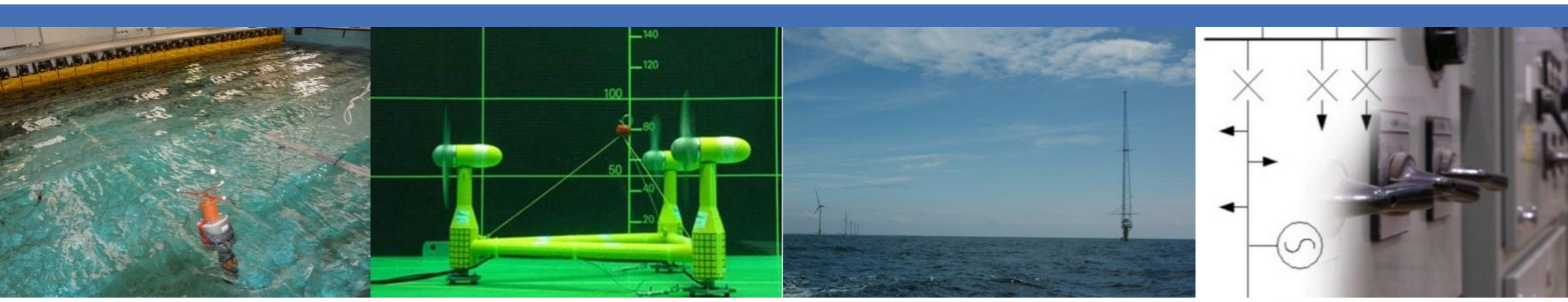
MARINET

Marine Renewables Infrastructure Network



WP2: Marine Energy System Testing - Standardisation and Best Practice

Deliverable 2.7

Tidal Measurement Best Practice Manual

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ABOUT MARINET

MARINET (Marine Renewables Infrastructure Network for emerging Energy Technologies) is an EC-funded network of research centres and organisations that are working together to accelerate the development of marine renewable energy - wave, tidal & offshore-wind. The initiative is funded through the EC's Seventh Framework Programme (FP7) and runs for four years until 2015. The network of 29 partners with 42 specialist marine research facilities is spread across 11 EU countries and 1 International Cooperation Partner Country (Brazil).

MARINET offers periods of free-of-charge access to test facilities at a range of world-class research centres. Companies and research groups can avail of this Transnational Access (TA) to test devices at any scale in areas such as wave energy, tidal energy, offshore-wind energy and environmental data or to conduct tests on cross-cutting areas such as power take-off systems, grid integration, materials or moorings. In total, over 700 weeks of access is available to an estimated 300 projects and 800 external users, with at least four calls for access applications over the 4-year initiative.

MARINET partners are also working to implement common standards for testing in order to streamline the development process, conducting research to improve testing capabilities across the network, providing training at various facilities in the network in order to enhance personnel expertise and organising industry networking events in order to facilitate partnerships and knowledge exchange.

The initiative consists of five main Work Package focus areas: Management & Administration, Standardisation & Best Practice, Transnational Access & Networking, Research, Training & Dissemination. The aim is to streamline the capabilities of test infrastructures in order to enhance their impact and accelerate the commercialisation of marine renewable energy. See www.fp7-marinet.eu for more details.

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LEGAL DISCLAIMER

EXECUTIVE SUMMARY

This document assembles best practice guidelines to assess flow conditions around tidal turbines during all stages of the design and development process. In progressing through the sequence of technology readiness levels experimental tests are usually performed at increasing scales. Advice is given for small scale experimental tests, up to resource and performance assessment at full scale installation sites. Recommendations comprise the selection of the appropriate test method and scale, design of equipment, data acquisition and analysis.

CONTENTS

1 INTRODUCTION

The development of tidal turbines requires the accurate assessment of the flow properties; in this case velocity magnitude and direction, turbulence and their spatial and temporal variations are of relevance. Experimental results depend entirely on the accuracy of measurement of these flow conditions and without full knowledge of these inputs, the results from experiments may be misleading.

The development of ocean energy devices from a basic concept to a large-scale prototype fully descriptive of units deployed at sea involves a sequence of experimental activities with specific objectives and demands. The dimensions and complexity of tested models increase as the concept technology readiness level (TRL) increases. In parallel to this, operating conditions established during experiments should be designed to be more and more representative of real operating conditions for the full-size device deployed at sea for energy harvesting.

In order to make possible experimental studies of increasing complexity and correspondence to real operating conditions, a range of model testing facilities with different characteristics are typically involved.
In this report the following classification is proposed:

1. Towing tanks
2. Flume tanks
3. Small-scale field testing sites
4. Full-scale field testing sites

In the following sections, basic characteristics of facilities falling into each group are described, and main aspects of design, set-up, execution and analysis of results of model tests are discussed. The description is intentionally general in order to cover a variety of aspects related to testing very different concepts including, but not limited to, horizontal axis turbines, vertical axis turbines and, oscillating foils. For a given device tests might be conducted with a series of different objectives such as concept evaluation, performance evaluation, unit-to-unit interaction, environmental impact assessment and, survivability.

In this framework, the document is intended to provide elements for the correct choice of facility to be used for a specific model test and to guide device developers and facility managers to conduct experimental work according to the best (possible) measurement practice for tidal energy converters.

In a laboratory the inflow can often be controlled, while field tests depend on measuring the naturally occurring variations. At full scale, measurements define the resource and are vital for the selection of installation sites. Although measuring the same properties, entirely different approaches can be employed in different situations. Since measuring the flow properties of the current flows is of such great importance, special advice is given for the use of state of the art acoustic Doppler based velocity measurement equipment.

This report presents best practices for tidal measurements, from small scale experiments performed in laboratories to full scale measurements used for site and resource assessment.

2 MEASURMENT PURPOSE

To the present date, much of the research in the field of tidal energy resources has focussed on relatively large scale assessment, like the prediction of the tidal levels and currents in known areas of potential. The tidal industry requires this large scale data; however, it is now becoming clear that additional detailed information on local spatial and temporal variations is also critical.

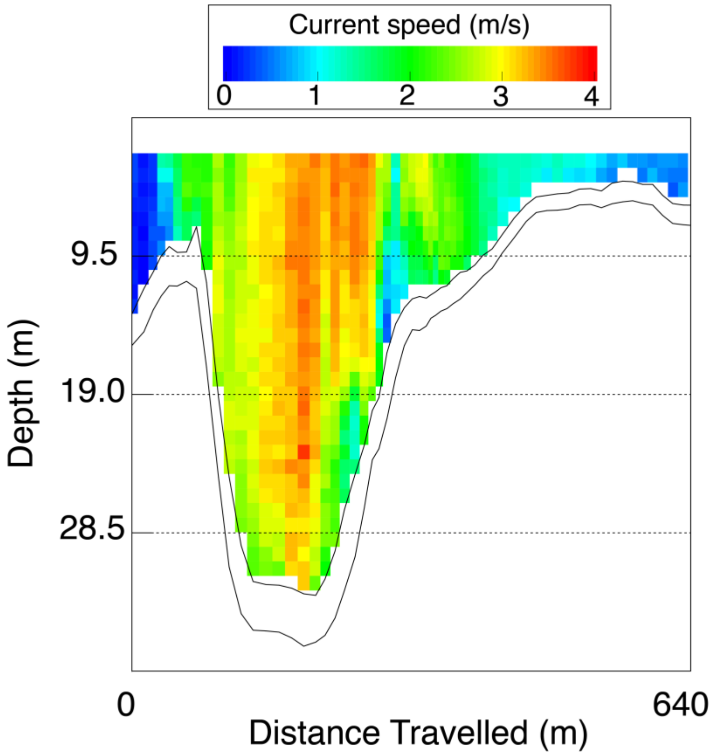


Figure 1: Velocity magnitude over transverse section of Strangford Narrows. Source: QUB.

Typical installation sites of tidal energy converters in narrows for example, can exhibit considerable changes in flow magnitude and direction within 10-20m, see Figure 1. Flow separation beside a large structure or rock can even create a sharp demarcation line with currents in opposite directions on each side. The occurrence of these steep gradients points to the need for:

- Extreme accuracy in establishing the position of a measurement
- Consideration of the validity of averaging algorithms employed in typical acoustic Doppler devices

These very small spatial variations can be crucial when determining the inflow condition to tidal turbines. Over a tidal cycle, flow velocities will of course change, but flow variations occur also on the scale of few minutes, seconds and even shorter and can affect fatigue life, performance and the wake recovery behind a structure. Last but not least, on many sites, waves will interact with the current and can become an important factor in the assessment of the inflow conditions.

A measurement campaign or a scale model test for a tidal site or device must thus be carefully planned and due consideration given to the scales that a given measuring device or test program can capture.

2.1 SCALING OF PHYSICAL PROPERTIES

Using standard similarity principles, the correct reproduction at small scale of physical conditions of real scale devices is governed by a number of non-dimensional parameters. The importance of each parameter may vary depending on the nature of the device to be tested and the objective of tests.

- Tip-speed ratio, TSR: for turbine rotors, this parameter defines the ratio between blade tip tangential speed and onset current axial velocity U. Denoting by Ω the turbine rotational speed and R the radius, this yields TSR = Ω R/U.

- Reynolds number, Re: parameter defined as the ratio between inertia and friction forces acting on a fluid mass. The Reynolds number is obtained by dividing the product of a characteristic length scale L and velocity U by the kinematic viscosity υ: Re=UL/υ.
- Froude number, Fn: parameter defined as the ratio between inertia and gravity forces acting on a fluid mass in the presence of a free surface. The Froude number is obtained by dividing a characteristic velocity U by the square root of the product of a characteristic length L and gravity g: Fn=U/√gL.
- Strouhal number, St: parameter defined as the ratio between a characteristic time associated with an oscillatory/periodic phenomenon and time associated with flow velocity. The Strouhal number is obtained as the product of oscillatory/periodic phenomenon frequency f and a characteristic length L divided by a characteristic velocity U: St = fL/U.

Dealing with tidal energy converters, scaling of physical properties can follow the well-established practice used in ship hydrodynamics with propeller testing. Comparing devices of identical shape and different scale, the tip-speed ratio is fundamental to ensure identity of kinematic conditions. Assuming the device is fully immersed, its performance is largely dependent on the Reynolds number. The Strouhal number is also important for the performance of oscillating foils and may influence the wake shed by structural members. Finally, Froude number scaling is necessary when the device interacts with the free-surface. Once the scale ratio between full-size and model-scale device dimensions is fixed, it is generally impossible to achieve a correct similarity with respect to all the parameters above. Based on the objective of the tests, the following matrix can be considered.

Objective of model test	***Similarity enforced***	***Experiment***
Device hydrodynamic performance	TSR, Rn,	Flume tank
Supporting platform sea-stationing, mooring, device survivability	TSR, Fn,	Towing tank, Ocean Basin

Table 2.1 Type of model test and similarity requirements

This list of non-dimensional parameters given above intentionally does not include another important parameter, the Cavitation number. This parameter is fundamental to ensure identity of physical conditions governing the occurrence of cavitation in the flow. Similarity of a scaled model with full scale normally requires that tests are performed in depressurised conditions. This is not possible in towing tanks operating at atmospheric pressure whereas similarity can be achieved in dedicated facilities like tunnels and circulating water channels where pressure can be controlled. See chapter 4 for further details. For particular model test objectives or device working principles, it might be necessary that the correct scaling of model dynamics should also be taken into account.

3 TOWING TANK EXPERIMENTS

Testing facilities inside laboratories provide a controlled environment for the development of ocean energy devices in the phases of Technology Readiness Levels (TRL) increasing from basic research up to analysis and validation of small scale prototypes. Typically, these phases are coded as TRL levels 1 to 4 or 5. Dealing with tidal energy converter (TEC) systems, there are basically two types of laboratory facilities where real operating conditions can be simulated to some extent:

- Towing tanks, where the model is towed while water is at rest (calm or wavy, see below);
- Flume tanks, where the model is kept fixed while water is forced to flow through.

The identification of key aspects related to testing TECs in flume/ flow tanks is addressed in the next section, whereas testing TECs in towing tanks is the subject of the present section.

Figure 2: Wave (left) and calm water (right) towing tanks at CNR INSEAN.

Towing tanks have been developed in many countries since the end of the eighteenth century for analysis and design of seacraft and marine structures in general. The problem addressed here is how to develop an effective measurement practice of tidal energy devices in facilities that typically have not been specifically designed for this purpose and are routinely operated for different tasks.

The term “towing tank” used here encompasses facilities with different characteristics. Strictly speaking, a towing tank is a rectilinear basin with length one/two orders of magnitude larger than width and depth (Figure 2). When length and width of the basin are comparable, the term “ocean basin” is typically used. Both types of facilities are equipped with carriages towing models with respect to water at rest.

In some cases, tanks are equipped with wave generators capable to produce wave patterns on the free surface. According to length/width ratio of the facility, waves can be directed in only one direction (towing tanks) or approach the model at an arbitrary angle (ocean basins).

Generally speaking, towing tanks provide an attractive option for undertaking detailed, highly controlled tests with very high repeatability of results. A major drawback of this type of facility is that the model is tested in water at rest (calm or wavy) and hence reproducing flow turbulence or velocity profiles to mimic real operating conditions in open sea or in a river can be very hard if not impossible.

Such limitations are partly overcome in facilities having sophisticated equipment specifically designed to simulate water currents or winds above the free surface. Unfortunately, there are only few facilities worldwide providing this type of equipment.

In the attempt to derive best practice guidelines for testing tidal energy devices in towing tanks, it may be useful to distinguish aspects that are relevant for any device being tested (including marine vehicles, platforms and ocean energy converters) and aspects peculiar for testing tidal energy devices.

Although the emphasis here is on the latter aspects, the problem is addressed in its generality.

The following aspects are considered of primary importance for the success of testing in a towing tank.

1. testing issues common to any type of marine vehicle or structure being tested (including TECs):
    a. blockage and model scale
    b. model manufacturing and installation
    c. testing conditions and measuring devices
2. testing issues that are peculiar for TECs:
    a. control mechanisms and PTO systems
    b. onset flow turbulence and non-homogeneity
    c. wave/current interaction

All the aspects above are discussed in some detail in the following pages. For the sake of clarity, the description is mainly referred to tidal devices in which the mechanism to convert water kinetic energy into mechanical energy is given by rotating turbine blades or by oscillating foils.

