ITTC Quality System Manual
Recommended Procedures and Guidelines

Procedure

Model Tests for Current Turbines

7.5 Process Control

7.5-02 Testing and Extrapolation Methods

7.5-02-07 Loads and Responses

7.5-02-07-03 Ocean Engineering

7.5-02-07-03.9 Model Tests for Current Turbines

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Table of Contents

Model Tests for Current Turbines

1. PURPOSE OF GUIDELINES

The purpose of this document is to offer guidance to research organisations on designing and performing model tests of current turbine devices at small, intermediate, and field scale in a reproducible environment at a hydrodynamic test facility suitable for testing such devices. This guideline addresses testing of devices intended to extract energy from both *tidal* currents, which typically involve bi-directional flow, and *ocean* currents, which typically involve unidirectional flow. Key issues addressed are:

- Definition of the stages of a device test program – Technology Readiness Level (TRL) definition.
- Summary of testing requirements/challenges for device type (ocean and tidal current, rotating and non-rotating, shallow or deep deployment, rigid mounting or flexible mooring) and device development stage.
- Coupling between model scale, choice of facility, device type, and experiment stage.
- Identification of common error sources associated with small to field-scale testing with guidelines on impact on test success, interpretation of test results and how to quantify and report measurement error.

2. DEFINITIONS, PARAMETERS & METHODOLOGY

The goals of testing can range from concept assessment to performance verification or device survival testing. The tests can be carried out at distinct scales, in generic or specific flow environments, and with varying degrees of complexity represented in the system. Potential environmental impact could be evaluated through planned small-scale testing with adequate scale-up prediction of performance or operation; for example, full-scale device noise prediction, cavitation performance or scouring impact based on small-scale evaluation. Particular types of experiments are addressed separately: concept testing, performance verification testing, and survival testing. Since each of the goals of these tests are distinct, e.g. power capture, unsteady loading (including dynamic stall) or fatigue, they require varying levels of similitude (environment and geometric), accuracy, reproducibility, and instrumentation. In addition, specific treatment of each major component of a device can also be tested separately, or more devices can be tested to simulate device-to-device interactions in an array.

The major components of a test specification are:

- Mission definition – purpose/goals.
- Definition of the types of tests needed to satisfy test purpose/goals.
- Test model design – similitude criteria, model scale, construction and function.
- Measurement requirements – data type, acquisition requirements, temporal and spatial resolution and accuracy.
- Selection of the test facility.
- Data processing and documentation.

2.1 Device Development Stage

The stages of development of current turbines are commonly described in the marine renewable industry in terms of Technology Readiness Levels (TRLs). These provide a consistent process enabling identification of a devices stage of development and identification of suitable test procedures for evaluating device performance at a defined stage of development.

This information can then be used to provide an unbiased assessment of a device for investment/development purposes independent of device type or scale.

In the case of the renewable energy industry, the following stages of Technology Readiness Levels (TRLs) are commonly considered (e.g. Mankins (1995)). TRL 1-3 correspond to research stages up to and including proof of concept, TRL 4-5 correspond to component, subsystem and system validation in laboratories and/or simulated operational environments and TRL 6-9 correspond to prototype demonstration in operational environment through to system proving via successful deployment.

The main objectives of tests in concept validation stages (TRL 1-3) are to validate the device concept, to validate preliminary numerical models used to predict energy output, to investigate device variables and physical properties that affect the performance or energy capture, and to optimise the device for power production using small scale models. The scale range in this stage is typically between 1:25 and 1:50 considering, for example, devices having a characteristic dimension at full scale of about 10-15 meters.

The main objectives of tests in the validation stage (TRL 4-5) are to validate the device design, to validate advanced numerical models of the device, to develop Power Take-Off (PTO) control strategies for improved power production, and to verify the mooring and foundation system using medium scale models. If known, the environmental conditions at a specific site should be used. The scale range in this stage is normally between 1:10 and 1:25. However, smaller scale models may be used to investigate items such as the survivability of supporting structures in extreme waves.

Tests in the system validation stage (TRL 6-7), and the prototype and demonstration stage (TRL 8-9) are typically carried out at large or full scale through field test sites at sea or in inland waters.

2.2 Types of Devices

Ocean/tidal current based renewable energy devices convert the energy of the moving water into electrical energy through a transformation of the water momentum into a mechanical motion, typically rotational or oscillatory. The primary difference between ocean and tidal current devices is the variation in directionality of the moving water used in energy extraction. Ocean applications involve a near unidirectional flow of water while tidal applications involve bi-directional flow.

Flow directionality is an important consideration in the design of a turbine device. Some turbine devices are designed to operate with reasonably symmetric loading and efficiency in tidal applications involving flow reversal whereas other designs require a unidirectional flow and thus must be aligned with the flow. The most common type of current turbine devices employs a rotational conversion, similar to that used in modern wind turbine systems, and encompasses a variety of design variants including fixed and floating devices with single or multiple turbines. For this type of device, a typical classification is based on the direction of the rotor axis with respect to the main direction of the flow. A different class of devices converts oscillatory motion into energy. Device technology is evolving rapidly as developers gain experience with large-scale field testing.

2.2.1 Horizontal Axis Turbines

Horizontal axis current turbine devices typically utilise multi-bladed turbine concepts similar in design to modern wind turbines. Horizontal axis devices consist of one or more rotors usually connected to a power-take-off (PTO) pod in an axial drive configuration. The turbine/PTO assembly is mounted to a tower or wing-type structure in either an upstream (turbine upstream of the tower) or downstream (turbine downstream of the tower) configuration. These devices can be rigidly mounted to the seabed floor, fixed to a floating barge/platform, or can be free-floating mid-water through a cable-moored attachment. The type of mount (upstream or downstream configuration, and rigid or free-floating mooring) can be an important factor to consider in mid-scale model testing as these factors can impact device performance, device loading and blockage corrections. Variations currently under development include contra-rotating turbines designed to minimise global axial moments on the device. Figure 1 illustrates common horizontal axis device configurations showing open and ducted units with bottom-mounted, floating and moored deployments.

