data set	Raw data accuracy
Upstream and downstream flow characteristics Flow velocities (from which the turbulence intensity can be evaluated)	Acoustic Doppler Velocimeter (ADV).	0 - 1 m/s	25 Hz during 2 mn	See ADV accuracy below
Water height or Waves	TDH sensor (Transmetteur De Houle)	0 – 100 mm 0 – 250 mm 0 – 500 mm	At least 20 points per waves length (20 Hz often used)	See TDH accuracy below
Turbine thrust	Load cells or strain gauges.	0 – 100 N	At least 20 points per waves length 25 Hz will be first considered	To be defined
Rotor speed	Controlled (and tachometer ?)	0 – 105 rpm (0-6 TSR)	To be defined	To be defined
Applied torque or equivalent	Motor (estimation of torque through electrical current measurement)	To be defined	To be defined	To be defined

Table 4 - Characteristics of the instrumentation.

Items that remain “to be defined” will be specified during the final technical discussions with Jeremy King for turbine optimisation of the turbine with regard to EDF flume.

Parasitic electrical losses will be provided in the motor characteristics.
Frictional losses will be accounted for through the methodology used to extract the parameters of interest. The turbine torque will be measured at a given rotational speed, with and without flow

current. The difference in the measured torque between the first and the second case will yield information of the turbine performance without frictional losses.

4.5.1.1 Characteristics of the SonTek ADV sensor

Parameter	SonTek 16 MHz MicroADV
Range of samples (Hz)	0,1 à 50
Distance of measurement (cm)	5
Resolution (cm/s)	0,01
Ranges of velocity (+/- cm/s)	3, 10, 30, 100, 250
Precision	1% of the velocity, with a minimum of +/- 0.25 cm/s
Size of the sensors	Ø = 8 cm
Volume of measurement	< 0,1 cm^3
Range of measurement	10^{-3} m/s to 2,5 m/s

Table 5 - Characteristics of the SonTek ADV sensor

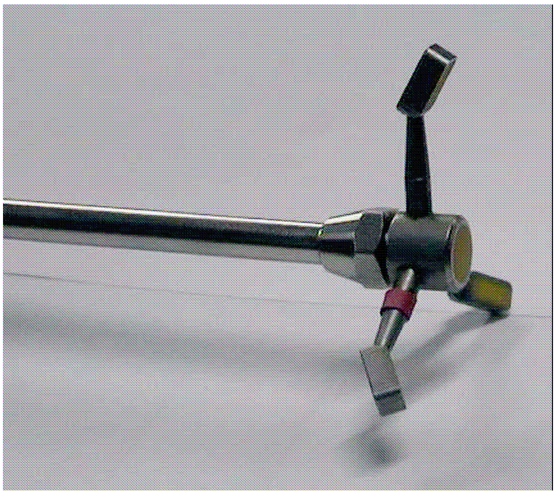


Figure 4: SonTek 3D ADV sensor head

4.5.1.2 Characteristics of the water height gauges

For the measurement of the free-surface (with or without waves) we use standard TDH (Transmetteur De Houle, in French) gauges which have the following characteristics (Figure 5).

Sensor: 2 stainless steel electrodes, diameter 3 mm.
Range of measurement: TDH 100 mm of clear water. TDH 250 : de 0 à 250 mm. TDH 500 : 0 à 500 mm.
Precision: smaller then 1 mm. Derivation with the temperature < 0,15 %/°C (from 0°C to 40 °C).
Features:

- Stainless steel electrodes: ∅ 3 mm,
- Space between electrodes : TDH 100 et 250 : 15 mm, TDH 500 : 20 mm.
- Weight : TDH 100 : 0.33 kg, TDH 250 : 0,35 kg , TDH 500 : 0,43 kg.
- Dimensions : TDH 100 : 190 x 56 x 110 mm. TDH 250 : 340 x 56 x 110 mm TDH 500 : 593 x 56 x 110
- Range of measurement : ± 20 mA or ± 10 V
- Supply : 220 V AC
- Output : ± 10 V filtered from 0.2 Hz to 1 KHz

- Number of channels : 6
- Connector : BNC

Figure 5: TDH waves height sensor

4.5.2 Instrumentation calibration

ADV are supplied with a certificate of calibration from the manufacturer. The ADV accuracy could also be verified in EDF test section.