3.1 BLOCKAGE AND MODEL SCALE

The concept of blockage is related to the fact that the model is tested in a confined flow. In particular, rectilinear towing tanks are typically long basins, where length is 20-50 times larger than width and depth. In ocean basins, depth is usually very low compared to length and width. When the model is towed, reflections can occur due to the interaction with side walls and the bottom. Flow confinement effects may determine a different behaviour of the model with respect to equivalent operating conditions in an unbounded environment.

For marine vehicles and structures, well established techniques exist to evaluate effects of blockage and, eventually, to correct the measured data. The maximum ratios between the size of the model and the size of the basin are determined in order to minimize the blockage effects. When dealing with energy conversion devices, blockage can have a sensible effect on unit performance during tests in free running conditions. A correct estimation of blockage is fundamental to determine the maximum dimensions of the model that can be tested in a facility. Simply speaking, the larger the model, the better is the reliability to predict the behaviour of the device at full scale. Nevertheless, the actual dimensions of the model come from a trade-off among other practical issues like:

- model handling inside the facility: a too-large model can raise problems for excessive weight or excessive size; constraints for model installation on the carriage frame need to be carefully analysed in advance.
- instrumentation requirements: a too-small model can make it difficult to install onboard measuring tools; conversely, a too-large model can determine high hydrodynamic loads that are beyond the capability of dynamometers, torque-meters and other devices in use at the facility.

Another consequence of the confined environment is the necessity of a sufficiently long time interval between successive tests to re-establish still water conditions. The problem is particularly important when tests are performed in wave conditions.

3.2 MODEL MANUFACTURING AND INSTALLATION

A first aspect to be carefully addressed is that small scale models tested in laboratories are only partly descriptive of full scale devices. Typically, towing tank tests are performed with simplified assemblies, where many components of the full scale device are missing. In many cases, only the component converting water energy into mechanical energy is represented (i.e., a turbine rotor or an oscillating foil) whereas inclusion of components supporting the element devoted to energy conversion is only partial or totally missing, (Figure 3). This may determine important differences between model operations with respect to full-scale. The impact of these differences on model performance should be accurately identified.

Special care has to be devoted to the manufacturing of the scaled model of the energy conversion device. The model is built from a high-quality CAD model and the consistency between manufactured model shape and the original CAD data should be controlled with suitable tools before testing. Features of the model requiring extreme precision have to be identified (i.e., rotor blade leading edge, trailing edge and tip). Connections between moving parts have to be established carefully in order to prevent excessive friction that would bias results of performance tests. The choice of model material should take into account the requirement that the model cannot undergo unrepresentative deformations during model tests due to, for instance, hydrodynamic loads acting on it.

Model installation to the carriage frame has to be as similar as possible to the layout of the full scale device. Towing tanks are suitable for testing immersed devices supported by a floating platform, whereas testing devices rigidly fixed to the sea bottom implies a sensible deviation from real operating conditions. Flume tanks should be preferred for testing the latter type of devices. Floating platforms supporting the model are to be avoided because of flow perturbations induced by the interaction with the free surface of the platform towed by the carriage. Moreover, model components converting current energy should be positioned at sufficient depth to avoid interactions with the free surface.

Hydrodynamic forces generated by the devices are to be estimated in advance in order to realize a safe and robust connection of the device to the carriage frame. This is to ensure that the model undergoes no unwanted motions or deformations during testing. In extreme cases, the model could be destroyed. Load estimates can be determined using analytical models or Computational Fluid-Dynamics (CFD) tools.

3.3 Testing conditions

Model test preparation implies that an accurate test matrix is defined. This matrix follows as a result of the costumer’s requests and facility manager’s knowledge of what the facility and the equipment can perform. The joint definition of the test matrix is a fundamental step for the success of a measurement campaign. Main parameters defining testing conditions of a given device are:

- Current speed
- Turbine rotational speed or oscillating foil frequency
- Device position with respect to waterline and to onset flow direction (i.e., yaw angle)
- Device layout settings (i.e., turbine blade pitch angle)

Towing carriage speed is set in order to reproduce, after scaling, the effects of an onset tidal current at given speed. Carriage velocity can usually be regulated with great precision and, in some cases it can be varied in time to simulate currents with variable speed. Given carriage speed, the maximum time that the model can be towed depends on the length of the tank. Turbine rotational speed is measured through suitable rotation meter devices, see Section 3.4. Particular care is necessary to measure rotational speed and carriage speed in order to have accurate estimates of the TSR value.

Tests can be conducted in calm water, or in the presence of regular/ irregular waves. Calm water tests are typically carried out to analyse device performance over a range of operating conditions. Wave tests can be addressed to analyse the effect of motions induced on a device installed below a floating platform. Survivability tests of floating devices also require tests in waves. A regular wave test is conducted fixing the frequency and the steepness (or amplitude) of the incident wave. Irregular waves are defined by a spectrum whose characteristics reproduce a test site’s features (shape, width and peak frequency). In case of testing a device in waves, limitations of wave making capability in the facility have to be carefully analysed to determine the correct scaling of the model.

3.4 Measuring devices

Test-rig and model are instrumented with suitable hardware to record testing conditions as well as to determine physical quantities representative of model operation and performance. Testing conditions are recorded through:

- Carriage speed
- Shaft rotational speed/foil oscillation frequency
- Water temperature

Carriage speed is imposed and is generally established with a precision of mm/s. Shaft and turbine rotational speed is usually recorded via optical sensors or encoders. Temperature data are essential to determine water properties like density and kinematic viscosity. Standard tables for fresh water are used to this purpose, see e.g., ITTC Recommended Procedure 7.5-02-01-03. Turbine hydrodynamic performance is determined by a dynamometer fitted on the turbine shaft. It determines thrust and torque at given rotational speed. In addition to that, the turbine model can be mounted on a six-components load cell to measure hydrodynamic forces and moments generated on the device.

Turbine power is obtained from rotational speed and torque measured on the shaft. It is worth noting that only the hydrodynamic component of torque is of interest in that passive torque related to friction losses of components like shaft bearings, gears and power converter is fully dependent on the particular test-rig used at model scale and is not descriptive of full-scale units. Friction torque is quantified by running the drive train with turbine blades removed and replaced by a turbine dummy.

Other measuring systems are often used for specific analysis. This includes the evaluation of loads and deflections on device components like turbine blades or the characterization of the velocity field in the fluid region surrounding the device. Each measuring device is connected to a data acquisition system where signals are conditioned and converted into physical quantity values. Raw data acquisition frequency is typically lower than frequency ranges associated to blade passing or foil oscillations. Time histories are recorded over a statistically significant number of turbine revolutions/foil oscillation cycles and raw data from dynamometer and load cells are averaged in time.
Before tests, all measuring devices should be calibrated. As a reference, guidelines established by ITTC for measuring instruments used in hydrodynamics testing facilities should be used. In particular, see Recommended Procedure 7.6-01-01, “Sample Work Instructions Measuring Equipment Control of Inspection, Measuring and Test Equipment.”

3.5 CONTROL MECHANISM

In principle, a small-scale device can be tested by reproducing conversion of mechanical power into electric power as in the case of a full size device in which the generator is connected to the electric grid. Experimental conditions based on this operating protocol are often referred to as “free-running” tests. Such type of tests may be useful to analyse specific operating conditions but this implies a careful design of the PTO system. Unfortunately, model dynamics and drive-train friction losses are hardly scalable with model size and hence results of model tests give only a limited insight into full-scale device performance.

These difficulties are overcome by developing a power conversion control strategy. Specifically, model tests are carried out via rotational speed control or torque control. In both cases, operating conditions are established by suitable regulation of the rotational speed (or power) generated by the electric motor/generator connected to the model. In particular, torque regulation is enforced by using electro-mechanical brakes that can generate prescribed resistive loads on the shaft. More frequently, speed-regulated turbine tests are performed by adjusting motor parameters in order to enforce a prescribed turbine shaft rotational speed. Varying this speed, turbine operating points at given carriage speed are analysed and delivered torque values are determined via dynamometer output. Acquisition is repeated at different carriage speeds to explore the TSR range of interest. Similar control procedures can be established for oscillating foil devices where the oscillation frequency is controlled.

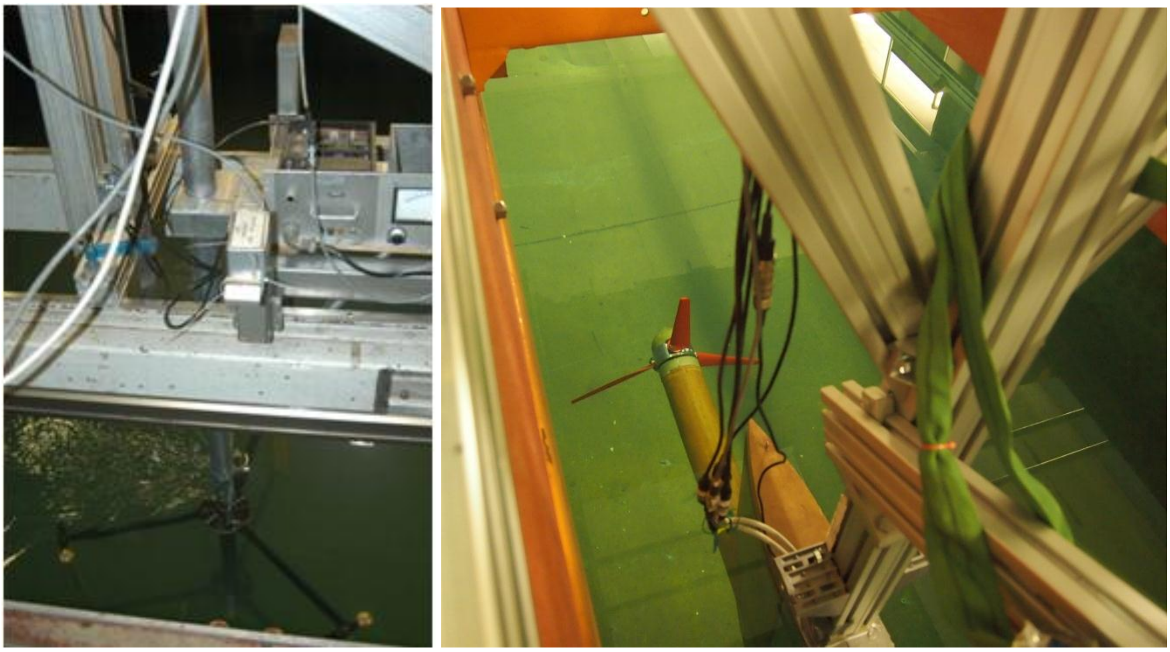


Figure 3: Test rigs for vertical axis turbine (left) and for horizontal-axis turbine (right).

3.6 Onset flow turbulence and non-homogeneity

The presence of background turbulence is a key parameter which strongly affects the hydrodynamic loads generated on turbine blades or the frictional drag on submerged structures. Moreover, it influences other important aspects, such as the rate at which the velocity defect in the wake of the turbine is replenished, which is a crucial point for the case of turbine arrays since it influences the power capture by downstream devices. A precise quantification of the effects associated with incoming turbulence is therefore mandatory when the optimal spacing between turbines should be determined.

Towing tanks with water current generators provide the possibility to test TECs with a given level of onset flow turbulence. Depending on system characteristics, non-homogeneous current velocity profiles can be established. However, towing tanks not having such devices are by far the majority. In this case, well-established ways of producing nearly homogeneous and isotropic turbulence in wind- or water- tunnels can be adopted. The standard procedure consists in manufacturing a grid consisting of a regular mesh of rods placed transversally with respect to the flow. In a towing tank, grids can be placed and held by a specifically designed frame in front of the turbine model. Turbulence intensity of a few percent of the free-stream velocity can be produced and characteristics can be varied to some extent by controlling the rod mesh spacing.

Although somewhat idealized with respect to real conditions, homogeneous isotropic turbulence (turbulent features do not depend on both spatial position and direction) represents the appropriate framework to test the effect of changing the level of turbulence intensity and the length scale of the dominant flow structures. This is the simplest type of turbulence and can be characterized through the Reynolds number associated to the length scale of the largest turbulent eddies in the flow and the intensity of velocity fluctuations. In order to represent full scale conditions, both eddy size L and intensity of velocity fluctuations u’ have to be scaled in order to preserve non-dimensional parameters like L/R and $u'/\Omega R$ involving model size and rotational speed.

3.7 Wave/current interaction

Research studies on the subject of wave/current interaction have demonstrated that the presence of current induces an increase of steepness of an onset wave pattern. Thus, the combined effect of waves and currents can be focused on specific model tests. The test can be designed either focusing on the device survivability or on the effect on the power generated by the device. According to the importance of each aspect the velocity of the carriage can be scaled respectively with the Froude number (Fn) or the Tip Speed Ratio (TSR).

In the former case, the velocity U of the carriage is used to determine the rotational speed Ω (using the TSR parameter); in the latter case, the velocity of the carriage is defined by the formula for the encounter frequency as follows $\omega_e=\omega+\omega^2 U/g \cos \beta$ (g is the gravitational acceleration and β is the angle between the incoming wave and the direction of motion of the device).

4 BASIN FLOW EXPERIMENTS

As an alternative to towing the rotor through still water experiments can be conducted in facilities where flowing water passes a fixed (or moored) turbine. The majority of flowing water tests have been conducted in flumes (which are essentially unidirectional channels) with a high length: width aspect ratio (Figure 4). Single and multi-rotor tests can also be performed in basins with flowing water. In flume tests the angle of incidence onto the turbine can be adjusted by changing the angle of attack of the rotor, while in basin tests the angle of the incident current may be variable. Fully multi-directional facilities as shown in Figure 5, allow the full tidal ellipse at a site to be simulated around a static model.