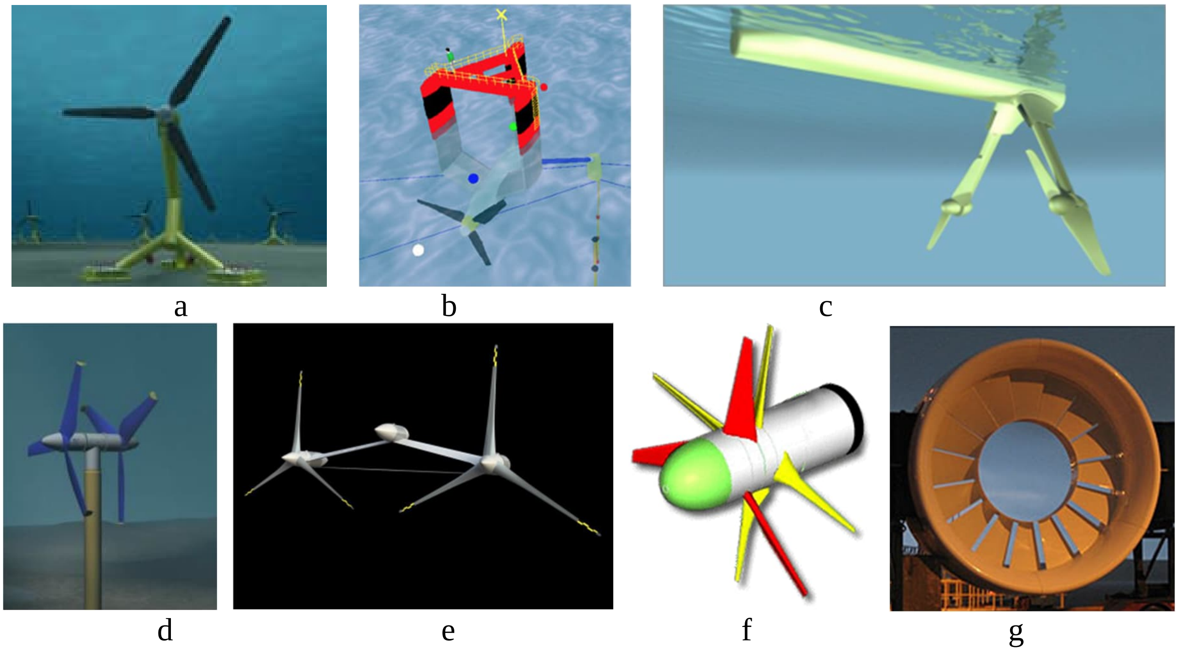


Figure 1. Examples of horizontal axis turbines: a) three-bladed bottom-fixed turbine b) floating single turbine device, c) floating dual turbine device, d) dual turbine bottom-fixed device, e) dual turbine mid-water device f) contra-rotating mid-water device g) ducted turbine

2.2.2 Crossflow Turbines

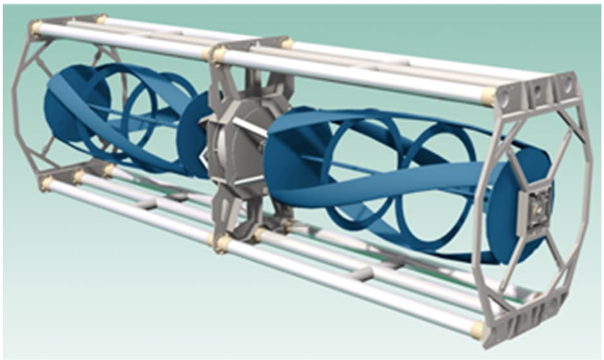
Crossflow current turbines are characterised by an orientation chosen so that the flow direction is perpendicular to the axis of rotation of the device. They are often similar in design to the Darrieus wind turbine concept, although Savonius and Gorlov turbines are also utilised. Vertical axis current turbines are the most popular type of crossflow devices, (see Figure 2). Similar to horizontal axis-type devices, crossflow turbines incorporate a PTO assembly typically in line with the rotating drive axis and a mounting arrangement that can be rigid or free-floating. The added mechanical structure of the device should be accommodated in small-scale testing due to its added blockage and increased drag.

2.2.3 Ducted Devices

The impact of adding a duct around an open horizontal axis (e.g. Figure 1f) turbine has been extensively studied in the wind energy arena. A well-designed duct can channel or accelerate the flow through the turbine in a manner similar to the guide tubes used in conventional hydro turbines. This is intended to increase the power generating efficiency of the open turbine device; however, there is some debate as to the validity of this premise (e.g. van Bussel (2007)).

These devices can be designed to operate in either ocean or tidal applications. Ducted units are associated with increased device drag when compared to a comparably sized (outer diameter of the device) open turbine device and could have additional blockage effects that will need to be accounted for in small scale device testing.

(a) Vertical axis Darrieus turbine cluster



(b) Gorlov turbine.

Figure 2 Examples of crossflow turbines

2.2.4 Oscillatory Devices

Oscillating devices often rely on a cyclic flow phenomenon known as Strouhal shedding to excite a lifting surface or cylinder into a controlled, cyclic motion, (e.g., Figure 3). The motion of the moving structure is then coupled to a mechanical or pneumatic/hydraulic drive system connected to the PTO. The drives convert oscillatory motion into a linear or rotating motion of a shaft used to drive a generator while the pneumatic/hydraulic systems use a pipe/valve network to pump a fluid through a turbine driven generator.