The TDH sensors will be calibrated in a basin (see Figure 6).

The calibration of load cells/strain gauges will be conducted by applying known loads to the support structure.

Figure 6 : calibration of the TDH sensors in a basin

5 Testing programme

5.1 Calibration tests

An important number of calibration tests are required to minimise measurement errors. These include:

- Flume characteristics in the absence of rotors i.e. measurement of in-flow conditions characterising the mean velocity and ambient turbulence intensity depth and lateral profile, and how these characteristics develop downstream.
- Evaluation of the required sampling period and frequency at which data is statistically stable. This will be different dependent on the intended analysis of the data, which includes mean flow characteristics and turbulence intensity.
- Individual instrumentation calibrations.

5.2 Blockage effects

Blockage will affect the results on performance and wake. Tests can be performed in a "blocked environment", as long as the conditions are known, however in order to make meaningful comparison between tests run with different water heights (and hence blockage ratio) and to some extent with the results coming out of the CFD workstreams, corrections for blockage will need to be made. Please refer to Appendix 4 for a first calculation of the blockage effect in channel 5.

5.3 Performance tests

Investigative tests will be conducted to confirm the final parameters of interest/measurement points, but initial consideration of the effects suggests the following values/positions.

The performance assessment will consist in measuring the rotor thrust and power, and in plotting the C_T & C_P vs Tip Speed Ratio (TSR) curves. The TSR will vary from 3.5 to 6 (mean value is close to 4.7, as in Table 1). The current velocity will be as high as possible and the TSR variation will be obtained through rotational speed variation.

The variables are the current velocity, the turbulence intensity (range to be defined after the base flow tests), the height of water and the waves. The variations will be independent from one another.

Two current velocities will be considered :

- 3 m/s at full-scale => U0 = 0.55 m/s (Fr = 0.19)
- 1.5 m/s at full-scale => U1 = 0.27 m/s (Fr = 0.10)

Two heights of water will be considered :

- 24 m at full-scale => H0 = 0,80 m (ϕ 0.60m + 2x 0.1m corresponding to 3m of clearance from the seabed and the free surface) (area blockage ratio 24%)
- 30 m at full-scale => H1 = 1 m (close to the maximum achievable height of water in flume 5) (area blockage ratio 19%)

One height of waves[5] (regular waves) will be considered :

- 6 m at full-scale, 10 s period => 0.2 m with a 1.8 s period

The mean water height considered will be 1 m in order not to exceed the maximum water height of the flume and to ensure the blade tips remain under the free surface.

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[5] At this time of the study, we suppose that this value is reachable. We may have to modify it because of the presence of the current or devices such as grids which may be used to increase/decrease the turbulence intensity.

5.4 Wake tests

The wake measurements will be performed at five operating points chosen from the Ct versus TSR curve. Three of them will help calibrate the numerical models, and the other two will help validate them:

- The first point corresponds to the lower TSR that can be reached,
- The second point should correspond to the Ct that occurs when peak Cp is reached, i.e. where Ct is a maximum before linear momentum theory breaks down,
- The third point corresponds to the higher TSR that can be reached,
- The fourth point (validation measurement) will be half way between the first and the second point,
- The fifth point (validation measurement) will be half way between the second and the third point.

The table in Appendix 5 (§ 10) provides an overview of the experimental programme. However, these tests might be subject to change because of the facility capabilities, and because of the first results on the decisive parameters which affect the performance and wake of the turbine.

Two kinds of tests will be performed:

- Investigative tests are tests where the wake is going to be measured :
  - Along the centerline downstream : 10 measurement points (every 0.5D)
  - At 4 crosses downstream + 1 cross upstream. For each cross, 10 horizontal and 7 vertical points equally spaced over height and width (around every 14 cm horizontally and 13 cm vertically): 5x(10(H)+7(V))=5x17=85 measurement points

- Detailed tests are tests where the wake is going to be measured :
  - Along the centerline downstream : 10 measurement points (every 0.5D) – see Figure 7,
  - At 4 crosses downstream + 1 cross upstream. For each cross, 10 horizontal and 7 vertical points equally spaced over height and width (around every 14 cm horizontally and 13 cm vertically) : 5x(10(H)+7(V))=5x17=85 measurement points – see Figure 8,
  - On one entire grid at appropriate location (same spacing as above) : 10(H)x7(V) = 70 measurement points – see Figure 9,

The aim of the centerline downstream test is to find the distance at which the ambient turbulence starts mixing the rotor influenced flow with the general flow.