Figure 4:Flume tank

Flume tanks have been developed in many countries to study/develop marine structures. The term "flume tank" used here encompasses facilities with different characteristics, with length one order of magnitude larger than width and depth. In some cases, tanks are equipped with wave generators capable to produce wave patterns on the free surface and for few of them, it is possible to modify the turbulence intensity of the flow.

Flume tanks are very well adapted for tidal energy converters characterization due to the fact that, contrary to towing tanks, the system is tested in its operational conditions: a fixed or mooring structure submitted to dynamic inflow conditions. In this kind of facility, velocity profiles, turbulence levels and wave and current interactions can be reproduced. The repeatability of the tests is also of great importance.

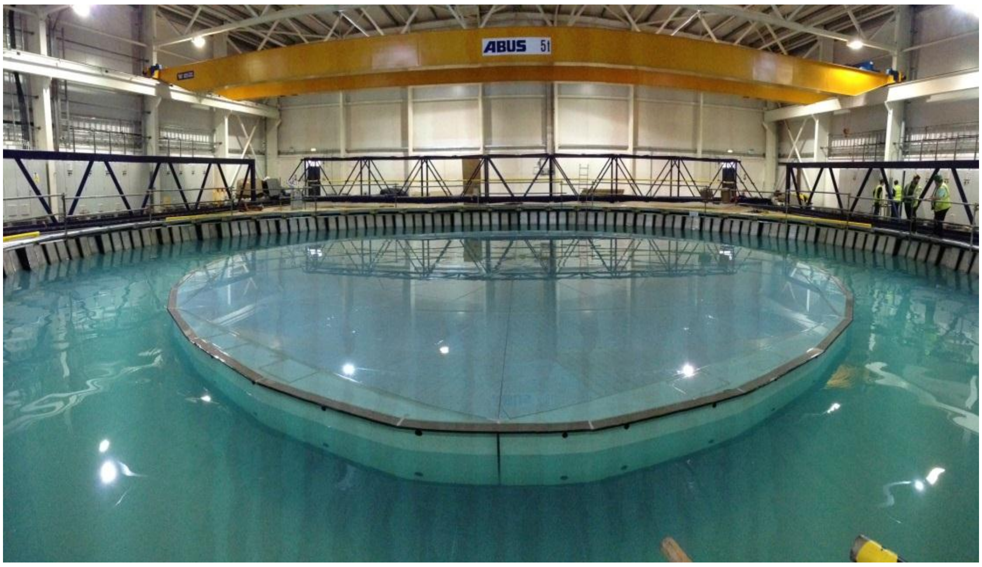


Figure 5: FloWaveTT Basin

Some facilities are also equipped with air flow plant around the perimeter to simulate winds above the free surface or to reproduce the motion of floating structures. However, such facilities are very limited. The following aspects are considered of primary importance for testing in a flume tank:

- current characteristics
- blockage and scaling effects
- turbulence and non-homogeneity
- wave and current interaction
- bathymetry

The standard similarity parameters defined in the previous section are also relevant for flume tank tests, Froude similarity is frequently used as it covers free surface effects and wave motion as is easily achieved.

Model installation in the tank has to be as similar as possible to the layout of the full scale device. Flume tanks are well adapted for testing immersed devices supported by a floating platform as well as devices rigidly fixed to the sea bottom. Figure 6 and Figure 7 show a few examples of devices already tested in the wave and current flume tank of Ifremer.

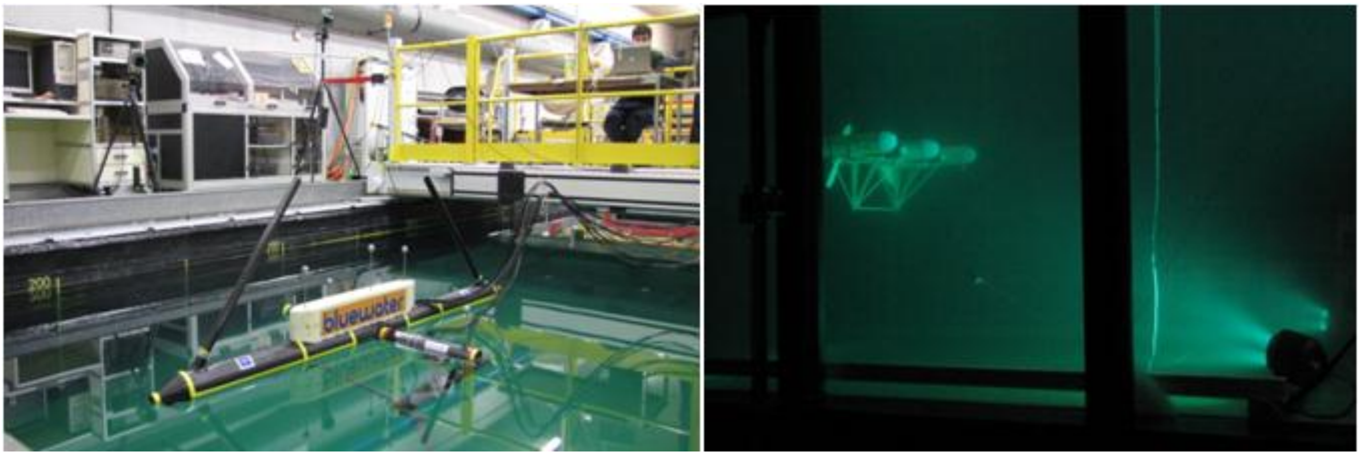


Figure 6: BlueWater floating platform and Plat-O immersed body

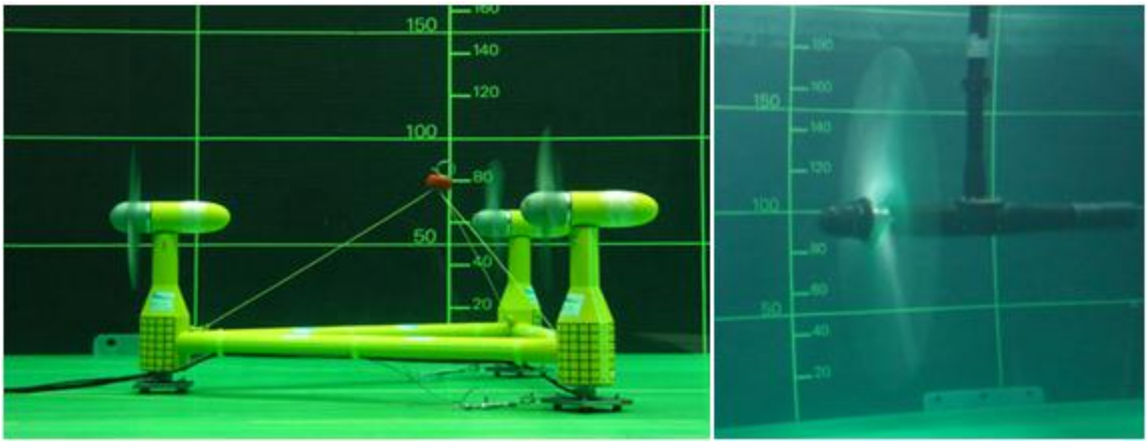


Figure 7: Delta Stream turbines (left) and Round Robin tri-bladed turbine (right)

4.1 Current characteristics

Contrary to towing tanks, the flow characteristics must be well known in a flume tank all around the test section in order to be able to characterize the turbine performance and wake effects. The current profile is the variation in velocity throughout the water column which is typically displayed as a function of height above the sea bed. This can be measured using acoustic or laser doppler velocimeter (LDV) systems. From these measurements, it is also possible to quantify the turbulence level and the turbulent kinetic energy of the flow. Measurements should be made over all the test section and not only in the location of the turbine.

The figures below gives an example of vertical current and turbulence intensity profiles obtained from LDV measurements in the wave and current flume tank of Ifremer. The dimensions of this flume tank are 18 m long by 4 m wide and 2 m deep. The flow turbulence in the tank is equal to 5% and can be increased to 25% when removing the flow straighteners.

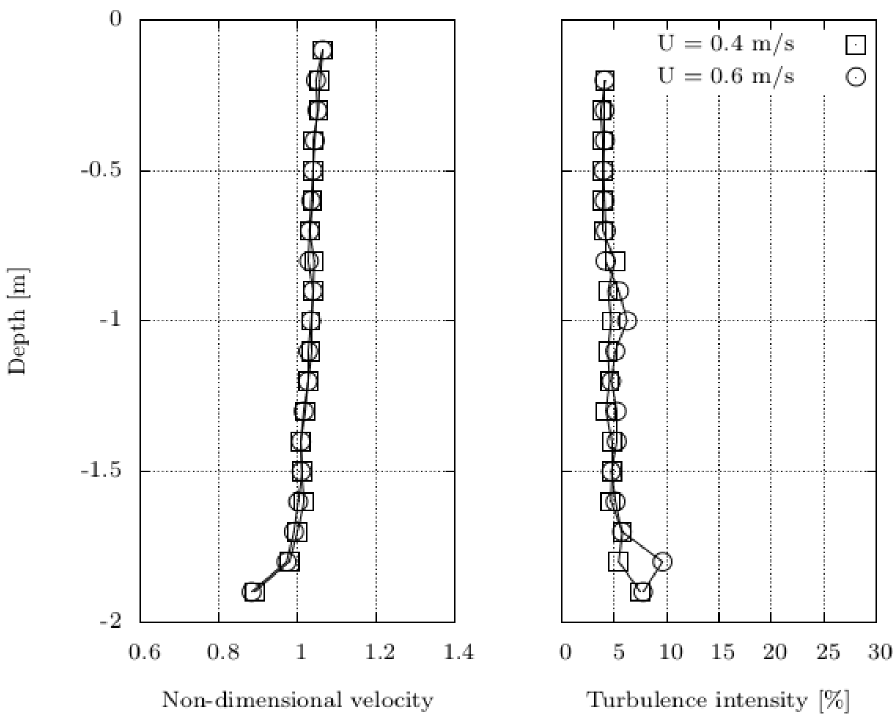


Figure 8: Example of vertical current and turbulence intensity profiles obtained from LDV measurements

These profiles can be modified in order to take into account some real site specificities. For example turbulence intensity can be adjusted to account for bathymetry or the influence of wave effects.

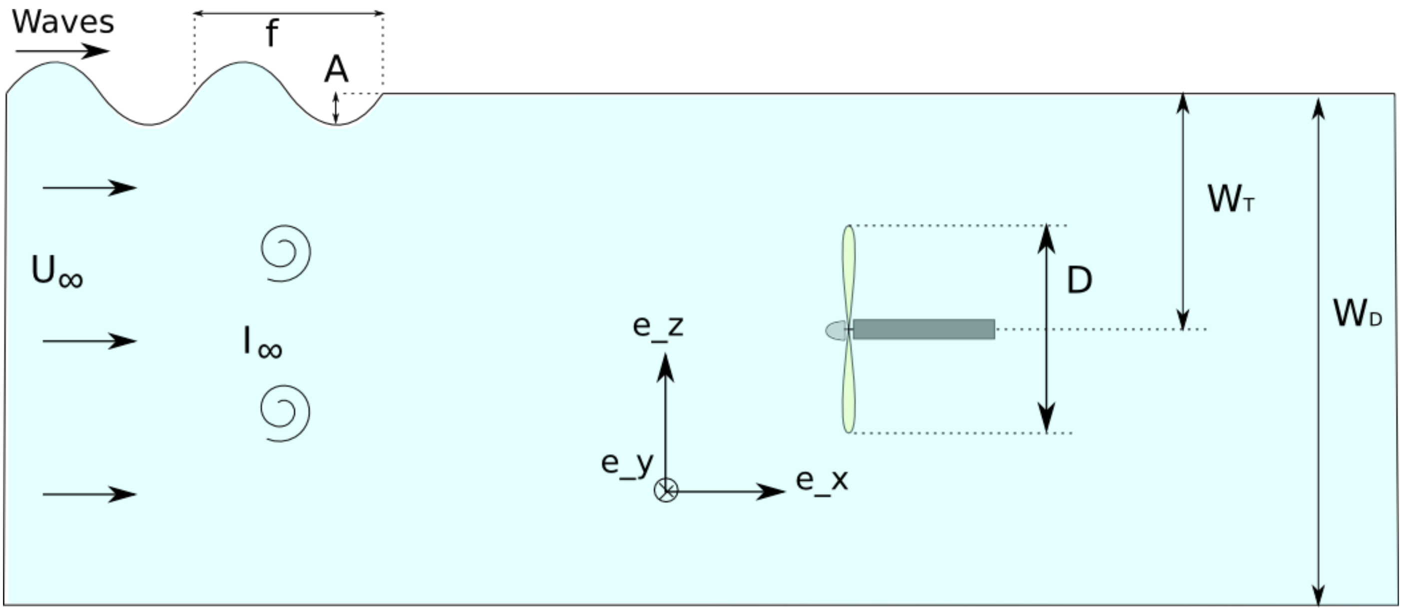


Figure 9: Schematic side view of a tank with an horizontal axis turbine

4.2 Scaling and blockage effects

To compare devices of identical shape and different scale, the tip-speed ratio is fundamental to ensure identity of kinematic conditions. Assuming the device is fully immersed, its performance is largely dependent on the Reynolds number. The Strouhal number is also important for the performance of oscillating foils. Finally, Froude number scaling is necessary when the device interacts with the free-surface. Once the scale ratio between full-size and model-scale device dimensions is fixed, it is generally impossible to achieve a correct similarity with respect to all the parameters above. Comparisons between flume tank trials and trials at sea at a scale close to one are not always accessible, even if existing.

Trials on a horizontal axis turbine at a 1/10 to 1/30 scale can be achieved by the use of a six-component load cell in order to measure the hydrodynamic forces acting on the system shown in Figure 9. The rotor can be connected to a motor-gearbox assembly constituted of gearbox, DC motor, ballast load and motor speed control unit providing active rotor speed control. A torque sensor can be directly fixed between the rotor and the motor to measure the torque as a function of the rotational speed. Friction from the seal between the rotor and the torque meter must be negligible. The pitch of the blades can also be adjustable but must be accurately controlled.

At small scale, the blade stiffness and surface roughness is very difficult to replicate and thus blade behaviour studies are difficult to carry out. At full scale sea water diffusion, ageing processes and high mechanical loads can result in very severe loading conditions.