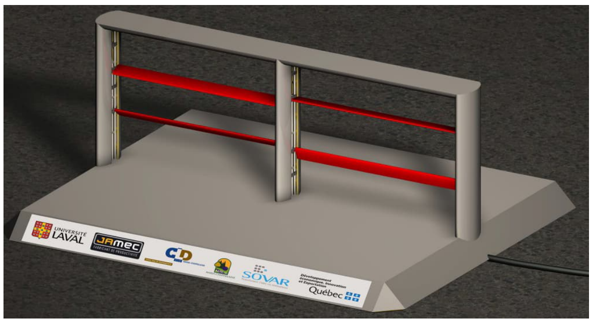


Figure 3 Example of an oscillating foil device

2.3 Facilities

Small scale testing of current turbine devices can be performed in a variety of laboratory facilities (tow-tanks, circulating water channels or flume tanks, cavitation tunnels and wave tanks) or field test sites. Laboratory facilities offer the advantages of controlled testing with a greater array of capabilities (instrumentation, sub-component testing, and improved methodology). Nevertheless, testing current turbines in these facilities implies limitations in the ability to reproduce environmental conditions such as onset flow non-homogeneity or turbulence levels that may characterise device operation at sea or rivers.

Choice of facility will depend upon many factors, including proximity of the device to the free surface and/or the seabed. In the case of rotor or rotor/nacelle testing for horizontal or vertical axis turbines at the concept design stage, all three types of facilities could be used. Where floating devices are being tested including the effects of the supporting platform, it is naturally beneficial to use a flume or tow tank with a free surface; where wave effects are important, then a flume or towing tank with a wave-maker must clearly be used.

Conversely for bottom-fixed devices when testing is intended to include the effects of the support structure, a tunnel or flume will offer advantages over a towing tank in ease of installation, and in modelling the effects of the boundary layer over the seabed on the flow around the supports. The importance of the impact of turbulence on the results obtained, and the turbulence levels achieved in tests in different facility types, should be carefully considered.

Relatively few studies have been performed to compare the results achieved for identical devices in a full range of different facilities; Bahaj *et al.* (2007) compare results from a towing tank and a cavitation tunnel, reporting little difference between the results when the rotor was installed in the towing tank such that the tip immersion was 55% of the turbine diameter. However, for a case in which tip immersion was reduced to 19% of turbine diameter the power coefficient was reduced by 10-15%.

A round robin study Gaurier *et al.* (2015) compared results of a turbine in two towing tanks of very different sizes, and two circulating water channels. The three key facility parameters which can influence the behaviour of the turbine were identified as blockage, Reynolds number and inlet turbulence. The largest differences were shown to be significant in the measured thrust coefficients and magnitudes of unsteady forces and torques.

Field tests provide opportunities for device evaluation in a realistic environment with the disadvantage of poor control over test conditions and limited versatility in instrumentation and methodology.

Important considerations for laboratory testing of current devices include:

- appropriate model/PTO scaling,
- proper inflow representation and the characterization of the inflow conditions (flow speed, direction, uniformity, steadiness and turbulence characteristics – small- and large-scale turbulent structures),
- tunnel or tank blockage,
- proximity to a boundary (such as free surface),
- combined wave and current interactions
- model mounting characteristics, and
- availability of instrumentation (invasive or non-invasive) of appropriate accuracy to meet test objectives.

2.4 Model Design and Scaling

2.4.1 Scale Ratio

The choice of scale ratio influences model manufacture, instrumentation and equipment and choice of facility.

Manufacturability: The test model, including model components and PTO must represent the full-scale device to a level of geometric and functional accuracy appropriate to the TRL of the tests. For tests at TRL 1-3 it may be appropriate to model only the rotor of a turbine, whilst higher TRL tests would also require an accurate model of the nacelle and tower. Consideration should be given to hydrodynamic performance, including issues such as surface finish, boundary layer transition, and model stiffness, to ensure that the hydrodynamic and hydro-elastic behaviour is representative. For small-scale models achieving adequate geometric accuracy and stiffness can be challenging (see Muthanna *et. al.* (2013)).

Instrumentation: The chosen model scale must provide adequate space for the required instrumentation, and model dimensions must be compatible with the capacity of maximum loads of measuring devices (torquemeters, dynamometers) and provide adequate space for other equipment (slip-rings, motors etc.). Instrumentation must have a level of accuracy to allow model performance to be quantified appropriate to the TRL of the test.

Blockage: The facility must be capable of producing appropriately scaled flow environment at the chosen scale. Particular attention should be paid to blockage, tip immersion in flume and towing tanks, and proximity to walls.

Where devices are tested in towing tanks, reflections can occur due to the interaction with side walls and the bottom, while flow confinement effects may lead to different behaviour of the model with respect to equivalent operating conditions in an unbounded environment.

Well established techniques exist to evaluate effects of blockage for marine vehicles and structures, and hence to correct the measured data. Corrections are typically based on the ratio between the cross section of the model and the cross section of the basin. This ratio should be reduced as far as possible in order to minimise blockage effects, and in the case of energy conversion devices, to minimise the effect on device performance.

Another consequence of the confined environment is the increased need of a sufficient time interval between successive tests to re-establish still water conditions. The problem may be particularly important when tests are performed in wave conditions.

Whelan *et al.* (2009a) present blockage and free-surface corrections for horizontal axis devices and propose an approach to correct results in the presence of blockage in conjunction with a free surface. Ross (2010) describes a study on wind tunnel blockage corrections applied to vertical axis devices. Special consideration should be given if non-axial flow conditions, common in current turbines, are to be considered (see Bahaj *et.al.* (2007)).