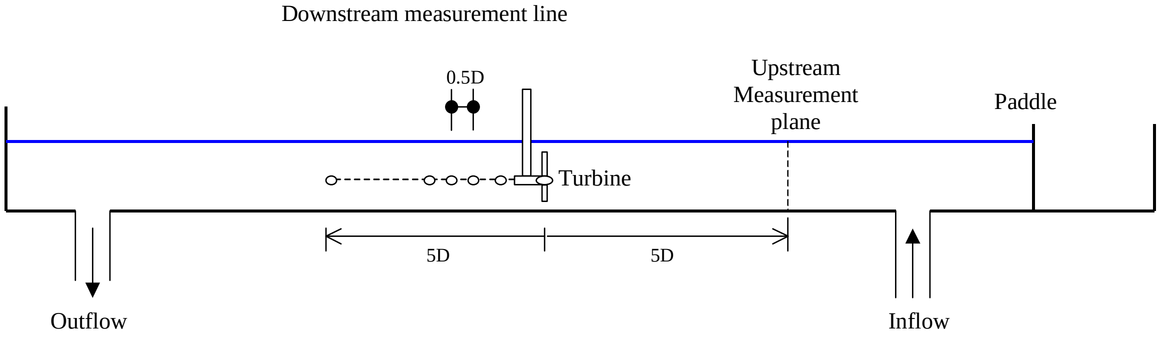

Figure 7 : Measurement points locations (10 measurement points, every 0.5D)

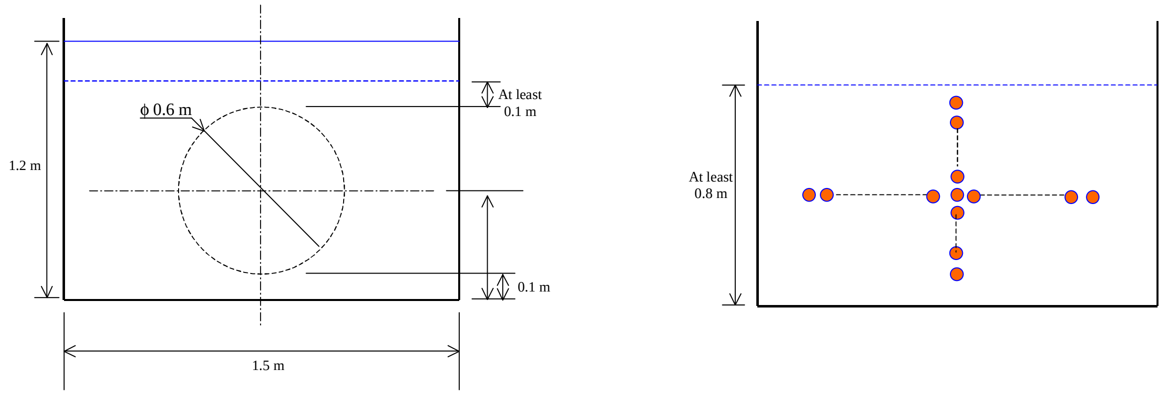

Figure 8 : Measurement points locations (at 4 crosses downstream + 1 cross upstream: 5x(10 (H)+7(V))= 5x 17= 85 measurement points)