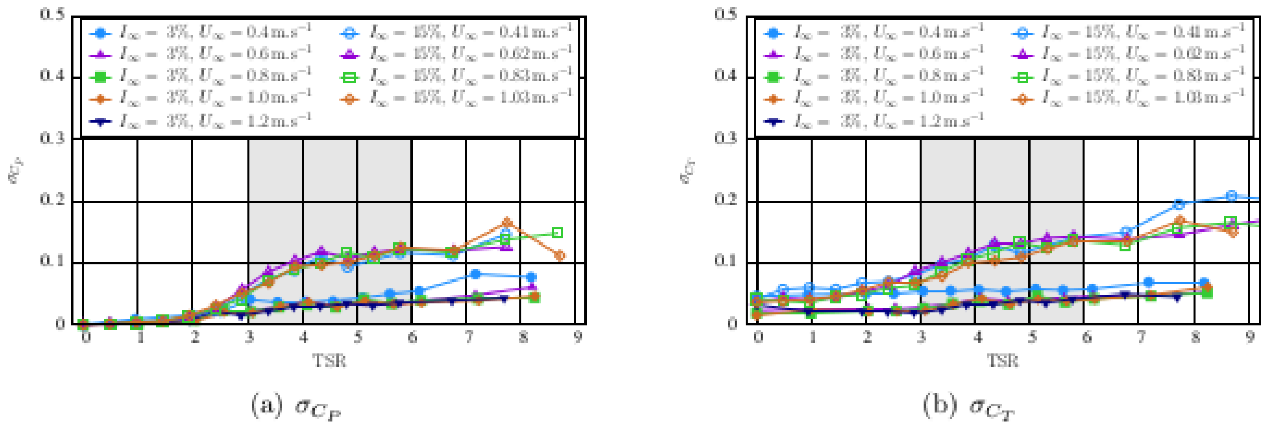
The concept of blockage is related to the fact that the model is tested in a confined flow. In flume tank, contraction effects can occur due to the interaction with side walls and the bottom. Free surface interactions can also modify the behaviour of the turbines, both in term of performance and wake expansion. A correct estimation of blockage is fundamental to determine the maximum dimensions of the model that can be tested in a facility. Simply speaking, the larger the model, the better is the reliability to predict the behaviour of the device at full scale but larger can be the potential source of additional errors associated with blockage effects. To mitigate against this, a blockage ratio less than 10% should generally be sought.

4.3 TURBULENCE AND NON-HOMOGENEITY

The turbulence intensity of the flow deeply influences the behaviour of a marine current turbine and also plays a major role in the interaction effects between two or more devices. The study presented in Mycek (2013) points out that, for a tri-bladed horizontal axis turbine, with conventional blade geometry, higher ambient turbulence intensity rates (15%) reduce the wake effects, and thus allows a better compromise between inter-device spacing and individual performance.

Although somewhat idealized with respect to real conditions, homogeneous isotropic turbulence (where turbulent features do not depend on both spatial position and direction) represents the appropriate framework to test the effect of changing the level of turbulence intensity and the length scale of the dominant flow structures. This is the simplest type of turbulence and can be characterized through the Reynolds number associated to the length scale of the largest turbulent eddies in the flow and the intensity of velocity fluctuations. In order to represent full scale conditions, both eddy size L and intensity of velocity fluctuations u' have to be scaled in order to preserve non-dimensional parameters involving model size and rotational speed. Ideally they should fit the turbulence characteristics of the chosen site.

Ambient turbulence intensity can influence the turbine behaviour, in terms of maximum retrieved power to a small extent. To a larger extent it impacts on force and torque fluctuations as shown in Figure 10 (Gaurier, 2012).



Standard deviation of the power C_P (left) and thrust C_T (right) coefficients, for $I_\infty = 3\%$ and 15%.

Figure 10: Variation of power and thrust for different turbulence levels

The ambient turbulence intensity also has a considerable influence on the turbine wake: the wake shape, length and strength largely depend on the upstream turbulence conditions. As shown in Figure 11, the higher the ambient turbulence I, the better the mixing and consequently, the shorter and weaker the wake influence.

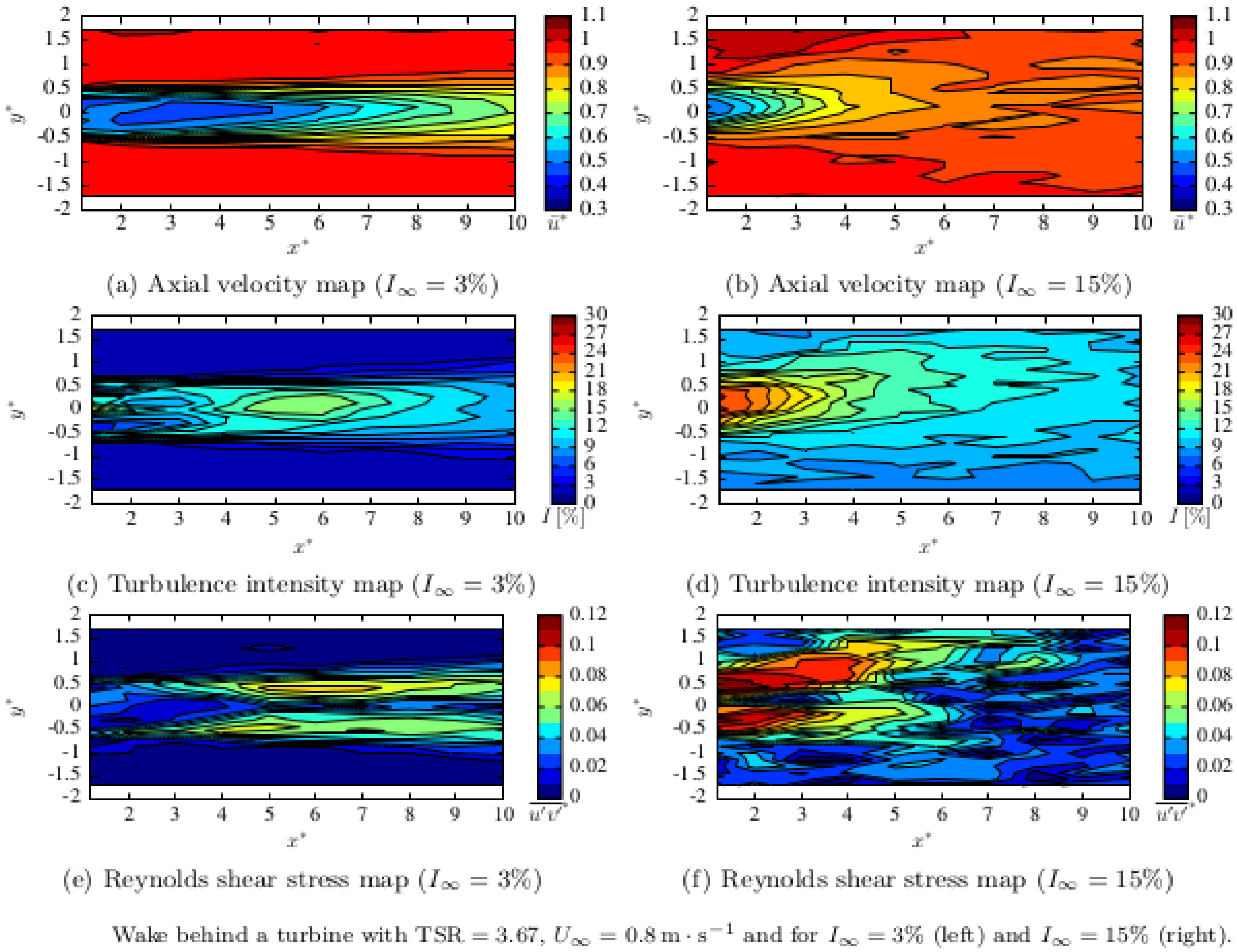


Figure 11 Wake behind a turbine for different levels of turbulence intensity.

4.4 WAVE/CURRENT INTERACTION

Research studies on the subject of wave/current interaction have demonstrated that the presence of current induces an increase in the steepness of an onset wave pattern. Thus, the combined effect of waves and currents can be focused on specific model tests. The test can be designed either focusing on the device survivability or on the effect on the power generated by the device. For example, in Mycek et al (2013) tests were performed on a 1/20 scale tidal turbine with strain gauge instrumented polymer blades. The test results under current alone compared to wave and current loading emphasize the strong influence of waves on the loading of turbine blades. The cyclic amplitude is directly related to wave conditions. These results indicate that in order to design blades it is not sufficient to consider only current loads, fatigue performance may be dominated by the wave contribution so detailed knowledge of both wave and current conditions is essential. The following figures give an example of vertical current and turbulence intensity profiles obtained from LDV measurements in the wave and current flume tank of Ifremer.

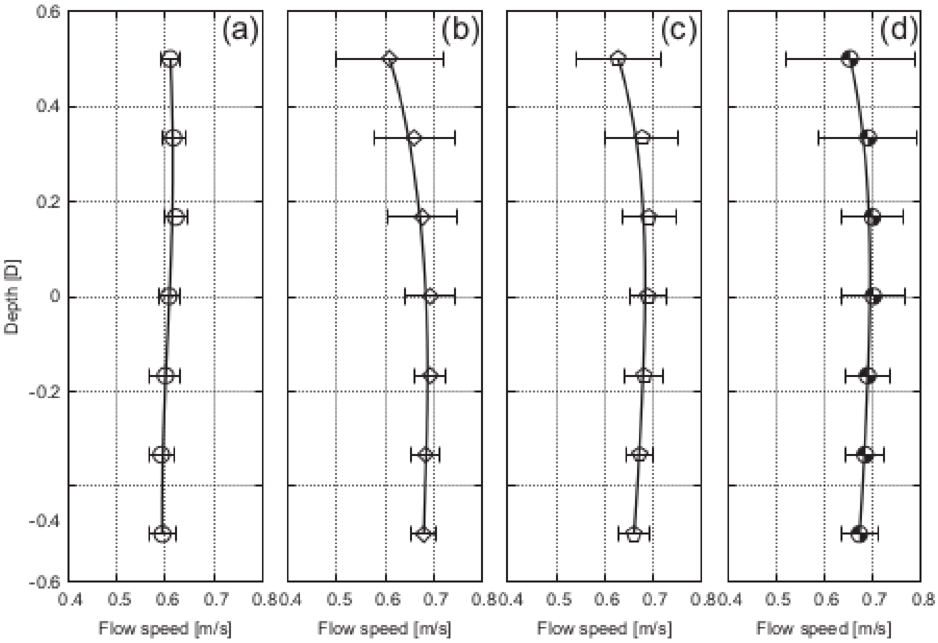


Figure 12: Example of current and combined wave-current profiles obtained from LDV measurements for several wave characteristics (0.5 to 0.7 Hz of frequency and 0.08 to 0.14 m of amplitude).

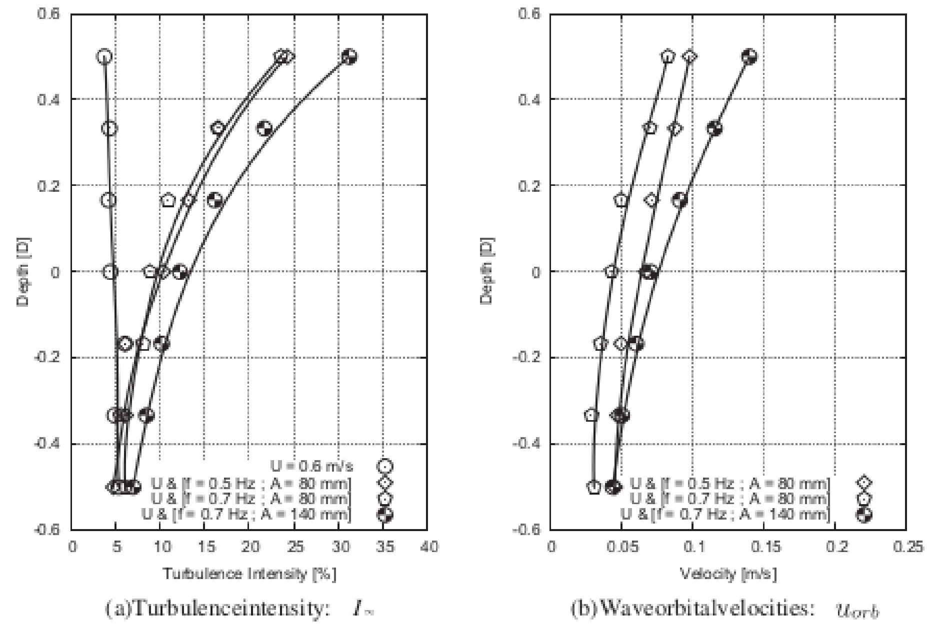


Figure 13: Example of turbulence intensity and wave orbital velocity profiles obtained from LDV measurements for several wave characteristics (0.5 to 0.7 Hz of frequency and 0.08 to 0.14 m of amplitude).

4.5 BATHYMETRY

In a flume tank, it is possible to simulate the main properties of a specific seabed like bathymetry and surface roughness. Particular attention should be paid to these site specific features in terms of their ability to generate turbulence and flow interactions emanating from the boundary layer. In many cases significant effort is required to characterise the flow before turbine trials.

5 SMALL SCALE FIELD TESTING EXPERIMENTS

Large scale model tests bridge the gap between small scale tank testing and full scale installations. Limitations of smaller scale laboratory testing have been discussed in section 2.1 and chapter 3 and 4**Error! Reference source not found.** Besides allowing for larger models and thus remedying some issues related to scaling, field testing in open waters resembles full scale installations and can be valuable to gain experience with offshore working conditions, without incurring the same cost.

Defining a best practice for this type of testing can only be preliminary, since very few tests have been performed and details published at this scale. Recommendations in this chapter are thus based on practical experience of a limited number of experiments and can be expected to change or be extended in the future as expertise develops. Because of the large scales, techniques for investigating the flow field are the same as for full scale tests. General recommendations for the application of these devices is given in the following chapter.