2.4.2 Similarity & Physics

The correct implementation of small-scale testing of a current turbine device beyond proof of concept requires a fundamental understanding of the underlying physics governing operation of the device and the appropriate similarity principles used in model scaling. The choice of governing similarity parameters can be dependent on device type and location. Key similarity parameters used in governing the operation and scaling of devices should include:

Reynolds number (Re): The chord-based Reynolds number is defined as:

$$Re_{0.7R} = \frac{\left((0.7\omega R)^2 + U^2\right)^{0.5} c_{0.7R}}{\nu} \qquad (1)$$

where ω is the rotational velocity, $c_{0.7R}$ is the turbine chord at a 0.7 radius ratio and U is the upstream velocity R is the turbine radius and ν is the kinematic viscosity of the fluid. The performance of foils used in current devices can be strongly dependent on Re scaling. The testing of a hydrofoil-based device at too low a chord-based Reynolds number can result in inaccurate results. Often the results show a reduced efficiency of the device with lower measured power capture. On the other hand, laminar flow over a hydrofoil can result is much lower friction drag and increased efficiency. It is important that turbulent flow is maintained over the hydrofoil in order obtain realistic full-scale lift, drag and moment results for a hydrofoil. It is recommended that, where possible, higher TRL tests be performed at the highest chord-based Reynolds number possible. Where testing is carried out at low Reynolds numbers, it is desirable to demonstrate the asymptotic behaviour of results with Re by varying Re over a range of tip speed ratios that cover the maximum power coefficient.

Froude number (Fr): The Froude number is defined as:

$$Fr = \frac{U}{\sqrt{gh}} \qquad (2)$$

where, h is a reference depth (such as tip emersion depth) and g is the gravitational constant. This should be considered when evaluating the performance of shallow depth, floating, or mid-water turbine devices in a wave-current environment

Strouhal number (St): The Strouhal number is defined as:

$$St = \frac{fL}{U} \qquad (3)$$

where f is a characteristic frequency and L is a characteristic length (normally chord or thickness). The Strouhal number is used to parameterise unsteady flows in which periodical phenomena can be identified with a representative frequency, such as oscillating foil-type current energy devices.

Cavitation number (σ): The cavitation number is defined as:

$$\sigma = \frac{p - p_v}{\frac{1}{2}\rho U^2} \qquad (4)$$

where, p is a reference pressure (usually defined at centreline but can be at the tip), p_v is the vapor pressure and ρ is the density of water. Cavitation inception, breakdown and collapse on a surface may impact device performance, radiated noise and surface damage. Appropriate small-scale testing should incorporate cavitation modelling when full-scale operation may be susceptible to cavitation. The correct scaling of cavitating flow phenomena at small scale requires tests to be performed in depressurised conditions that can be established in dedicated facilities.

Tip-Speed ratio (λ): The tip-speed ratio is defined as:

$$\lambda = \frac{\omega R}{U} \qquad (5)$$

where ω is the rotational velocity, R is the turbine radius and U is the upstream velocity. Tip-speed ratio is an important kinematic parameter in scaling rotating turbomachines such as pumps turbines and propellers. The inverse of tip-speed ratio is proportional to the corresponding kinematic parameter (advance ratio) used for screw propellers. The scaled performance of rotating turbomachines is strongly dependent on matching the full-scale tip-speed ratio while maintaining appropriate Reynolds number magnitudes.

Other parameters: In unsteady flow, the magnitude of the unsteadiness and the *reduced frequency* (*k*) are also important. These are discussed in more detail in section 3.3.2.

2.5 Environmental Parameters

The nature of discrepancies between lab and real-world environment depends on the facility type whether flume tank, tow tank or water tunnel. Limitations to creating the particular environment should be specified. The key characteristics to scale in a device test depend on the purpose of the test. For example, performance testing may require Reynolds number scaling, whereas for studies of wake flow dynamics or free-surface effects studies Froude scaling may be important particularly in installations close to the free surface.

It should be noted that accurate characterization of the full-scale environment is often not available, especially during concept design studies when field sites will often not have been licensed. Even in cases where site measurements have been made, it is unlikely that data will exist for all locations within an array. The local bathymetry will inevitably affect the flow environment around individual devices in a manner which may not be possible to model.

2.5.1 Current Testing

Mean flow and turbulence characteristics should be quantified on both the inflow and outflow boundaries. The impact of device pitch and yaw on device performance may have to be assessed depending on deployment site flow characteristics. Evaluation of surface wave impact on performance and mooring may be necessary depending on deployment site and depth. Bottom mounted devices may require proximal flow field mapping in the vicinity of the device mount along the facility floor. Cavitation susceptibility testing may be necessary depending on device design and deployment site depth considerations.

2.5.2 Tidal Testing

Tidal device testing can involve similar environmental testing concerns as those defined above for current testing. Reverse flow operation, typical in tidal applications, should be assessed relative to performance and device loading. In the case of tests aimed at analysing model motions to align the whole device or parts of it to reversing current direction, special attention should be devoted to achieving a correct scaling of all relevant similarity parameters, including the effects of transient motions.

2.5.3 Other Environmental Factors

Device noise evaluation may be necessary if permitting agencies require full-scale noise predictions relative to marine animal impact. Local and far-field bed floor erosion tests can be performed in specialised facilities and may be necessary for the river and some tidal deployment environments. The impact of device energy extraction on the local macroscopic environmental flow characteristics may have to be modelled to properly assess the environmental impact such as reduced tidal penetration into a bay or redirected river flow characteristic.