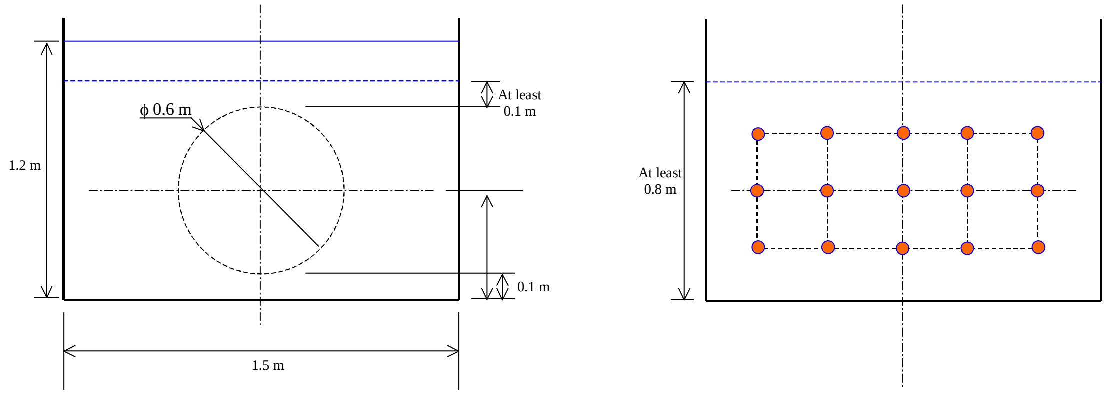

Figure 9 : Measurement points locations (grid at appropriate location : 10(H)x7(V) = 70 measurement points)

The variables are the same as for the performance tests i.e. the current velocity, the turbulence intensity, the height of water, and the waves. The variations will be independent from one another.

Two current velocities will be considered :

- 3 m/s at full-scale => U0 = 0.55 m/s (Fr = 0.19)
- 1.5 m/s at full-scale => U1 = 0.27 m/s (Fr = 0.10)

Two heights of water will be considered :

- 24 m at full-scale => H0 = 0,80 m (ϕ 0.60m + 2x 0.1m corresponding to 3m of clearance from the seabed and the free surface) (area blockage ratio 24%)
- 30 m at full-scale => H1 = 1 m (area blockage ratio 19%)

One height of waves[6] (regular waves) will be considered :

- 6 m at full-scale, 10 s period => 0.2 m with a 1.8 s period

5.5 Test schedule

The test schedule is provided below and gives an insight about the main parameters the measurement campaign will focus on. It is consistent with the tidal subproject plan as defined in WG0 D2.

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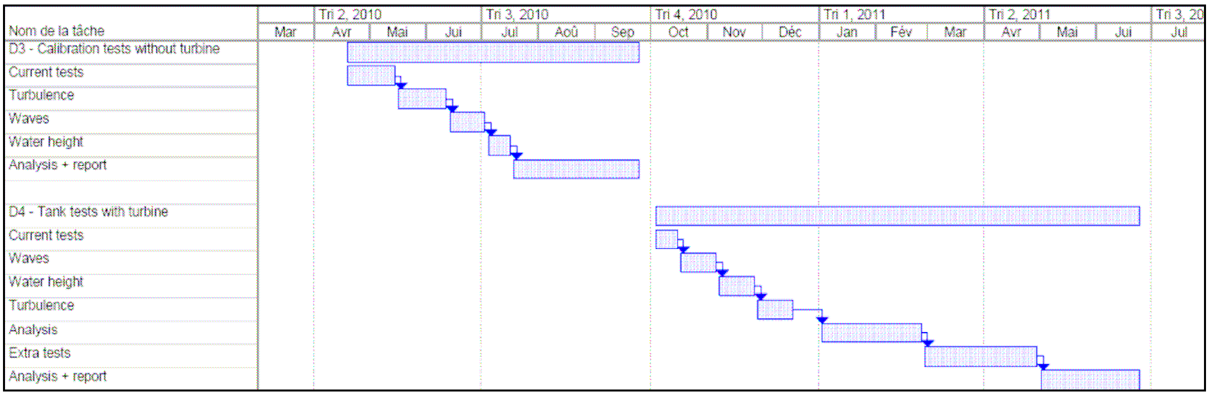
[6] At this time of the study, we suppose that this value is reachable. We may have to modify it because of the presence of the current or devices such as grids which may be used to increase/decrease the turbulence intensity.

EDF reserve the right to modify this subtask schedule, as it is subject to experimental constraints, and might also be modified by some subtasks results.



6 NEXT STEPS

6.1 Outstanding decisions

Facility

The natural turbulence intensity of the flume should provide information as to whether we should aim at decreasing or increasing it to obtain a different turbulence intensity. The way the turbulence intensity will be increased or decreased will be addressed in the base flow tests to be performed between April and June 2010.

Support structure

The support structure effects on the flow will be minimized. The design of a suitable streamlined structure is yet to be finalised (before the end of June 2010).

