ITTC Quality System Manual

Recommended Procedures and Guidelines

Guideline

Uncertainty Analysis for a Wave Energy Converter

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Uncertainty Analysis for a Wave Energy Converter

1. PURPOSE OF PROCEDURE

The purpose of this document is to provide guidance for ITTC members to perform Uncertainty Analysis (UA) of Wave Energy Converters (WECs) following the ITTC Guideline 7.5-02-07-03.7, "Wave Energy Converter Model Test Experiments".

This guideline is based on ISO (1995) and in line with other ITTC uncertainty analysis (UA) procedures such as ITTC Recommended Procedures and Guidelines (7.5-02-01-01, "Guide to the Expression of Uncertainty in Experimental Hydrodynamics" and 7.5-02-06-05, "Uncertainty analysis for free running manoeuvring model tests") that are recommended to maritime experimental facilities. The main purpose and measurement variables of WEC tank tests depend on the targeted Technology Readiness Levels (TRLs) of the device. Model tests of WECs have some differences from tests of other offshore structures including several additional challenges as listed in the ITTC Guideline 7.5-02-07-03.7.

2. INTRODUCTION

Testing the performance of WECs requires a detailed understanding of the device interactions with ocean waves. For instance, Figure 1 illustrates a simplified wave energy conversion chain where it can be seen that a part of the incoming wave energy (E_I) is reflected (E_R) and/or transmitted (E_T) due to the wave–device hydrodynamic interactions, with the rest of this energy representing the energy absorbed by the device (E_A). This absorbed energy is the maximum energy that can be further converted into useful electricity (E_E) after considering the radiated energy (E_D) due to device motions and/or the chamber's free surface oscillations in case of oscillating water columns, and the energy losses (E_L) in forms of viscous, turbulences and mechanical losses.

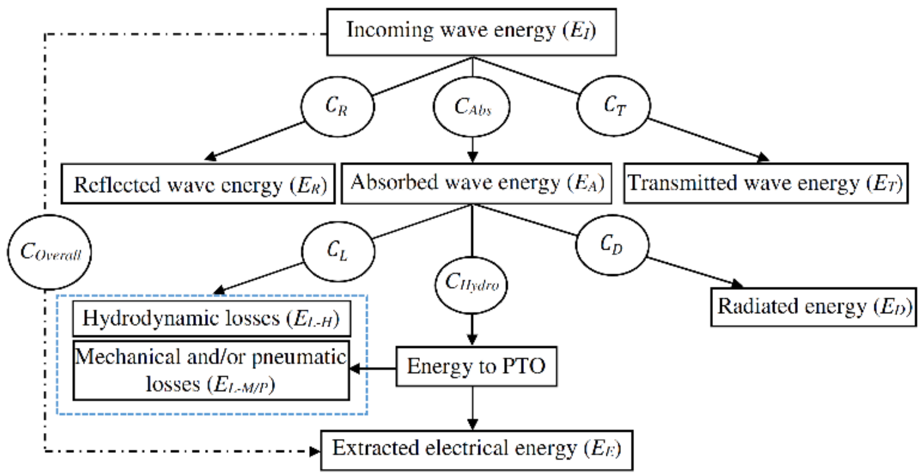

Figure 1: Energy conversion chain in a WEC

The conversion efficiency between each energy component is represented by a coefficient (C). According to the energy conservation principal, an energy balance model can be written as in Equation (1). For early TRLs (1–4) (Nielsen, 2002) where the full Power Take–Off (PTO) system is not included but simulated by the use of orifices, mesh or damper, the extracted mechanical energy (E_E) is not directly measured, instead it is estimated based on experimental measurements and power train efficiency assumptions. As a result, quantifying the uncertainties in the output energy/power requires a methodology that considers the different uncertainties in each relevant measured parameter. A part of the extracted mechanical energy can be converted to electrical energy, for example by utilizing an electric generator that adds more uncertainty in the final output energy; however, this uncertainty is not included in the current procedure.

$$E_I = E_R + E_T + E_D + E_L + E_E \quad (1)$$

As reported in ITTC Guideline 7.5-02-07-03.7 model tests of WECs can have different purposes. Once the objectives of the test have been identified, it is possible to select appropriate uncertainty analysis and design the experiment methodologies. Although every test procedure is individual, the adoption of the general outline test process formulated by AIAA (1999) and adopted by the ITTC Procedures 7.5-02-01-01 provides a means of introduction and integration of uncertainty assessment into each phase of the experimental process, with appropriate decision points and reporting. It stresses the importance of uncertainty analysis as "the foundation of all [towing] tank experiments", and that UA should be performed both prior and post experimental work as part of the planning and designing of the test as well as the post–processing of the results.