Two main methods can be identified, as in a towing tank a test rig can be moved in still water, or, as in a flume tank, the rig can be moored in a natural flow (river or tidal stream). Knowledge of classical laboratory testing techniques applies to these methods as well; the following section only highlights the additional requirements and possibilities of large scale field tests. Both testing methods require a test rig; recommendations for the design are presented in the following section.

5.1 TEST RIG DESIGN

Figure 14: Field testing rig used for still water towing and stationary testing. Source QUB.

1. In some cases a scale model of the original full-scale support structure can be employed, but usually auxiliary installations are required to carry the measurement equipment.
2. A catamaran is ideal for most cases, offering large working areas and allowing for the deployment of sensors at arbitrary positions in front and behind the tested device, which would usually be installed close to the middle of the rig.
3. Fitting two outboard engines at each hull improves manoeuvrability and course keeping abilities. In some cases low towing velocities are difficult to obtain since often outboard engines produce relatively large minimum power even at their lowest rpm. The installed engine power must of course be sufficient for safe navigation even in adverse weather conditions. If many tests are conducted at very low velocities an additional, dedicated propulsion system might be required.
4. In any experimental setup it must be assured, that the wake of the auxiliary structure does not interfere with the incoming velocities. A procedure to assess the wake is given in section 5.3.
5. A catamaran can provide a large working area with no or minimal wake around a device mounted in the middle.
6. The design of the test rig should allow the placement of measuring equipment at arbitrary positions. To place a probe below the water surface often requires long and slender support structures, which are prone to vibrate when water passes at higher velocities. The wake of these structures as well as the vibration of the

equipment can introduce errors. Kwon (2002) recommends some drag reducing shapes which can easily be added to a mounting pole and reduce vibrations.

7. For towing tests, Atcheson (2012) recommends to carefully isolate the engines from the main structure, for example by using rubber pads between the deck and catamaran hulls, to reduce vibrations.
8. Windage should be reduced to a minimum. In lake towing tests excessive windage can reduce the operational range of the rig by raising the minimum speed or affecting the ability to drive it straight along the track. In moored testing the rig might not align well to the incoming flow.
9. The test rig should be equipped with a cabin or similar sheltered area to protect data acquisition systems and connected computers as well as improving working conditions for crew members.
10. Performing tests with a classical hull shape is possible, for example by mounting a device at the bow of a boat (Schottel, 2013), but complicates measurements of the incoming flow and does not allow the assessment of the device's wake.

5.2 Still water towing experiments

In principle towing experiments in open waters are very similar to towing tank tests described in chapter 3. While environmental conditions in a laboratory can easily be controlled, tests in open water require monitoring and assessing these conditions. Wind can create unwanted surface currents; an anemometer should be used to investigate the influence of wind on localised velocities. Atcheson (2012) showed that wind of up to 8m/s can influence currents up to a depth of about 1.6m below the surface. It is thus recommended to test models in deeper layers of water, whenever feasible.

A site survey should be conducted to investigate the bathymetry and ambient current in the lake. Depending on the size of the model the blockage ratio should be assessed but in most cases the dimensions of the test rig will be very small compared to the cross section of the lake.

Even if the cross section is wide, analysis should be undertaken to ensure that the blockage of the turbine relative to the water depth is small or similar to the full scale application. The ambient currents are best assessed using bottom mounted sonar equipment over a few days or even weeks at different locations along the proposed track to capture the effect of changes in the environment. Taking the bathymetry, ambient wind and current direction into account, the track should be chosen according to the following criteria:

- It should be positioned over the deepest part of the lake
- The track should be oriented to align with the current direction

The speed of the rig is equal to the inflow velocity of the turbine; great care must thus be taken to control the thrust of the propulsion system. An independent speed log for the driver of the rig facilitates this work greatly but in most cases variations in rig speed are unavoidable and need to be accounted for in the post processing.

In many large-scale field towing tests the inflow can be expected to be homogenous and turbulence in still water can usually be assumed to be negligible, so a DADP is a good choice to measure the inflow profile. ADVs or similar should also be used to investigate the wake of the test rig or any auxiliary structures. It is recommended to map the flow close to any object that might interfere with the flow in the area of interest to establish the boundary of the undisturbed volume of water available for measurements on model devices. On a catamaran, comparisons between an ADV in the (undisturbed) centre-line and a second sensor off the centre-line are easily possible and should be used to ensure homogeneity over the test volume.

Sonar devices usually offer an option to measure directions relative to the sensors coordinate system. Care must be taken to align these devices carefully and the orientation should be recorded. Further guidance on the deployment of DADP's is given in chapter 6. Ideally the mounting mechanism of the sensors should allow independent adjustment of depth and orientation.

5.3 Stationary testing in natural currents

Experimental tests of scale models in natural flows at a fixed position are most similar to the final installation. All the measures detailed in section 5.1 equally apply to stationary tests.

Additionally, the test rig must be revised to ensure safe operation in often rough conditions. The mooring site must be carefully selected, taking into account

- Accessibility
- Current and wave conditions
- Suitability for mooring
- Licensing/Permissions

Before installing a test rig, a site survey including mapping of the bathymetry and currents should be performed. Since the velocity range available for testing cannot be influenced after installation of the test rig, the selection of the test site defines the success or failure of an experiment, and every effort should be made to assure that the required conditions are met during the time of testing. Tidal flows often show great variations in space and time, conditions might change significantly even in narrow channels, making this initial preparation work much more challenging than for towing tests.

The best way of positioning the test rig in the flow depends on many factors, so no general recommendation can be given. In many cases a mooring system might be the best choice but must be designed carefully, taking into account the loads of the rig and the, often more significant, drag of the turbine. Because of the variations in incoming flow and the reversing flow direction over a tidal cycle it is recommended to let the test rig free to align itself to the flow and thus guarantee an undisturbed inflow. ADVs should also be used to assess the turbulence levels in tidal streams, since they have considerable influence on structural loads and power output.

5.4 Scaling

As explained in detail in section 2.1, different scaling laws can be applied and the correct choice is not always trivial. If the device is tested far below the water surface and the Reynolds Number is significantly different from the full scale device, Reynolds scaling is more appropriate but may in practice be difficult to achieve. Since large scale field testing aims at testing relatively large model scales, Froude scaling might be applicable in most cases without incurring large errors due to incorrect Reynolds numbers. If the motion and wave resistance of an auxiliary structure is to be measured, Froude scaling must be applied.

6 FULL SCALE FIELD TESTING

The European Marine Energy Centre (EMEC) has developed a set of protocols that have been designed to provide a uniform methodology, and ensuring consistency and accuracy, in tidal measurement. Information in this section can be found in more detail in the “Assessment of Tidal Energy Resource” which is available from EMEC (EMEC, 2013). *Assessment of Tidal Energy Resource* has been submitted to the International Electrotechnical Commission (IEC) Technical Committee (TC) 114: (Marine energy – Wave and Tidal Energy Converters) as part of a suggested work programme, and formed the basis of the international Technical Specification IEC TS 62600-201 tidal energy resource characterization and assessment document, due for publication.

Figure 15: Full scale tidal test site at EMEC.(Aquatera, courtesy of EMEC)

Measurement best practice will be reliant upon the resource assessment stage with regards to full scale field testing EMEC has identified four main stages of assessment:

- stage 1 - site screening;
- stage 2a - pre-feasibility study;
- stage 2b– full-feasibility study; and
- stage 3 - design development.

Stage 1 is classed as resource assessment and stage 2 and 3 as site assessment. Best measurement practice for stages 2b, the latter stages of site feasibility and stage 3, where devices are likely to have been deployed are documented below.

6.1 CURRENT MEASUREMENT

6.1.1 Estimation of current speed

Relative to the stage of tidal development there are numerous methods available to estimate the velocity of the tidal current or current speed. The scale of the assessment will determine the method of estimation; this section will focus on pre-feasibility to the design development stage of resource assessment. Typical tools for best tidal measurement practice at these intermediate and advanced scale testing would be harmonic analysis, measurement extrapolation, modelling and field survey assessments.

The tidal height and tidal current characteristics at the site shall be identified and reported. As a minimum this should include graphs of typical daily, monthly and annual tide height, current speed and direction. These graphs may be generated directly from measured data or may be calculated from tidal height and current constituents derived from the data using harmonic analysis software, according to the stage of the investigation.

Existing long-term data sets and tidal constituent data maintained by the national hydrographic office or oceanographic data centre responsible for the region should be accessed. Tidal characteristics from all tidal height stations and tidal current stations in the area of interest shall be determined. Further tidal height data including tidal constituents may also be obtained from appropriate satellite databases. If additional location specific tidal height data is required, an appropriate survey should be conducted. These approaches to obtaining data require use of appropriate methodologies, and an appropriate assessment of the uncertainty in the data should be reported.

6.1.1.1 Harmonic analysis

Harmonic analysis separates observed tide or tidal currents into basic harmonic constituents by means of a mathematical process (NOAA, 2013). Harmonic analysis is based on the assumption that tidal variations can be represented by a finite number (N) of harmonic terms of the form:

$$V_j \cos(\sigma_j - g_j),$$
$$j = 1, 2, \ldots N$$

where V_j is amplitude, g_j is phase lag on the equilibrium tide at Greenwich and σ_j is an angular speed. Harmonic constituents are used to predict the tidal range and/or current at a chosen site over a specified period. In general tidal prediction accuracy increases with the number of constituents used. At the latter stages of resource assessment and design development harmonic analysis should be carried out for a minimum of 20 constituents, certainly including the 10 most significant constituents. Thirty days of current data (i.e. one month) usually allows for the extraction of at least 23 constituents. Harmonic analysis can be carried out using the *Matlab* based tools such as "t-tide" (Pawlowicz *et al.*, 2002) or "*UTide*" (Codiga, *et al.*, 2011).

Least-squares analysis and other mathematical procedures can be used to determine tidal constituents for a measured or modelled data set. Using industry standard software, time series of velocity at 10 minute intervals over the survey period will be predicted. Method validation can be carried out by means of comparison of predicted tidal range estimations and tidal range measurements from tidal gauges.

Harmonic analysis decomposes the observed time series for horizontal velocity into constituents of known frequency associated with lunar and solar periodicities. Each harmonic constituent has an associated amplitude and phase. There are not yet generally accepted standards for conducting harmonic analysis at tidal energy sites and, as observed by Godin (1983), prediction of currents is much less routine than prediction of tidal elevation. Two illustrative examples are given here.

First, if ebb and flood tides are asymmetric in intensity (as can result from local topographic/bathymetric influences), harmonic analysis will alias significant energy into integer multiples of the underlying constituent (conceptually similar result to the Gibbs phenomenon in Fourier analysis (Kreyszig, 1983), though by entirely different mechanisms). For the M2 constituent, this is not entirely problematic as integer multiples of M2 are included in standard harmonic analysis. However, the same cannot be said for other constituents, particularly compound tides (i.e., MK3).

Second, analysis can be conducted independently for the two components of horizontal velocity (i.e., north and east components), jointly using complex analysis, or jointly using horizontal velocity (i.e., ebb and flood velocity magnitude signed negative and positive). The accuracy with which these options represent the tidal currents may be site specific and no peer-reviewed analysis has yet been conducted to identify a preferred approach.

These uncertainties do not preclude harmonic analysis as a useful tool, but do lead to some ambiguity in the interpretation of the results. The accuracy with which the harmonic constituents represent the underlying measurements should be quantified and reported (e.g., percentage of variance explained, "goodness of fit"). The resulting constituent amplitudes and phases may then be used to make a time series prediction of currents over a full calendar year. While there will be variations in the velocity distribution between calendar years (i.e., nodal corrections for long-term periodicities over the 18.6 year tidal epoch), these are likely to be on the same order as the uncertainties in harmonic analysis. Consequently, at this time, it is recommended to use a mean year prediction with the nodal factor closest to one. Some good years include 2001, 2011, 2020 (Zervas, 1999). The calendar year time series may then be subjected to histogram analysis in order to develop a probability distribution of velocity for estimation of the annual energy production (AEP).

6.1.1.2 Measurement Extrapolation

An alternative to harmonic analysis is direct extrapolation of measurements, as informed by harmonic periodicities. This results in a probability distribution that is subject to some uncertainty, but perhaps, not worse than the uncertainties associated with direct harmonic analysis. However, the statistical model will fail to mimic long term variations such as the 18.6 year epoch.

For direct extrapolation of measurements, a procedure for developing a probability distribution is applied to the measurement time series (either hub height or area-weighted). Since this distribution is based on observations which include an incomplete number of periodic cycles (e.g., neap-spring, apogean-perigean), the resulting distribution may deviate from the distribution that would be obtained by observing currents over the entire 18.6 year epoch.

Observations should be at least 30 days in length to avoid significant errors, while longer observations would further reduce uncertainty. While this method does carry some uncertainty, it overcomes the limits of harmonic predictions with respect to ebb/flood asymmetries and topographic/bathymetric influence that are unlikely to be accurately reproduced by harmonic constituents.

Polagye and Thomson (2013) evaluates the time for various resource metrics to converge to their expected value if averaged over the tidal epoch. This is done through a prediction of current velocity over the tidal epoch from harmonic analysis of a 1-year observation of currents at a tidal energy site (Admiralty Inlet, USA). It is assumed that the topographic and bathymetric distortions of these currents that are not well-described by traditional harmonic constituents will follow the same convergence pattern (i.e., they are a response to harmonic currents). Various metrics are calculated from the epoch time series. The epoch time series is then broken down into 190 day observations, the starting point of each staggered forward in time by 20 days (no beating of harmonics at this fundamental frequency). In Polagye and Thomson (2013), mean DADP data is shown to converge to within 5% of the epoch mean for observations of at least 30 days or greater than 70 days. This is driven by the fundamental neap-spring periodicity common to all tidal energy sites.

6.1.1.3 Modelling

The measurements discussed in Section 6.2.1 provide a good measurement of waterlevel and currents but these are limited as they are point measurements and depend upon the instrument location and the length of the survey. Modelling provides means to obtain information in space and time provided there is knowledge of the local bathymetry. Reliability of model data directly correlates with the quality of the bathymetry data and boundary conditions. Real point measurements of tidal current and metocean conditions, such as wind and pressure, are necessary for calibration and validation of the numerical model (Ingram et al.,2011). Table 5.1 shows a non-exhaustive list of available hydrodynamic models.