Device

There might be a need to iterate between the subcontractor and GH in order to optimise the blade design on manufacturing process and mechanical strength criteria. This will also be addressed before the end of May 2010, in order for the scale model to be constructed at the end of September 2010.

Information regarding the thrust, torque, and rotor speed measurements are still outstanding, and will be defined during the final technical discussions with Jeremy King in May/June 2010.

6.2 Next deliverables

The next deliverables in this work package are D2 and D3, and for both the delivery date is 1st October 2010.

In D2, the last modifications to the scale model will be provided to our subcontractor, and the scale model will be constructed and installed.

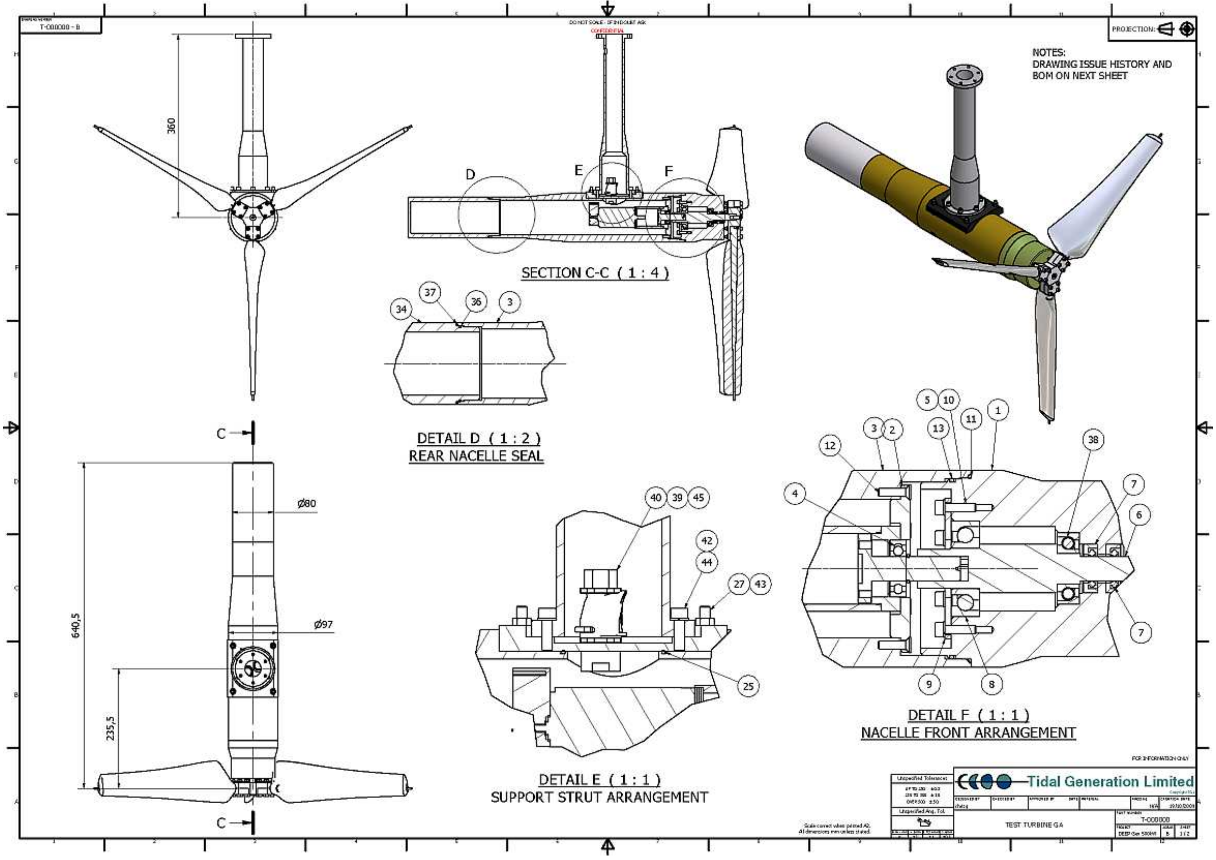
D3 will consist in mapping the base flow with different environments (current velocity, turbulence intensity, water height and waves).