3. UNCERTAINTY CLASSIFICATION

A measurement is a process of estimating the value of a quantity. Every measurement is accompanied by error(s). This error is defined as the difference between the measured value and the 'true value', and can be decomposed into bias error and precision error as illustrated in Figure 2.

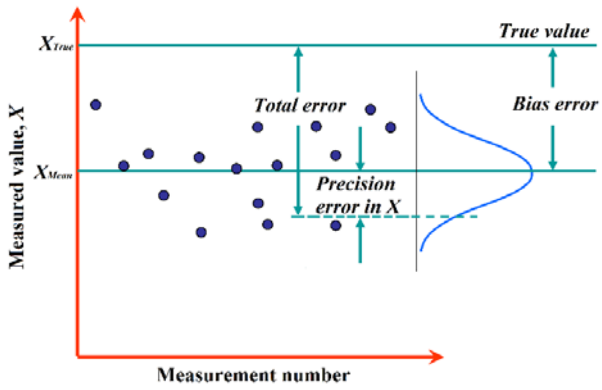

Figure 2: Bias and precision errors in a measurement.

Instead of using precision and bias errors, ASME PTC 19.1 (2005) uses the terms systematic and random errors. The former refers to the portion of total error that remains constant in repeated measurements of the true value throughout the test, while the latter describes the portion of the total error that varies in repeated measurements and causes scattering in the measured data.

The true value of a measured quantity is usually unknown. Therefore, the objective of uncertainty analysis is to estimate reasonable limits that combines the bias and precision errors and to construct an uncertainty interval within which the true value of the measured variable can be expected to lie within a chosen level of confidence (Forgach, 2002).

ISO (1995) classifies uncertainties into three categories: Standard Uncertainty, Combined Uncertainty, and Expanded Uncertainty.

3.1 Standard uncertainty ($\boldsymbol{u}$)

ASME PTC 19.1 (2005) utilizes two major classifications for measurement uncertainties, random and systematic uncertainties, and describes the limits to which random and systematic errors may lie within a chosen level of confidence. On the other side, according to ISO (1995), the standard uncertainty of the result of a measurement can be grouped into two types, Type A uncertainties and Type B uncertainties, depending on the method and information available for estimation of uncertainty. Type A uncertainty components are obtained using a method based on statistical analysis of a series of observations/repeats, whereas Type B uncertainty component is obtained by means other than repeated observations such as prior experience, professional judgements, manufacturers' specifications and calibration of the sensors (ITTC Procedure 7.5-02-01-01).

Considering the Recommendation INC-1 (1980) (Kaarls, 1981) that indicated that the term 'systematic uncertainty' can be misleading and should be avoided, the ISO classification will be considered in this document. Accordingly, the standard uncertainty (u) that combines both uncertainty types is given by Equation (2) as the root–sum–square (RSS) combination of Type A uncertainty (u_A) and Type B uncertainty (u_B).

$$u = \sqrt{(u_A)^2 + (u_B)^2} \tag{2}$$

3.2 Combined standard uncertainty ($\boldsymbol{u_c}$)

The final result from an experiment is not always being measured, instead it is calculated from different measured parameters using a mathematical model. Consequently, quantifying the uncertainty in this result requires a methodology to combine the uncertainty associated with each parameter. In other words, the combined standard uncertainty (u_c) of the output variable is obtained from the uncertainties of a number of other quantities (input) considering that the quantities are either correlated (dependent) or not (independent).

For example, considering a quantity of interest (Y) defined in Equation (3) (called Data Reduction Equation, DRE) as a function (f) of other measured quantities ($X_1, X_2, \dots\dots, X_N$), the general equation for the combined standard uncertainty in Y is given in Equation (4). It is based on a first-order Taylor series approximation of the measurement equation of quantity $Y = f(X_1, X_2, \dots\dots, X_N)$ and its estimated value (y) (ISO, 1995):

$$Y = f(X_1,\ X_2, \dots\dots,\ X_N) \tag{3}$$

$$u_c^2(y) = \sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i) + 2\sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \left(\frac{\partial f}{\partial x_i}\right)\left(\frac{\partial f}{\partial x_j}\right) u(x_i, x_j) \tag{4}$$

where u_c is the combined uncertainty of the Y estimated at $Y = y$; y is estimate of Y and calculated from Equation (3) at $X_i = x_i$; x_i is the estimate of X_i; $\frac{\partial f}{\partial x_i}$ is the partial derivative of f with respect to the X_i (commonly referred to as sensitivity coefficients or Uncertainty Magnification Factors, UMFs) and evaluated at $X_i = x_i$; $u(x_i)$ is the standard uncertainty associated with the input x_i evaluated at $X_i = x_i$; and $u(x_i, x_j)$ is the estimated covariance associated with x_i and x_j. In cases of practical interest, Equation (4) can be reduced to a simple form by neglecting the second term assuming the different x_i to be independent to each other ($u(x_i, x_j) = 0$).