2.6 Test Case Parameters

2.6.1 Proof of Concept Testing

Test programs aimed at devices in the TRL 1-3 stage of development may encompass small-scale experiments or analyses focused on understanding an operational concept. These activities can often be accomplished in small-scale laboratory environments at reasonable cost and time. Accurate characterization of power capture and other detailed, quantitative results may not be a focus at this program stage and qualitative operational characteristics may be the desired outcome to provide confirmation of the feasibility of a concept idea.

Concept design testing requires the least level of accuracy in both the representation of the environment and of the model itself; it may be used to verify overall or relative trends seen in numerical modelling, but it is generally not intended to verify the accuracy of numerical modelling efforts. Concept testing will often be used to evaluate multiple distinct designs based on key metrics (i.e. relative stability, relative power performance, etc.). A deployment environment does not have to be identified to run these tests as generic environments will suffice. Moreover, scaled models designed for concept testing may represent only key components of the whole device, e.g. a simplified mock-up of the rotor without components like platforms, mooring devices, etc.

Proof of concept testing often involves small-scale model testing (with a model smaller than 1:25 scale) aimed at exploring whether a device design responds to a hydrokinetic load in a fashion broadly expected - for example, whether a new rotor design rotates under hydrodynamic loading with a shaft resistance applied to simulate a power take-off. These tests should be conducted using good experimental practices. All relevant test parameters should be characterised, such as model geometry and scale, flow characteristics, model performance (shaft rpm, foil oscillating frequency or shaft torque for example). Measurement uncertainties should be estimated following ITTC guidelines (see section 3.6)

2.6.2 Energy Capture Performance Tests

Energy capture performance tests for horizontal axis turbines are similar to open water marine propeller tests except that power is extracted instead of added to the flow. Determination of device performance over a range of test conditions is the main focus. The general approach set out in the ITTC Recommended Procedure 7.5-03-02.1 *Propulsor Open Water Test* should be followed. Model scale can vary from small to near full scale depending on the device design.

Inflow characteristics, such as flow speed and direction, turbulence levels, turbulence structure (small scale vs. large scale), spatial uniformity (mean flow spatial gradients) and flow unsteadiness must be properly modelled and quantified. If an additional goal of the test is the validation of numerical codes for performance prediction, measurement of outflow characteristics may also be required. The model geometry must be accurately represented; power take-off modelling must represent the design tool modelling of power take-off function and must provide adequate loading and accurate representation of scaled performance as this can strongly impact overall device function (see section 3.2). All key model performance parameters must be measured, such as model motion (rotational speed or flapping frequency and amplitude), shaft torque, component vibration and deformation under load, and model loading (drag, lift or moments).

Data normalization and presentation should follow the general principles of ITTC Recommended Procedure 7.5-03-02.1 *Propulsor Open Water Test*. However, some exceptions will result from differences in conventional practice between turbine and propeller testing. Results for turbines are typically presented in terms of power coefficient C_P, thrust coefficient C_T, and torque coefficient C_Q and plotted against tip-speed ratio :

$$C_P = \frac{P}{\frac{1}{2}\rho U^3 A} \tag{6}$$

$$C_T = \frac{T}{\frac{1}{2}\rho U^2 A} \quad (7)$$

and

$$C_Q = \frac{Q}{\frac{1}{2}\rho U^2 A D} \quad (8)$$

P is the power, T is the turbine thrust, Q is the turbine torque, U is the flow velocity and A is the swept area of the turbine. For ducted turbines, the swept area is typically defined as the area of the duct.

The impact of non-axial flow on both energy capture performance and device loading will be significant for some devices in some locations and in these cases the test plan should reflect this. Bahaj *et al.* (2007) report a 30% reduction in power coefficient for a yaw angle of 30 degrees.

2.6.3 Survivability

Survival testing is an extremely important test when designing a product for the ocean. Extreme conditions produce very large motions and forces and there are limited numerical codes capable of accurately estimating a device response to the extreme conditions. Hence, the most viable way of obtaining loads (mooring and structural), measuring motions, and verifying designs in extreme conditions is through testing. Typical topics of interest are:

- Fatigue
- Life cycle
- Unsteady loads
- Extreme Event – over-load testing
- Tow out and Installation

Testing in extreme conditions can challenge the capabilities of facilities. It is important to obtain statistically relevant data that can be used to ensure a design will in fact escape a catastrophic failure (see ITTC Recommended Procedure 7.5-02-07-02.3 *Experiments on Rarely Occurring Events).* Where there are particular structural loads of concern, then the model should be constructed to allow accurate measurement of these loads in both the turbine and support structure. Where off-axis flows are relevant, transverse as well as longitudinal loads should be measured. Tests should cover cases in which the device is shut-down in addition to operational tests.

For floating structures, accurate scaling of the mooring system can become extremely important. Often the mooring system is nonlinear in its response to the large motions expected to be seen; this nonlinearity needs to be captured in the design. ITTC Recommended Procedure 7.5-02-07-03.1 *Floating Offshore Platform Experiments* and where appropriate 7.5-02-07-03.4 *Hybrid Mooring Systems* should be followed.

2.6.4 Unsteady Inflow and Loading

Current devices in realistic environments may undergo unsteady inflow conditions for a variety of reasons. These include: the effects of turbulence in the current (in some cases exacerbated by upstream bathymetry); the impact of waves; for floating and/or mid-water devices; and the impact of device motions. In many cases, the main impact of unsteady inflow is related to the increase in the blade loading rather than the reduction in power capture (Milne *et.al.* (2013)). Several issues of experiment design for tests in unsteady conditions may require different practices from those adopted in steady conditions. These are discussed further in section 3.3.