7 APPENDIX 1 : SCALE MODEL OVERALL DESIGN

Please refer to attached document “WG4 WP1 D1 General arrangement.pdf”.

It has been approved by the ETI that detailed drawings will be provided to EDF only.

Summary :



8 APPENDIX 2: ARGUMENTS FOR MODIFYING THE MODEL SCALE ROTOR GEOMETRY

Please refer to attached document “20100225-104330BT01.doc”, provided by GH.

Summary:
This document is a technical note detailing the arguments for modifying the model rotor geometry from that of a full scale design. It provides justification of the rotor design approach that has been adopted by GH as input to the ETI work package deliverable WP4WG1D1. This document uses 1/30th scale as the basis for discussion, however the same arguments apply to the experimental rotor geometry being developed for WP4WG1D2.
This document includes performance predictions for 3-bladed rotors using GH Tidal Bladed, a rotor design tool based on a blade element momentum (BEM) method.

9 APPENDIX 3: ROTOR DESIGN

The blade twist and chord distribution was provided by GH.

Please refer to attached document “20100225-104330BT02.doc”

Summary:
This document is a technical note accompanying the rotor design that has been performed by GH as input to the ETI work package deliverable WG4WP1D1. Justification for modifying the rotor geometry was provided in the previous technical note 104330/BR/01. A 3-bladed rotor of 0.6 m diameter has been designed using GH Tidal Bladed, a rotor design tool based on a blade element momentum (BEM) method. This note details the considerations and procedure adopted in the design of the model scale rotor. A spreadsheet is annexed to this technical note.

10 APPENDIX 4: PRELIMINARY ESTIMATION OF BLOCKAGE EFFECTS IN EDF FLUME

The wake, the extracted power and the measured thrust in the experiment will be different from the ones which would have been obtained in open water at the same scale, because of the presence of the flume walls. This is not an issue since CFD models will be calibrated and validated against the experiment and therefore will reproduce the experiment with the flume walls. However, quantifying this difference may be of interest when trying to estimate rotor characteristics in unbounded conditions.

Bahaj proposes an estimation of the blockage correction for wake expansion based on an actuator disc model of the flow through the turbine in which the flow is presumed to be uniform across any cross section of the stream tube enclosing the turbine disc ("Power and thrust measurements of marine current turbines under various hydrodynamic flow conditions in a cavitation tunnel and a towing tank", A.S. Bahaj, A.F. Molland, J.R. Chaplin, W.M.J. Batten, Renewable Energy 32 (3) (2007), pp. 407–426.). Other work has been performed on the subject, such as “Whelan J. I., Graham J. M. R. & Peiro J., A free-surface and blockage correction for tidal turbines JFM-08-FT-0705”.

The following calculations are based on the previous Bahaj publication.

The results show that the measured power coefficent Cp will be 17% higher and that the measured thrust coefficient Ct will be 12% higher than the ones which would have been measured in an "open water" configuration.

Please refer to Figure 10 below for the velocity notation.
$U_T = U(x)$ i.e. the measured free-stream axial velocity.

In the calculation below, inputs are in green and outputs (blockage effects) are in blue.

Width	L	1,5	m
Water Height	h	1	m
Rotor swept area	A	0,283	m^2
Tunnel Area	Lh	1,5	m^2
Blockage	B_1	19%	-
C_T (measured)		*0,85*	-
C_P (measured)		*0,45*	-
TSR		4,71	-
U_3 / U_2	1,773		

$U_1 / U_2 =$ 1,27 (Eq. A.1)

$U_T / U_2 =$ 1,588 (Eq. A.4) (=Eq. A.2)

$U_1 / U_T = U_1 / U_2 * U_2 / U_T =$ 0,80

$U_T / U_0 =$ 0,94 (Eq. A.5)

$C_{P0} = C_P * (U_T / U_0)^3 =$ 0,37 $(U_T / U_0)^3 =$ 83%
$C_{T0} = C_T * (U_T / U_0)^2 =$ 0,75 $(U_T / U_0)^2 =$ 88%
$TSR_0 = TSR * (U_T / U_0) =$ 4,42

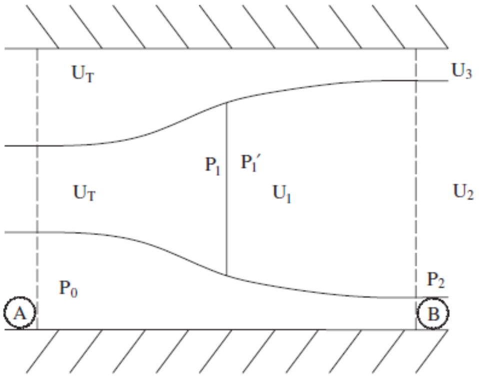


Figure 10 - Taken from Bahaj et al (2007).