Models	Dimensions	Grid Structure	Models	Dimensions	Grid Structure
ADCIRC	2D/3D	unstructured	Mike Models (11,21,3)	1D/2D/3D	Structured/unstructured curvilinear
ADH	1D/2D/3D	structured	RICOM	2D/3D	unstructured
CH2D/CH3D	2D/3D	Structured (curvilinear)	RMA Models (2,10,11)	2D/3D	unstructured
DELFT	2D/3D	Structured (curvilinear, rectilinear and spherical)	ROMS	2D/3D	Curvilinear structured
DIVAST	2D	Structured	SELFE	3D	unstructured
ELCIRC	3D	Unstructured, flexible	SUNTANS	2D/3D	unstructured
ELCOM	3D	Structured (orthogonal)	TELEMAC	2D/3D	structured
GEMSS	1D/2D/3D		TFD	1D/2D/3D	structured
GETM	3D	Structured (orthogonal curvilinear)	TRIM	2D/3D	structured
HRCS	2D/3D		UnTRIM	2D/3D	unstructured
Mars	2D/3D	structured	POM	2D/3D	structured

Table 5.1 Hydrodynamic models

Model resolution during stage 2b and 3 (see section 6) should be as high as practicably possible. The area of the model should be sufficient in coverage to include all important hydrodynamic effects and be inclusive in that calibration and validation of tidal range and/or currents is possible. This will take into account area, bathymetry available, computing time, computing costs and cost compared with other methods of data collection such as field surveys. Fine grid resolution should be of the order of 50m or better where error in peak and average velocities is expected to be below 10%. The model should be run for a minimum period of 30 days, preferably 3 months, from which annual datasets may be extrapolated. Modelled monthly velocity data may be validated against field survey data as discussed in Section 6.2.1, validation is essential for tidal measurement best practice. Two dimensional models will be sufficient at stage 2 but vertical velocities should be taken into account at stage 3; 1m bins are recommended.

Using a numerical model to generate estimations of tidal conditions is a valuable tool in the evaluation of tidal resource but there are limitations that need to be considered. 2 dimensional models which provide barotrope currents cannot accurately represent surface or bottom currents and models can suffer from interference from natural phenomena, for example strong atmospheric forcing conditions that lead to storm surges or experience influence from wave and wind. All aspects should be evaluated and depending on the application results should be used with caution. Any 3D phenomena, such as thermal stratifications, that may have an effect in identified areas should be impact assessed and tidal influences should be identified by means of harmonic analysis before modelling is commenced. Local point measurements can be instrumental in analysing 3D model results where potential influencing factors have been identified (Ingram et al., 2011,p26).

6.2 Application of Acoustic Doppler devices

Two different types of sonar devices have been developed to measure flow velocities and can be bought from several suppliers: Divergent-beam Acoustic Doppler Profilers (DADP) and Acoustic Doppler Velocimetry (ADV) sensors. While DADP's provide averaged data for many locations, for example the velocity profile over the depth, ADVs provide data at one position but with high temporal resolution and are suitable to assess levels of turbulence. Algorithms have been devised to assess the level of turbulence from DADP data, but the application of these methods is limited by several conditions and not widely used (Lu ,1999),(Thomson,2012) and (Richard ,2013).

Both devices rely on seeds in the water to function well; very clear water might cause issues and require the addition of seeds to the inflow. In general this is however not an issue in natural water bodies. Both devices can be deployed at a fixed position, for example fixed to the bottom to measure the current over a long period of time at one site, or on a moving vessel, for example to survey the spatial variation in an area.

DADP's can usually be configured to provide velocity data in several bins over a defined depth. More bins, that is a better resolution of the velocity profile over the depth, leads to a decrease of the signal to noise ratio. The user must weigh his requirements to find the ideal settings for his application and conditions.
Some DADP's can also measure the wave condition, but during the measurement of the wave conditions (several minutes) no current measurement may be performed. In many cases it seems sufficient to monitor wave conditions once per hour, but it is difficult to give general advice.

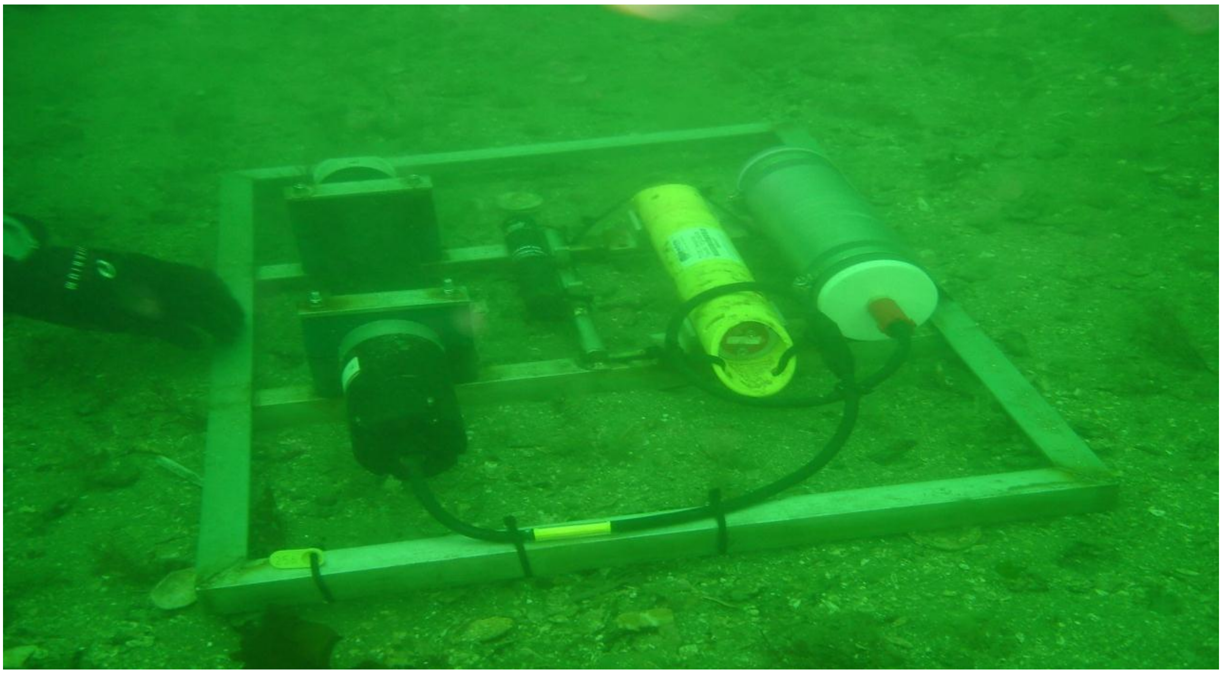


Figure 16: DADP with battery pack and Sonardyne transponder mounted on frame deployed on seafloor.(Courtesy of D. Pritchard, QUB.)

The following list contains general advice on the use of this type of equipment; more detailed explanations for specific applications are given in the following sections.

- A major source of error in relation to current direction is the magnetic compass in the DADP, used to reference the direction of the flow velocity to earth coordinates. The first source of error is missing or inadequate compensation for the surrounding metal structures, like the deployment frame or vessel structure, which can render heading information useless.
- Variations in the magnetic heading from true north can be significant and many engineers might not be familiar with the relevant corrections that have to be applied.
- DADP's are also usually equipped with roll and tilt sensors. Especially in bottom mounted DADP's, the information from these sensors can be helpful to establish whether the device moved during deployment, in which case the data is probably severely corrupted.
- The exact position of the DADP is always crucial, as mentioned before, within a distance of 10m velocities might vary significantly, (Kutney *et. al,* 2013).
- For a bottom mounted device, deployment position can often only be checked if the device is deployed directly below the boat, depending on the water depth significant errors can be introduced at this stage.
- The exact position of the boat is best established with the help of differential GPS, but then the exact position of the GPS antenna on the boat should also be recorded. Post processing of the data can be simplified somewhat if the GPS antenna is mounted directly on top of the DADP.
- Another common cause of measurement errors is the choice of the appropriate coordinate system like for example WGS84 or local coordinate systems, and the conversions between these.

- A simple way to control the accuracy of the GPS measurements is to record the same fixed position several times and compare the resulting position. For example, on a vessel mounted survey, the position of the boat fixed to the jetty could be recorded at each departure and return.
- The setup file and all post processing settings, data filters or similar should always be made available together with the data, to allow any end user to review and control all stages of processing.
- Deploying DADP's in floating torpedoes connected to acoustic release systems and sacrificial weights can save diving time. Experience has shown that the strong currents force the float to move excessively which pollutes the data.

6.2.1 Field survey

As mentioned in Section 5.1.1.2 point measurements are vital in the measurement of tidal conditions. They provide a measurement in a given location over a specified survey period and can be used to calibrate and validate tidal models.

For full scale tidal measurements, survey periods of at least 1 month are required but three months is the preferable deployment length for tidal measurement instruments to record during the latter resource assessment phase and design phase of developer deployments of Tidal Energy Converters (TEC). Measurement techniques will vary dependent on resource, vessel availability, meteorological conditions and the presence of TEC. Unless a "point measurement" technique such as current meter is clearly sufficient, transect or static tidal measurement surveys will be carried out using (acoustic) current profile measurement devices.

Calibration of tidal measurement instruments must be carried out or obtained by any organisation that wants to comply with requirements of ISO/IEC 17025:2005. Where current profilers can be calibrated a calibration certificate must be provided, otherwise a certificate of conformity is required with evidence to suggest tidal measurement device(s) to be used are in serviceable state before deployment.

Any pressure gauge equipment should also have a calibration certificate. Where it can be avoided redeployment should not be carried out during a test period. If it is deemed necessary the current profiler must be redeployed in the same location, most preferably leaving the seabed frame in place removing only the tidal measurement device (IEC, 2013).

Transect surveys are carried out towing a vessel mounted acoustic instrument to measure currents under a moving vessel. Preferably they should be carried out during a typical spring tidal cycle; although this can be limited by boat availability and meteorological conditions. Such surveys provide an estimation of the spatial variation in the velocity distribution of the survey site as well as providing an indication of tidal turbulence and flow reversals or discontinuities arising in the survey area (Legrand, 2009).

Transect surveys should be processed into suitable vertical and horizontal bins, for example 1m vertical bins and 25-50m horizontal bins. The ideal sampling frequency is at least 1Hz with the first bins within 5m of the sea surface. Transect surveys can show a bias in measured water velocities with the direction of vessel motion of up ± 5cm/s and have vertical variability. To compensate for this bias transects should be measured in both directions over a relatively short time interval of <10min with an average of the two transects calculated.
Typical Transect Survey output data should comprise:

- Time (UTC), year, month, day, h, min, s
- Location (lat long WGS84)
- Velocities in 3 directions
- St dev in 3 directions
- Temperature
- Pressure
- Cell start depth and cell stop depth
- Average velocity with direction

- Quality indicators and confidence levels for the horizontal positioning of the vessel

Transect surveys can be limited due to stormy weather conditions, limited analysis potential and measurement of tidal conditions that represent a typical annual cycle. Usually a static survey is preferable to a transect survey. The tidal measurement device is deployed on or near the seabed in an upward facing position. Measurement devices may also be moored closer to the sea surface on tethered buoys (Teledyne, 2009). Location of the static survey will be dependent upon agreeable bathymetry and the presence of TEC. The sampling frequency should be at least 1 Hz. Survey periods of a minimum of 30 days are needed but 3 months is recommended. The device to be utilised should be able to record the temporal variation in tidal velocity, in three orthogonal components, vertically throughout the water column (IEC, 2013).

Measurement bins should be spaced between 0.5m and 2m, preferably at 1m intervals, this should be sufficient to resolve the variation in current speed. The data collection period should be 2 to 10 minutes recording three current direction (*u,v,w*) and depth (*z*) in each bin for each time interval. The standard deviation in the velocity measurements should not exceed 5cm/s and 5° for current direction measurement (IEC, 2013: p27).

If tidal measurement is to be carried out in the presence of a TEC the tidal measurement instruments should be positioned to capture the ambient current behaviour but without the influence of the current by the TEC. They should also be sufficiently close that they provide an accurate representation of a tidal current measurement of the local tidal regime within ± 10% of the water depth relative to a known chart datum (IEC, 2013:p21). Placement of the tidal measurement instruments should be either in-line with or adjacent to the TEC. The placement should minimise the influence of blockage effects, horizontal shear and variations in bathymetry. Two tidal measurement instruments are preferable to one in this case in case one of the devices is damaged; they can also provide two datasets for comparison (IEC, 2013: p28).

When carrying out tidal measurements using the in-line formation, (see Figure 18), measurement instrumentation should be deployed in-line with the TEC one upstream of the TEC extraction plane on the flood tide and the other upstream on the ebb tide. The measurement instrumentation should be between 2 and 5 equivalent diameters between the outermost edge of the measurement volume from the tidal measurement instrument and the projected area of the TEC extraction plane. If the adjacent formation has to be deployed (see Figure 19) the two measurement instruments should be placed adjacent to the TEC, one starboard and one port of the TEC extraction plane. Measurement instrumentation should be between 1 and 2 equivalent diameters to lateral extent of the TEC extraction plane. For floating point TEC technology a current profiler may be mounted on the TEC using the in-line or adjacent technique; bottom mounted measurement instrumentation in ebb and flood tides can be position within aforementioned diameters; if none of these methods are suitable an array of bottom mounted current profilers can be deployed in conjunction with the development of a justifiable correction methodology for example the site performance of a site calibration (IEC, 2013: p21).

If deviation from the tidal measurement best practice guidelines is required, details of such deviation should be documented, justified and reported as necessary during the data analysis phase.