2.6.5 Arrays and Clusters

A distinction may be drawn between an array and a cluster: a “cluster” consists of several units of the same device mounted/appended to a single framework, e.g., a floating platform for a vertical axis device such as shown in Figure 2 (a), whilst an “array” consists of many identical devices deployed in confined areas where fluid-dynamic device/device interactions are expected.

For an array with many devices installed, the interaction of the devices can be determined through tests involving a limited number of systems. Typically, the number of devices to be used in a small-scale array test would be dependent on the device type and the intended array geometry at full-scale deployment. The important parameters and characteristics of an array test are impact of upstream devices on downstream performance and loading both steady and unsteady. Due to the cost and scale constraints, the behaviour of arrays involving a large number of devices may be evaluated by numerical modelling.

2.6.6 Noise Measurements

Current turbine devices may also be sources of noise with characteristic spectral signatures due to cavitation, structural vibration of components (blade or drive train) and operational noise due to component design (bearings, gear train, etc.). ITTC Procedures related to noise sources and impact to the environment (ITTC Procedures (7.5-02-03-03.3 “Cavitation Induced Pressure Fluctuations Model Scale Experiments,” 7.5-02-01-05 “Model scale noise measurements,” 7.5-04-04-01 “Underwater Noise from Ships, Full Scale Measurements,”) should be reviewed for relevance. Additional information on noise measurements can be found in the 27th ITTC Proceedings and the final report by the Specialist Committee on Hydrodynamic Noise (2014). The report also reviews the responses of a survey on both full scale and model scale noise measurements.

3. DESCRIPTION OF TEST PROCEDURE

3.1 Model Manufacture and Installation

Model manufacture should be performed such that the scaled model function or scaled component static and dynamic response is not compromised or different from that expected at full-scale operation. Materials should be selected to ensure that the scaled sub-component deflection, deformation or response is scaled to or less than anticipated in the full-scale system. The scaled blade deformation under load should be comparable to or less than that anticipated at full scale operation.

The installation of small-scale testing of moored devices or free-floating devices should be clearly documented as installation could impact device performance or loading. In general, the model should be designed and manufactured to geometric scaling principals when possible. Model preparation and installation should follow ITTC Recommended Procedures 7.5-01-02-02 *Propeller Model Accuracy* and 7.5-03-02.1 *Propulsor Open Water Test*).

The model should be carefully aligned with the flow direction and moving components properly aligned with one another to reduce friction, undesired loading or vibration due to misalignment. Bearings and seals should be properly sized and selected to reduce overall friction in the PTO model. Run-in or burn-in tests should be conducted at the beginning of any test program to allow bearings and seals the opportunity to align and seat ensuring minimal resistance to operation. Model function and instrumentation should be pre- and post-calibrated following ITTC Recommended Procedures 7.6-01-01 *Control of Inspection, Measuring and Test Equipment* for general guidance, 7.6-02-09 *Calibration of Load Cells* for sample guidance on load cells, 7.5-02-03-01.1 *Propulsion/Bollard Pull Test* and 7.5-02-03-02.1 *Open Water Test* for installation and calibration for propulsion and propeller open water tests.

Full scale deployment site characterization is a critical component to model testing. Model installation in the test facility should consider the appropriate modelling of the flow kinematics on small scale model performance. Flow field characterization and modelling should consider turbulence generation, steady vs. unsteady flow and wave characteristics. Small scale model installation must properly scale mooring characteristics in floating devices and depth from the surface characteristics as wave motion can influence device performance through induced device motion, structural loading, and alteration of inflow kinematics. Measurement instrumentation should be carefully selected to provide adequate frequency response, spatial resolution and accuracy. Data acquisition systems should be specified to meet minimum sampling frequency and filtering requirements with adequate sampling resolution.

3.2 Power Take-Off Modelling

Ocean/tidal based renewable energy devices are typically designed to operate over a specific range of conditions, rpm or oscillation frequency, for optimal power generation. The optimal conditions are usually maintained by loading the device to hold rpm or oscillation to a desired range through the Power Take-Off (PTO) system, comprised of drive train, power generation and power electronics. Model-scale device testing must include some form of PTO modelling. In tests of model current devices, the PTO can be represented by direct electrical power generation, by mechanical/hydraulic/pneumatic loading or by using a speed or torque control drive. In all cases, friction associated with bearings and seals must be carefully assessed in order to minimise the impact on the measured power.

Model test set-ups developed for mid-level TRL stages should include the possibility to test both rotor operation at prescribed rotational speed and/or torque and in free-running conditions. The latter condition is in principle better descriptive of full-scale device operation but requires adequate model scaling and a careful design of the PTO system. Free-running tests in unsteady conditions are particularly challenging, since system dynamics must be modelled correctly.

3.2.1 Electric power generation

Either permanent magnet or inductance generators can be used in small scale model testing using direct-drive or gearbox coupling. Full-scale devices often have the power generator installed in the device nacelle. Space limitations in small-scale model testing may require a revised configuration where the generator is installed in a downstream dynamometer or outside the facility. These adaptations, used to accommodate space limitations, often involve additional components like seals, bearings and gearbox configurations.

Experimental conditions based on this operating protocol are often referred to as “free running” tests. These tests may be useful in principle to analyse specific operating conditions, but this requires careful design of the PTO system. Key properties include system efficiency, resistance to movement which can impact turn on/off characteristics of the device and system tares. For small-scale tests, model dynamics and drive-train friction losses cannot normally be scaled appropriately; thus small-scale free-running tests can often give only a limited insight into full-scale device performance.

Where a PTO for a horizontal or vertical axis device is represented via direct power generation, the characterization of power requires measurement of the flow velocity, measured using the approach normally adopted for the facility, the rotational velocity of the rotor, typically measured with a tachometer or encoder and the electrical power generated. In this case the tip-speed ratio is controlled only indirectly via the flow velocity and the electrical load.