11 APPENDIX 5: EXPERIMENTAL PROGRAMME

The following table provides an overview of the experimental programme. However, these tests might be subject to change because of the facility capabilities, and because of the first results on the decisive parameters which affect the performance and wake of the turbine.

Detailed tests are tests where the wake is going to be measured :

- Along the centerline downstream : 10 measurement points
- At 4 crosses downstream + 1 cross upstream. For each cross, 10 horizontal and 7 vertical points equally spaced over height and width (around every 14 cm horizontally and 13 cm vertically): 5x(10(H)+7(V))= 5x17= 85 measurement points
- On 1 grid at appropriate location (same spacing as above): 10x7 = 70 measurement points

Investigative tests are tests where the wake is going to be measured :

- Along the centerline downstream : 10 measurement points
- At 4 crosses downstream + 1 cross upstream. For each cross, 10 horizontal and 7 vertical points equally spaced over height and width (around every 14 cm horizontally and 13 cm vertically): (10(H)+7(V))= 5x17= 85 measurement points

In order to modify the operating points, the inflow speed will remain the same, and the rotor speed will vary.

	Parameters	Measurements	Number of flow measurements
Tests without turbine	Current U0, <u>U1</u> TI 0, <u>TI1</u>[7] No wave Water height H0, <u>H1</u>	Base flow mapping	10 grids at the future location of the tubine
Support structure on its own	Current U0 TI 0 No wave Water height H0	Drag force Wake	1 investigative test
Support structure on its own	<u>Current U1</u> TI 0 No wave Water height H0	Drag force Wake	1 investigative test
1st test (reference test)	Current U0 TI 0 No wave Water height H0	Ct(TSR) Cp(TSR) Detailed wake	5 detailed tests (each test corresponding to one operating point)
2nd test	Current U0 <u>TI 1</u> No wave Water height H0	Ct(TSR) Cp(TSR) Detailed wake	5 detailed tests (each test corresponding to one operating point)
3rd test	<u>Current U1</u> TI 0 No wave Water height H0	Ct(TSR) Cp(TSR) Wake	2 investigative tests (each test corresponding to one operating point)

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[7] The turbulence intensity TI 0 of the flume is not know yet, and part of this work will consist in finding a way to generate another turbulence intensity TI 1.

4th test	Current U0 TI 0 Wave 1 Water height H0	Ct(TSR) Cp(TSR) Wake	2 investigative tests (each test corresponding to one operating point)
5th test	Current U0 TI 0 Wave 0 Water height H1	Ct(TSR) Cp(TSR) Wake	2 investigative tests

Table 6: Experimental programme (underlined values are the variable parameters)

Parameters	First value X0	Second value X1
Current velocity	0.27 m/s (1,5 m/s)	0.55 m/s (3 m/s)
Turbulence intensity	To be defined	To be defined
Water height	0.8 m (24 m)	1.0 m (30 m)
Wave height	No wave	0,2 m, 1,8 s (6 m, 10 s)

Table 7: Experimental data (values inside brackets are full-scale equivalent data)

12 APPENDIX 6: PRELIMINARY QUOTE FOR THE TURBINE MANUFACTURING

As written in § 4.4, the third party EDF are proposing to use for the scale model will provide a set of concept drawings to the ETI and to the PerAWAT consortium (see Appendix 1) but not a set of full, detailed drawings. However, EDF as the purchaser of the scale model will have get a set of full, detailed drawings from the third party. The quote attached to this document has been provided for these circulation restrictions.

Please refer to attached document “Amalgam Quote Ref M H 240210-1656.doc”

Summary:

To produce one complete scale turbine model for the purposes of tank testing	£7,040.00
To provide complete suite of manufacturing drawings for above turbine design	£6,600.00

Total £13,640.00