The results from any transect field survey, for tidal range and/or tidal velocities shall include the following information for each site location:

- Location of the survey (given in a coordinate system consistent with the bathymetry data in Section 6.3.1), with exact coordinates of transect lines;
- Exact date and period of survey, with time along each transect;
- Maximum currents observed;
- All images (e.g., contour plots etc.) should be presented with a consistent reference abscissa (e.g., plotted West to East on the x-axis).
- Details of any problems or issues arising during the survey. Any manipulation of DADP output data shall be reported and justified.
- An assessment of the overall quality of data collected should be conducted. The percentage of data that has been found to be good quality should be calculated. Data that is believed to be erroneous shall be

highlighted, and for purposes of further data manipulation, can be removed from the record. All Quality Assurance / Quality Control practices applied to the data sets must be noted.

6.2.2 Correcting for Clock Drift

Internal clocks for different pieces of instrumentation may drift over the course of a deployment. This complicates the process of data assimilation, as two measurements with the same time stamp may not be sampling the same event. While the use of a centralized controller with a single clock simplifies assimilation, it also introduces a single point of failure into an instrumentation package, which may be undesirable. Assuming that clock drift is linear over the deployment, time stamps should be corrected through the following procedure:

- Configure and deploy instrument from a computer with a clock recently synchronized with an NTP source.
- Upon instrument recovery, compare instrument clock with NTP source.
- Compute difference between instrument and NTP and correct instrument time stamps, assuming a linear drift.
- If the clock drift is relatively minor in comparison to the phenomena of interest, it may be possible to neglect it without effect.

6.2.3 Depth Quality Control

Most DADP's include a pressure sensor to simultaneously acquire the depth of water column while performing a velocity measurement. Depth quality control is performed by correcting for an abrupt change in depth. The difference in the depth for consecutive measurements shall be calculated, and if this difference is greater than the specified threshold value, it shall be replaced with a mean depth value of the previous and next measurements.

6.2.4 Side Lobe Interference

Acoustically solid boundaries (hard substrate, water surface) contaminate adjacent bins as side lobe reflection from the solid boundary obscures returns from sound scatters for the primary beam. The zone of expected contamination is given by:

$$D = H(1 - \cos\phi),$$

where H is the water depth (m), ϕ is the beam angle relative to vertical (deg). In practice, this zone may be somewhat larger or smaller and should be visually identified in a time series by spuriously high velocities or spurious directional shifts, as shown in Figure 17. Another common source of bias relative to measurement volume size and proximity to a surface is the impact of the spatial scale of the flow gradient relative to the measurement volume size. It is a common practice to bury a part of the sampling volume in the bed floor or surface with the intent of obtaining a velocity measurement as close to the surface as possible. While this practice can increase noise, it can also bias the velocity statistics through the alteration of the velocity ensemble.

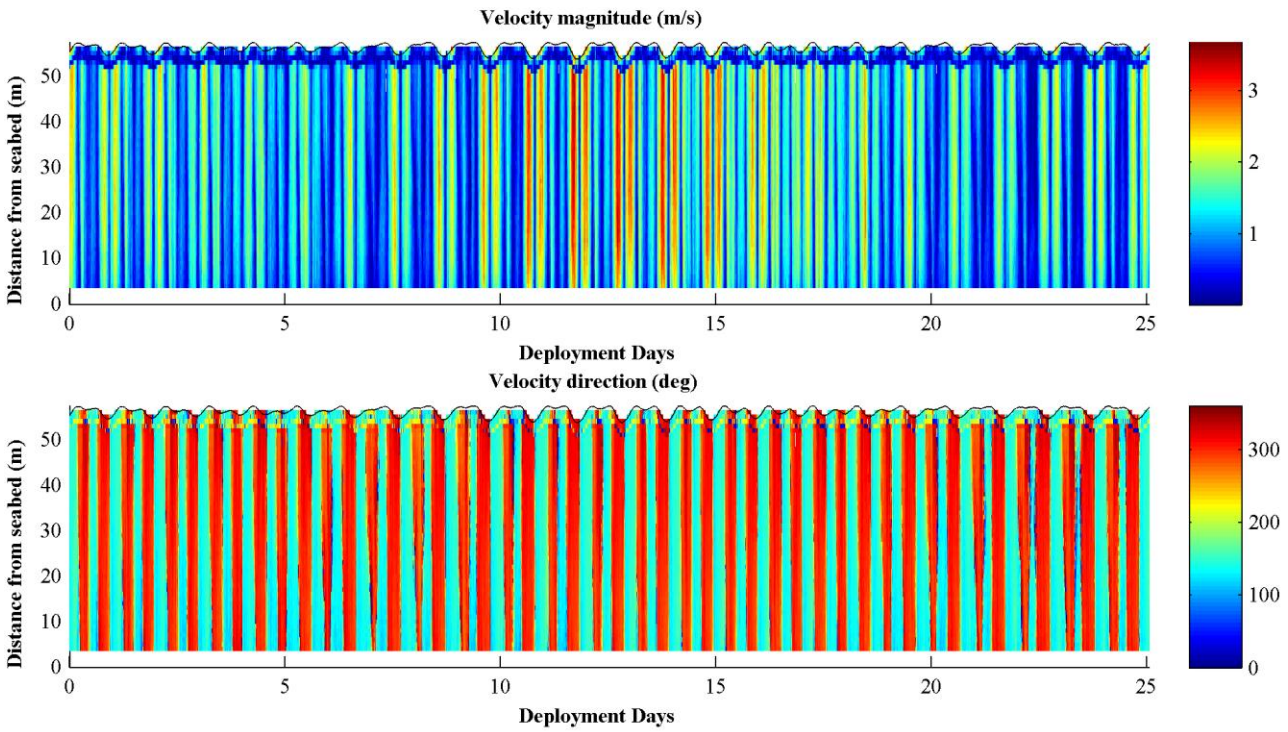


Figure 17 Contamination of horizontal current velocity within 4m of the free surface for a bottom mounted DADP (Neary et al.2011).)

6.2.5 Velocity Quality Control

The histogram of the velocity data measured can be used for quality control. It is generally expected that the histogram will resemble a near Gaussian distribution. Two major peaks with a sudden cut off in the histogram could be an indication of velocity ambiguity problem, which can generally be avoided by increasing the user defined velocity range until the histogram follows the near Gaussian distribution. Whereas spikes in velocity measurements cannot be avoided, they should be removed or replaced with representative values. For this purpose, the differences between the velocities from consecutive measurements in a burst for all the corresponding bins shall be calculated. If these differences are higher than the specified threshold value, they shall be removed/replaced.

The threshold values for quality control depend on test conditions, experimental setup and quality of data, and often need to be defined manually. One of the methods to detect and replace spikes is the Phase-Space Thresholding (PST) technique (Goring and Nikora, 2002), which does not need the user to define the threshold, considered as an advantage from a practical point of view. The PST algorithm employs a three-dimensional Poincaré map (phase-space plot) in which the fluctuating component of a time series and its first and second time derivatives are plotted against each other. Calculation of the standard deviations of the variables in each dimension and the rotation angle of the principal axis are used to construct an ellipsoid, which denotes the boundary of the Universal criterion. Any points lying outside of this ellipsoid are designated as spikes and are removed and replaced. This step iterates until no more point lies outside of the ellipsoid. Other methods that are often used include the modified PST method (Parsheh et al. 2010) and spectral noise filtering (Goring and Nikora, 1998),(Garcia et al., 2005),(Thomson et al. 2010) for turbulence intensity. Details on quality assurance and quality control protocols, including the PST method are described by Gunawan et al. (2011) and Gunawan and Neary (2011).

6.2.6 Current Profile

The current profile is the variation in velocity throughout the water column which is typically displayed as a function of height above the sea bed (IEC, 2011). This can be measured using the Doppler current profiler acoustic tidal measurement device as described in section 6.2.6.

6.2.7 Tidal Fluctuations

Tidal turbulence is the fluctuation of the flow velocity in a tidally induced current (IEC, 201: p19).Tidal fluctuations refer to spectrally resolved tidal harmonics. Current techniques are not adequate in providing an accurate measurement of tidal turbulence.

6.2.8 Directionality

Directionality of tidal flow has implications on the design development phase with implications on turbine performance, capacity factor and structural loading (Harding and Bryden, 2011). Principal directions can be extracted from tidal directions as recorded by methods mentioned in section 6.2.

6.3 Site conditions

The primary focus of tidal measurement is current velocity estimation and the associated immediate influencing factors as mentioned in the section above. However site conditions can prevent tidal measurement surveys as well as affect the longevity of the survey and the survivability of the tidal measurement equipment. The sections below provide details of the factors, other than those already discussed, that should be taken into consideration regarding tidal measurement best practice.

6.3.1 Bathymetry

Bathymetry is an influencing factor on the characteristics of tidal flow. In addition to tidal characteristics, depth and the characterisation of the seabed (sediment, texture and morphology) (Crown, 2013) are analysed to determine where TECs and TEC arrays are situated. There are a range of techniques that can be used to assess bathymetry such as acoustic surveys, side-scan and multi-beam sonar, video cameras and geographical information systems (Crown, 2013). A summary of topographic flow characteristics should be produced to ascertain sufficient flow homogeneity at a chosen location.

The *IHO Standards for Hydrographic Surveys* (2008) documents the minimum required standard to be achieved when carrying out benthic surveys. Particular attention should be paid to *Special Order surveys* that should be carried out in areas where water depth is no greater that 40m recommended for berthing areas, harbours or critical shipping channels. *Order 1a surveys* may be limited to areas between 40m and 100m where larger or man-made features may be of concern to shipping (IHO, 2013).

The bathymetric data already available shall be reviewed, e.g. contact with the oceanographic centres responsible for the region concerned is recommended. If existing data is to be used, then the collection techniques for the original data and their appropriateness shall be reviewed, e.g. by comparison to modern techniques. Such data should be used with an element of caution. If a bathymetric survey is required to complement and expand the available existing data in the specific region of interest, the survey should be conducted in accordance with the IHO Standards for Hydrographic Surveys (2008). Reporting of bathymetric survey activities shall be completed to the standard of the ICES Guidelines for Multibeam Echosounder Data (2006).

A map of all the surveys that have been undertaken and for which data is available, should be provided. The following information should be provided for each survey:

- Date of survey;
- Survey methods used;
- Accuracy of various parameters;
- Coordinate system and transformation used to convert to/from WGS84 for later use;
- Chart/tidal datum applied;
- Availability of data in electronic form.

There is no accepted world standard definition of tidal datum or chart datum used for navigation charts and tidal height graphs. Many nations have developed their own definitions. It is particularly important for numerical modelling purposes to have bathymetric depths referenced to a fixed geodetically determined datum, which can be referenced to true local mean sea level. Tidal or chart datum used on all worldwide navigation charts is not a fixed datum but changes as tidal range changes.

6.3.2 Tidal Range

Data should be collected from the two closest tidal gauges in opposing directions from the area of interest. Profile plots should be create for annual, monthly and daily profiles, this data can be collected using associated admiralty prediction software. Tidal range should be provided derived from each of the survey methods over a specific period; this can be compared with previous or other related work (Legrand, 2009: p 31).

An example from EMECs Fall of Warness test site has been included showing a semi-diurnal tide (see Figure 20). Further information can be obtained from the UK 'Class A' tidal gauge network , held by the National Oceanography Centre (NOC, 2013).

6.3.3 Meteorological and Metocean conditions

Results obtained from harmonic analysis describe the predicted tidal currents during the survey period without consideration of meteorological effects. Results may be compared with actual field recorded measurements to estimate the influence of effects such as wind, wave and surge, and any other interactions on the tidal current (Legrand, 2009: p 38). In certain circumstances tidal currents are affected by wave-induced phenomena such as stokes drift arising from surface waves of long or moderate period and of sufficient amplitude to penetrate to various levels of water column. In tidal assessment survey areas containing TECs, where wave-current interaction has been cited, installation of wave sentry devices should be considered and data recorded at same time intervals as tidal measurements (Swift, 2009:p 5).

Meteorological data to be used for determining the importance of the wind and atmospheric pressure shall be identified and reviewed. The relevant data includes the wind and the atmospheric pressure. The locations, period of record and an assessment of the quality of the data shall be reported. In the absence of sufficient measurement data, an alternative is to obtain data from combined numerical models with processed satellite derived wind data.

The influence of local wind conditions on the results of numerical modelling simulations of periods coincident with the field data should be assessed by including a generic representative set of wind velocities (e.g. utilising satellite re-analysis wind data coincident with the model simulation time period). The model simulation results including wind forcing should be compared with model simulation results obtained without including wind forcing.
Note: The wind data record may assist in assessing the source of unresolved variability or persistent residual errors observed in numerical model simulations when compared with field data. If required, measurements should be undertaken following the methodology described in IEC 61400-12-1

The variation of atmospheric pressure should be recorded during any field data collection using appropriate means (e.g. a barometric pressure sensor and data-logger). This information may be necessary to account for meteorological atmospheric pressure variations impacting on the resource (e.g. in extreme cases, storm surge).