3.2.2 Resistance Loading

Resistance loading is usually accomplished with a drag type device attached to the PTO drive shaft. This can be mechanical, hydraulic or magnetic in design. This type of system is designed to control the rotation or oscillation rate of the device and does not directly simulate a power generation system. Typically, the power generated by the device is converted into heat within the PTO model or motion of a fluid within a hydraulic/pneumatic system.

At very early TRL stages it is possible to calibrate the resistance loading against rotational speed prior to the tests so that the only measurements required during tests are flow velocity and rotational speed. Particular attention should be paid to repeatability of calibration in the context of variations in temperature, humidity etc.; guaranteeing repeatable behaviour of friction devices in particular may be challenging. It should also be noted that this approach will not work for devices which require active intervention for starting. It is preferable to measure shaft torque so that power can be derived directly from the product of torque and speed. This can be accomplished using a fixed or rotating torque transducer; use of a rotating device will usually require a slip ring to transfer wiring from rotor to stator.

3.2.3 Speed/Torque Control

As an alternative to the approaches described above, a speed-controlled motor may be used to drive the rotor at a prescribed rpm. In this case the power is typically derived from measurements of shaft torque and rotational speed. In this approach the tip-speed ratio for the test is controlled directly through the combination of specified rotational speed of the motor and the onset flow velocity. It is important to ensure that the motor and controller have adequate torque to maintain steady speed throughout the range of tip-speed ratios of interest. As an alternative to controlling speed, a similar approach may be utilised to control the torque.

Similar control methodologies can be established for oscillating devices where oscillation frequency rather than rotation is controlled.

3.3 Unsteady Inflow and Loading

If device performance in unsteady flow is to be assessed, then several issues should be considered over and above those of importance in steady tests.

3.3.1 Generation of Unsteady Velocity

The procedure used to generate the unsteadiness in the inflow will depend upon the type of unsteadiness expected the level of characterisation available for the unsteady flow in the proposed installation site, and the type of facility being used. If the unsteadiness of interest largely consists of relatively small-scale turbulent structures, then it may be possible to introduce turbulence in a flume by introducing a grid or other structure upstream of the device; similarly in a towing tank test a grid may be attached to the carriage forward of the device. This type of approach requires careful characterisation of the flow field (mean velocities and turbulence) generated at model scale. To this purpose, advanced velocimetry techniques such as Laser-Doppler Velocimetry (LDV) or Particle Image Velocimetry (PIV) should be used to quantify the inflow turbulence structure. Turbulent quantities of interest would include the inflow turbulent:

- Reynolds Stresses – normal (velocity variance or local flow turbulence intensities) and shear stresses,
- Length scales – integral (primary) and dissipation

- Spectral content – characteristic periodicity in the inflow that could contribute to a defined forcing function on the rotor.

The experimental measurements and estimations of the above turbulent quantities has been well documented in the standard open literature on the quantification of turbulent flow. The classic texts by Tennekes and Lumley (1972), Hinze (1975), Schlichting (1979) and Bernard and Wallace (2002) provide good sources for the definition and measurement of the above quantities. The ITTC Recommended Procedure 7.5-02-03-02.3 *Nominal Wake Measurements by LDV Model Scale Experiments* provides a discussion of how mean flow, variance and harmonic characteristics can be measured. It is recommended that the ITTC 7.5-01-03-02 *Uncertainty Analysis, Laser Doppler Velocimetry Calibration* and 7.5-01-03-03 *Uncertainty Analysis Particle Image Velocimetry* guides be referenced for a discussion of the operation of LDV and PIV, how to assess measurement uncertainty and for a list of relevant references on the use of these instruments.

If the unsteadiness of interest is related to wave motion, then the device may be tested in waves in a wave-current tank (e.g. Gaurier *et al.*, 2013) or towed in waves (e.g. Barltrop *et al.*, 2006). Testing directly in waves naturally can provide the correct distribution of unsteady velocity over the rotor plane; however, this approach presents particular challenges with scaling. A further option is to introduce an unsteady velocity by oscillating the device in the presence of a mean flow, either using an oscillatory carriage in a flume tank (e.g. Whelan *et.al.* (2009b)) or by using an oscillatory sub-carriage mounted on a towing carriage in a towing tank (e.g. Milne *et.al.* (2011)). This approach results in an idealised unsteady flow which is uniform over the rotor plane, but which may allow investigation of the unsteady phenomena using a frequency-domain approach.

3.3.2 Unsteady Inflow Scaling

The presence of unsteadiness, particularly related to wave and/or device motion naturally requires an approach based on Froude scaling. The magnitude of the unsteadiness may be characterised as:

$$\mu = \frac{\tilde{u}}{\bar{u}} \tag{9}$$

where $\tilde{u}$ is the amplitude of the unsteady velocity and $\bar{u}$ is the mean velocity. Similarly, the frequency of the unsteadiness can be characterised by the *reduced frequency (k)* which can be defined in this context as

$$k = \frac{\pi c f}{\omega\, r} \tag{10}$$

where f is the frequency, c is the local chord, ω is the rotational speed and r is the radial location. Milne *et al.* (2014) report tests with values of μ up to 0.25 and reduced frequencies at 75% of the turbine radius up to 0.05, which are stated to correspond approximately to 100% and 50% respectively of values calculated from full-scale site measurements.

Achievement of matched full-scale unsteadiness combined with limitations on the achievable magnitude of the unsteady velocity may lead to reduced mean velocity, which can then result in relatively low Reynolds number. This in turn may lead to questions regarding the reliability of the data acquired in unsteady flow. Particular challenges may be faced where tests are conducted in waves, since the requirement to achieve the same scale on the rotor and the waves in order to generate a realistic unsteady velocity profile may lead to unrealistically low Reynolds numbers.