For example, the regular wave energy (E) per unit width given as a function of the incident wave height (H_W) and length (λ_W) is:

$$E = \frac{1}{8}\rho g H_W^2 \lambda_W \quad (5)$$

Considering the uncertainties associated with all the parameters in Equation (5) including the water density (ρ) in the testing facility and the gravitation acceleration (g), and that all parameters are independent, the Data Reduction Equation (DRE) can be applied to calculate the uncertainty in the wave energy (u_{E_I}), giving:

$$u_c^2(E) = \left(\frac{\partial E}{\partial \rho}\right)^2 u^2(\rho) + \left(\frac{\partial E}{\partial g}\right)^2 u^2(g) + \\ + \left(\frac{\partial E}{\partial H}\right)^2 u^2(H_W) \left(\frac{\partial E}{\partial L}\right)^2 u^2(\lambda_W) \quad (6)$$

The sensitivity coefficients for all parameters in Equation (6) are summarized in Table 1.

Table 1: Sensitivity coefficients for a regular wave energy

Parameter	**Sensitivity coefficient**
ρ	$\frac{\partial E}{\partial \rho} = \frac{1}{8} g H_W^2 \lambda_W$
g	$\frac{\partial E}{\partial g} = \frac{1}{8} \rho H_W^2 \lambda_W$
H_W	$\frac{\partial E}{\partial H_W} = \frac{1}{4} \rho g H_W \lambda_W$
λ_W	$\frac{\partial E}{\partial \lambda_W} = \frac{1}{8} \rho g {H_W}^2$

The mean and standard uncertainty for the fresh water density are calculated based on ITTC Recommended Procedures 7.5-02-01-03, “Fresh Water and Seawater Properties” as 998.207 kg/m^3 ± 0.0105 kg/m^3 at a temperature of 20 ± 0.10 °C, while the mean and standard uncertainty for the gravitational acceleration according to ITTC Recommended Procedures and Guidelines 7.5-01-03-01, “Uncertainty Analysis, Instrument Calibration” are 9.80665 m/s^2 ± 0.0057 m/s^2 assuming rectangular/uniform distribution. On the other hand, uncertainties in wave height and length are estimated from Equation (2) considering both Type A and B uncertainties as described in Section 4.

It is not always possible to mathematically formulate the Data Reduction Equation. In that case, a proper numerical model can be employed to find a linear relation between each variable (input) in the DRE and the final output. This technique is extensively discussed in ITTC Procedure 7.5-02-06-05, but it is briefly explained in the following. In order to find the Uncertainty Magnification Factors (UMF) of a certain input parameter, at least two simulations are required. The initial condition for the second simulation for the input parameter must be controlled such that a highly linear trend can be drawn. This can be achieved by carefully studying the relation between the input and output variables for a range of initial conditions such that a linear slope representing the UMF can be determined. The simulation model does not have to be very accurate, but it is important that the trend is correctly predicted.

3.3 Expanded uncertainty (U)

The combined standard uncertainty (u_c) maybe thought of as equivalent to ‘one standard deviation’, but we may wish to have an overall uncertainty stated at another level of confidence. From practical viewpoint, in experimental hydrodynamics and flow measurements, an interval with a level of confidence of 95% is justifiable (ITTC Procedure 7.5-02-01-01). Accordingly, the expanded uncertainty (U) with this confidence level requires scaling the combined standard uncertainty (u_c) using a coverage factor (k) as given in Equation (7).

$$U = ku_c \tag{7}$$

Usually a coverage factor k = 2.0 is used for a level of confidence of 95% in that the quantity of interest (Y) is expected to be located in the interval delimited by $y - U$ and $y + U$ 95% of the time. However, it is worth noting that k = 2.0 assumes a Gaussian distribution with at least 61 data sampling size (this provides a degree of freedom of 60). For a lower number of samples/repeats used to calculate a standard deviation, a student T–Distribution must be used to determine the coverage factor (see ISO 1995), which commonly is provided in T-Distribution tables.

4. EVALUATION OF STANDARD UNCERTAINTY

4.1 Evaluation of Type A uncertainty

When a set of several repeated readings has been taken, each individual observation is expected to have a different value from other observations due to the random variations of the influence quantities, or random effects. From these repeats, the standard uncertainty (u_{S-A}) is defined as the estimated standard deviation of the mean as in Equation (8).

$$u_A = \frac{s}{\sqrt{n}} \tag{8}$$

where s and n are the standard deviation and the number of repeated observations.