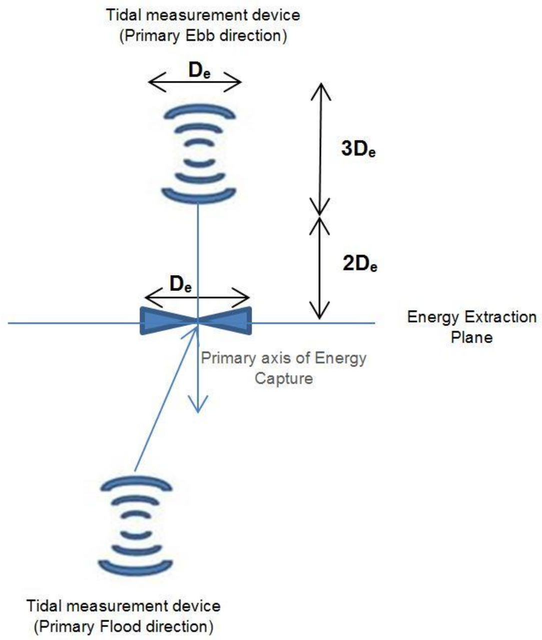


Figure 18: Plan view of in-line orientation for current profiler (After: IEC)

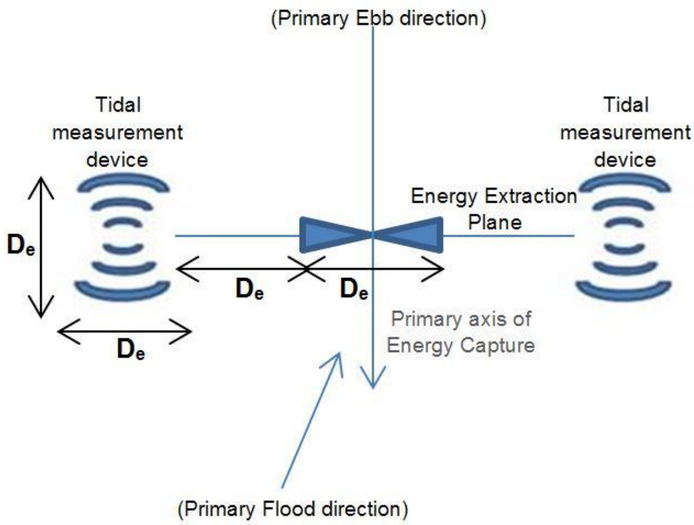


Figure 19: Plan view of adjacent orientation for current profiler (After: IEC)

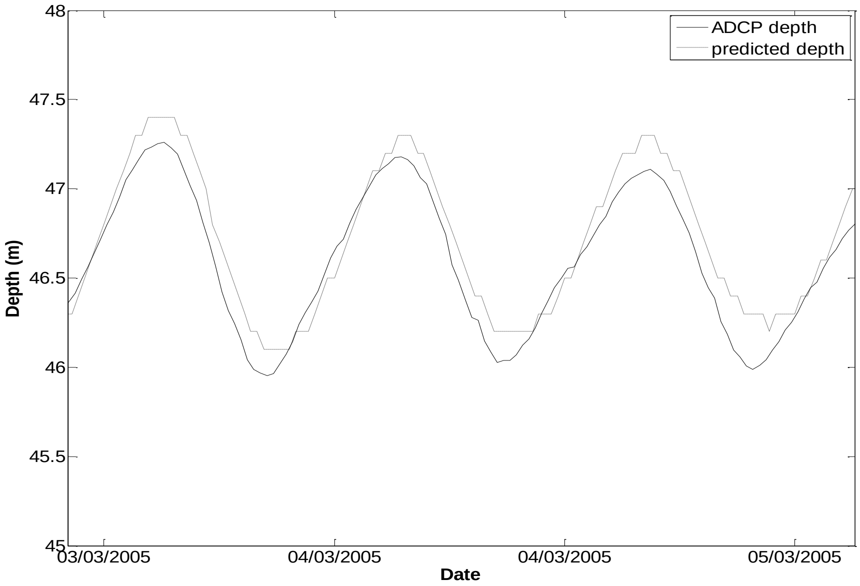


Figure 20: Tidal range showing measured and predicted values at EMEC.

6.3.4 Wave Climate

Existing wave data at the location of interest shall be reviewed. If sufficient information is already available at a specific location, there might not be a need for further measurements. If the area of interest is not exposed to swell waves, or it is considered that the wave climate can be modelled using appropriate long term wind datasets, there might be no requirement for a wave monitoring survey, but the decision shall be explained and an assessment of the wave characteristics detailed.

The recommended approach for gathering wave related data is to use a waves-enabled DADP unit. The validity and source of all wave data shall be verified and provided

6.3.5 Flow structure/Eddies/Turbulence

Tidal eddies, flow structure and turbulence may have a potential impact on both the design of a TEC and the long term tidal energy resource. Navigation charts should be consulted in detail. However, in many cases charts include very limited information on eddies. For the Stage 2B and 3 resource assessments, it is strongly recommended that detailed hydrodynamic modelling (at least 2D) should be validated with the mobile DADP data with respect to eddy formations

Eddies are ubiquitous in strong tidal flows. They have been observed in Pentland Firth (Scotland), Minas Passage (Nova Scotia, Canada), Discovery Passage (British Columbia, Canada) and Cook Strait (New Zealand). Large scale tidal eddies are usually referred to as “separation” eddies caused by flow impinging on a headland or island. The eddy forms in the lee of the headland or island. Multiple counter rotating eddies, of different sizes, may exist in the same location and the location of eddies is usually different in the flood and ebb current directions. Where eddies exist, flood and ebb currents, at a specific location, may be very different in magnitude.

Large scale, low frequency tidal eddies are an important factor determining the magnitude of small scale high frequency turbulences. Eddies and turbulence form a continuum of scale and frequency with eddies at the largest length scales and turbulence the smallest length scales. This continuum is best thought of as “overall current variability” because the important scales or frequencies for TEC design or tidal resource depend on the scale of the tidal system and size of the TEC device.

It is not currently known what scale, frequency and magnitude of current variability (resulting from eddies/turbulence) are important, nor are the limits of hydrodynamic (tidal) and CFD modelling used for turbine design known. This is a subject of ongoing research.

Alternative remote sensing techniques such as Synthetic Aperture Radar (SAR) have shown some promise in estimating surface current velocities and flow structure. SAR or other appropriate techniques should be considered as a method for identifying eddies during Stages 2B and 3 and may allow verification of detailed modelling studies.

6.3.6 Stratification, Seawater Density and Sediment Measurement

The international thermodynamic equation of seawater – 2010 (known as TEOS-10) (IOC, SCOR and IAPSO, 2010) should be utilised to determine density profiles from CTD data, and the results obtained reported and interpreted. Field data will be specific to the measurement location. Additional analysis of potential density structure and density driven flow both in the region of interest for development, and the wider area to be simulated in the numerical model can be achieved to some extent by analysis of historic databases. Historic databases can be useful sources of ocean salinity and temperature throughout the intended model domain. The decision as whether or not to include modelling of temperature and salinity transport during Stage 3 shall be reported and justified. One such database is NODC (Levitus) World Ocean Atlas:

Existing density, salinity and temperature data at the location of interest shall be reviewed. If sufficient information is already available at a specific location, further measurements may not be required. CTD (conductivity, temperature, density) data near the project site to be used to determine the relative importance of stratification and horizontal density driven currents, as described above, shall be identified and reviewed. The location, period of record and an assessment of the quality of the data shall be reported.

6.4 Power and Resource Prediction

Annual Energy Production (AEP) or the dimensionless coefficient of power

$$c_p = \frac{\rho a U^3}{2P}$$

where ρ denotes the density of the water, a the area swept by the blades , U the flow velocity and P the mechanical power are often used to assess turbine performance. Models build at large scale can be expected to be equipped with a fully functional electric generator; the power output can thus easily be monitored. The biggest uncertainty in the coefficient of power or AEP stems from uncertainties of the flow velocity. Any error affects the result with the power of three, thus great care must be taken. If the inflow is sufficiently uniform, depth averaging over the height of the diameter seems sufficient to obtain a representative inflow velocity. In other cases more complex averaging methods might be required, for example for measurements affected by waves, turbines reaching into the boundary layer of the bottom or large scale flow structures.

Ingram et al., (2011) recommends the following formula to obtain a performance velocity U_{Ref} from a DADP measurement with k bins of height z_k and width b_k as follows:

$$U_{Perf} = \left[\frac{1}{A}\sum_{k=S}^{k=1} U_k^3 \, b_k z_k\right]^{1/3}$$

With A denoting the notional capture area of the device:

$$A = \sum_{k=S}^{k=1} b_k z_k$$

Besides the flow magnitude, the direction is of paramount importance. Typical turbine blades are sensitive to the direction of the incoming flow. Some turbine designs are build to align to the incoming flow while others are not, in any case the sensitivity of the device to variations of inflow direction should be controlled.

While further research is needed, it is strongly recommend to carefully evaluate the following features in order of decreasing importance:

1. Variation of velocity magnitude over depth
2. Variation of direction over depth
3. Variation of magnitude/direction over the width

Large scale devices will influence the flow at the site and complex simulations will be required. For small scale projects which have little if any impact on the underlying hydrodynamics of the site, it may be sufficient to use direct in situ measurements of the tidal flows for determining the tidal resource instead of numerical model simulations. The method applies to studies consisting of a single TEC, for which the measurements would need to coincide with the expected turbine location. This method may also apply to small (such that energy extraction has minimal effect on the flow field) Stage 3 projects in which the spatial variability of the tidal flows is weak. In order to demonstrate weak variability in the tidal flows and hence justification for extrapolation of the measured flow field, mobile DADP surveys shall be undertaken. If the spatial variability of the flow field is determined to be significant, then this method may still be used, provided measurements are made at each individual turbine location (as long as energy extraction shall still have minimal effect on the flow field).

As illustrated in Figure 21 measurements of the instantaneous velocity (horizontal or predominant current direction), ideally over the energy extraction plane (EEP) of the TEC, are required for accurate calculation of the mean velocity, turbulence intensity and the AEP. At a minimum, however, one should at least measure mean velocity at the centre-line of the EEP, (e.g. the hub height of an axial flow TEC). Since turbulence is currently not considered in the IEC Technical Specification 62600-200 on TEC performance, this annex describes mean flow measurements only.

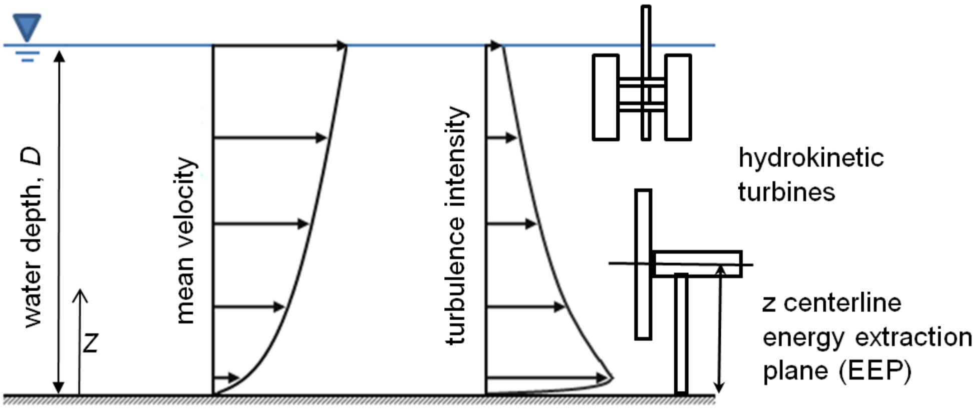


Figure 21 Typical distributions of velocity and turbulence and sketch of horizontal axis turbine(Neary et al. (2011)).

6.5 GUIDELINES FOR MEAN VELOCITY MEASUREMENTS

This section considers protocols and practices for measurements of mean velocity used for power production estimates. Generally DADP's are used, these instruments are not, in general, sufficient for turbulence characterization. DADP deployments at tidal energy sites should include bottom tripod mounts and buoyant moorings in order to provide a stable platform for long term measurements on the order of weeks to months. Arrays of ADVs can also provide the required mean flow information, provided that care is taken to prevent interference from the mooring (e.g., vortex shedding or flow alteration within the sample volume).

Current profilers shall include heading, pitch, and roll sensors in order to convert measurements from instrument coordinates to earth coordinates. Time series of these quantities should be inspected to verify that the platform did not significantly move over the course of the deployment. This should also be verified by noting, with best possible accuracy, the deployment and recovery locations. If these differ by more than 100 m and orientation sensor time series show movement, the data should be considered suspect.

6.5.1 Instrument Configuration

As for the IEC Technical Specification 62600-200 (dealing with TEC performance assessment), instruments should be configured to obtain a vertical resolution of no less than 1 m. The vertical extent of the EEP should be within the range of the current profiler (i.e., profiles extending only to hub height are discouraged). The sampling rate should be selected such that the horizontal uncertainty in the averaged velocity is no greater than 5 cm/s.

6.5.2 Data Requirements

Measurements should be averaged to an ensemble period that filters the majority of turbulent motion from observations. This is likely to be on the order of several minutes, depending on the specific site. For example, Thomson et al. (2012) determined that a five minute averaging period was sufficient for this purpose. In the absence of other information, a five minute averaging period is recommended.

Vertical bins for which more than 5% of the data have been rejected should be excluded from the analysis. This can occur close to the surface, particularly for sites with large tidal ranges. Inclusion of these bins can result in erroneous calculations if, for example, measurements of that bin are only possible around high tide, rather than evenly distributed over ebb and flood.

6.5.3 Vertical Shear

Depending upon the size of the TEC in question and flow characteristics, there may be significant vertical shear over the power capture surface. By convention, in the wind energy industry, AEP is calculated using “hub height” velocity distributions. For horizontal axis rotors, this is the nacelle hub height. For vertical axis or cross flow rotors, this is the mid-point of the rotor in the vertical dimension. The use of hub height velocities implicitly assumes that either (1) vertical shear is negligible or (2) in a sheared flow the higher velocities above the “hub” are approximately compensated by the low velocities below the “hub”.

Because the importance of vertical shear is not yet well-established for TECs, it is recommended that the following analysis be conducted for both hub height velocity and area-weighted velocity. Area-weighted velocity is the measured velocity at each vertical bin weighted by the fraction of the rotor swept area present in each bin. Analysis presented in Kawase et al. (2011) and Thomson et al. (2012) found that the hub height approximation was not significantly different from the area-weighted result for either mean flow conditions or turbulence intensity. These are, however, site-specific results and should not be accepted as generic without further inter-site comparison.
Horizontal shear in the mean flow is also possible, though, in general, horizontal gradients would be expected to be significantly weaker than vertical gradients.

6.5.4 Turbulence

The effect of turbulence on AEP is not yet sufficiently well-understood to give definite answers. The averaging period is intended to filter the majority of turbulent fluctuations from the horizontal velocity time series.
Because velocity spectra for tidal energy sites are continuous (i.e., unlike wind velocity spectra measured in homogeneous terrain, there are no frequencies without significant energy) it is not, in general, possible to establish a clear delineation between “turbulent” and “mean” flow conditions.

6.5.5 Off-Axis Flow

While tidal currents are often asymmetric (i.e., ebb and flood not entirely co-linear), the effect of off-axis currents on AEP is not yet sufficiently well understood.

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