3.3.3 Control Strategy for Unsteady Tests

In unsteady flow, careful consideration should be given to the turbine control strategy.

If the desire is to model accurately the behaviour of the full scale system including the generator, then the dynamic response of the generator to the unsteady loads should be modelled correctly. Conversely, if the intention of the tests is to characterise the hydrodynamics of the rotor in unsteady conditions then the more idealised solution of using a speed-controlled motor may be preferable to remove the effects related to angular acceleration and deceleration of the rotor.

3.4 Extrapolation to Full Scale

All results of model tests are presented as prototype values. Model values are scaled to full scale by applying the proper similitude laws. Appropriate ITTC procedures as discussed in sections 2.6 and 3.1 should be referred to for dimensional analysis relative to specific device tests, which will vary with both device type and test type. Key examples will include ITTC Recommended Procedure 7.5-02-03-02.1 *Propulsor Open Water Test*, as well as 7.5-02-07-03.1 *Floating Offshore Platform Experiments* for floating devices in waves.

Blockage corrections are normally required, as eliminating the impact of surfaces completely may be nearly impossible given the need to increase the size of the test model and available facilities. If blockage corrections are not made this may result in overestimated power extraction, higher thrusts and an error in location of the optimum tip-speed ratio. A method like Whelan et.al. (2009a) or Bahaj et.al. (2007) shall be adopted to correct for the blockage.

As discussed earlier, there are also many important factors in energy conversion tests that are not addressed by standard scaling procedures. Special considerations are needed to address their effects. Computational Fluid Dynamics models can be used to predict device performance at full scale and to provide guidance about extrapolation methods.

3.5 Presentation of Results

The following provides a recommended outline of a generic test procedure and report. An actual test procedure may consist of a sub-set of these elements and may vary dependent on the test purpose and device type.

A) Purpose of the Test
B) Facility Characterization
   i) No-model baseline performance.
   ii) Facility dimensions and model size capacity
   iii) Operating ranges and test capabilities
C) Model & Installation
   i) Model Scale
   ii) Model Complexity – simplified, system, component.
   iii) Model function/operation
   iv) Model installation: Mooring, Foundation and constraints
   v) Model Dimensions/calibration
   vi) Model mass/inertia properties for unsteady tests
D) Measurement Systems
   i) Purpose of the measurements and required performance/accuracy.
   ii) Instrumentation Type: Invasive vs non-invasive; Imbedded versus free-field; Steady versus dynamic; Operational characteristics and requirements
   iii) Resolution – Spatial and temporal
   iv) Calibration requirements
E) Types of Measurements
   i) Model motion and deformation
   ii) Flow field measurements
   iii) PTO measurements
   iv) Environmental measurements
F) Test Matrix
   i) Test parameters and conditions – Scaling parameters, operating conditions
   ii) Measurements locations
   iii) Recommended practices
   iv) Design and off-design testing (including specification of what is regarded as

off-design testing – e.g. is yaw regarded as off-design).

v) Steady v unsteady performance (unsteady inflow – variable direction or speed, plus non-uniform inflow).

vi) Self-starting / Shutdown conditions.

vii) Testing in waves for floating devices. Wave field generated and a description of the wave generation technique. Model alignment to wave field.

viii) Component & Sub-component testing: Component and system loading; Subcomponent function

ix) Test repeatability & required number of repeat conditions for desired accuracy.

x) Installation & Recovery tests.

G) Data Acquisition

i) System performance – rates, resolution, number of channels, sequential or simultaneous sampling, noise levels/floors

ii) Data Analysis

iii) Data calibrations and corrections: bias errors, blockage corrections, Zeroes or Tares.

iv) Normalizations – use of proper velocity, length and time scales. Use of standardised parameters and relations accepted by the appropriate testing community.

v) Statistical Analyses; Steady vs dynamic studies

vi) Uncertainty analyses

3.6 Uncertainty Analysis

Uncertainty analysis should be performed following the approach presented in the ITTC guidelines 7.5-02-02-02 *Uncertainty Analysis, Guidelines for Resistance Towing Tank Tests* and 7.5-02-03-02.2 *Uncertainty Analysis Example for Open Water Test*, 7.5-01-03-01*Uncertainty Analysis, Instrument Calibration*, and, where relevant, 7.5-01-03-02 *Uncertainty Analysis, Laser Doppler Velocimetry Calibration* and 7.5-01-03-03 *Uncertainty Analysis Particle Image Velocimetry*. The ITTC guideline 7.5-02-07-03.15 "Uncertainty Analysis - Example for Horizontal Axis Turbines" provides a recommended guideline for the application of uncertainty analysis for a current turbine and provides an example of a current turbine test uncertainty analysis.

4. PARAMETERS; SYMBOLS

A	turbine swept area, $= \pi R^2$,	m^2
C_p	turbine power coefficient	
C_T	turbine thrust coefficient	
c	chord,	m
D	turbine diameter, $= 2R$,	m
Fr	Froude Number	
f	frequency,	Hz
g	gravitational constant,	m/s^2
h	reference depth,	m
k	reduced frequency	
L	characteristic length,	m
p	reference pressure,	Pa
p_v	vapour pressure,	Pa
Q	torque,	N·m
R	turbine radius,	m
Re	Reynolds number	
r	radial location,	m
St	Strouhal number	
T	thrust,	N
U	upstream velocity,	m/s
u	flow velocity,	m/s
λ	tip speed ratio	
μ	amplitude of unsteady velocity,	m/s
v	kinematic viscosity,	m^2/s
ρ	fluid density,	kg/m^3
σ	cavitation number	
ω	rotational velocity,	rad/s

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