The standard deviation (s) of the n repeated readings is calculated from Equation (9).

$$s = \sqrt{\frac{\sum_{k=1}^{n}(q_k - \bar{q})^2}{n-1}} \tag{9}$$

where q_k is the k^{th} repeated reading and $\bar{q}$ is the mean value of the whole repeated readings as given in Equation (10):

$$\bar{q} = \frac{\sum_{k=1}^{n} q_k}{n} \tag{10}$$

Testing of WECs usually includes a large number of conditions, and therefore, it is not practicable to carry out multiple repeats for every experimental run. It may be more feasible to only select unique test conditions such as at device's resonance for which repeat runs should be undertaken so that Type A uncertainty can be estimated. Numbers of repeats should be as large as practicable, but this is subject to cost and schedule constrains. ITTC Procedure 7.5-02-01-01 stated that 10 repeats should provide a reasonable estimate of Type A uncertainty.

According to ISO (1995), the following conditions should be considered for experiment repeatability:

A) The same measurement procedure,
B) The same measuring instrument used under the same test "environmental" conditions,
C) The same location, laboratory, or field location
D) Repetition over a short period of time, roughly, tests are performed in the same day.

The repeated runs should include sequential and non–sequential repeats (see ITTC Recommended Procedures 7.5-02-07-03.1, "Testing and Extrapolation Methods Loads and Responses, Ocean Engineering Floating Offshore Platform Experiments").

4.2 Evaluation of Type B uncertainty

As mentioned in Section 1.1, Type B uncertainty is not based on statistical methods, but its evaluation is usually based on experience and judgment. Therefore, it heavily depends on considering all relevant information available, which may include (ISO, 1995):

- Previous measurement data;
- Experience with or general knowledge of the behaviour and properties of relevant materials and instruments;
- Manufacturer's specifications;
- Data provided in calibration and other certificate, which must be traceable to National Metrology Institutes (NMI);
- Uncertainties assigned to reference data taken from handbooks.

The proper use of the pool of available information for a Type B evaluation of standard uncertainty calls for insight based on experience and general knowledge, and is a skill that can be learned with practice. Type B uncertainty is usually evaluated based on information quoted in a handbook, manufacturer's specification, calibration certificate, etc. In this case, the standard uncertainty can be provided as a multiple of an estimated standard deviation or a confidence interval. Other means of obtaining a Type B uncertainty are by assuming the provided data follow a certain distribution (such as normal distribution), but when it is only possible to estimate bounds (upper and lower limits) for the measured quantity, and there is no specific knowledge about the possible values of this quantity within this interval/limits, one can only assume a uniform/rectangular distribution.

Testing WEC's includes utilizing different sensors such as wave probes, load cells, pressure transducers, motion tracking system, etc. There are elemental Type B uncertainties that are an inherent part of each sensor, calibration, the data acquisition system (DAS), processing and analysis. Uncertainty sources that are commonly provided by the manufacturer includes non–linearly, hysteresis, zero offset drift, non–repeatability, resolution, etc. Sensor calibration is mandatory for all instruments before being used in the experiment so that instrument's uncertainty can be characterised. However, the calibration process itself includes uncertainties. All calibration should be performed through either system calibration or end–to–end calibration with the same DAS and software as utilized during data collection. The calibration results should be reported so that new calibrations can be compared. Most instrumentation is highly linear; therefore, a linear fit of the calibrated data is usually applied, and the standard uncertainty is defined by the standard error of estimate (SEE) as in Equation (11). Further details with examples on linear and non–linear calibration curve fitting and uncertainties in mass used in calibrating load cells is provided in ITTC Procedure 7.5-01-03-01.

$$SEE = \sqrt{\frac{\left(y_j - \hat{y}_j\right)^2}{M-2}} \tag{11}$$

where and M is the number of calibration samples/points and $y_j - \hat{y}_j$ is the difference between calibrated data point and the fitted value.

5. UNCERTAINTY ANALYSIS FOR DESIGN OF EXPERIMENT

Uncertainty analysis is necessary for planning an experiment, and/or improving the results of future experiments. The purpose of Design of Experiment (DoE) is to optimise in advance an experimental process in order to collect high quality data, which means minimizing as much as possible uncertainty sources. The flow chart in Figure 3 illustrates the required steps to test a WEC in a cost-effective way.

The chart in Figure 3 breaks down the test procedures into a series of steps that should be considered during testing WECs, especially small and medium scale (TRL1–TRL4) (Nielsen, 2002) considering the limited large tanks available for testing large scales.

In any test preparation, a pre–test uncertainty analysis should be performed during the planning and designing phases of the test with the same computer code applied during the test. This enables the identification of critical measurements that need to be measured more carefully and/or factors that may need to be repeated more than others to drive uncertainty to desired levels. This analysis includes primarily Type B uncertainties unless data are available from previous tests for an estimate of the Type A uncertainties. Selection of an instrument may involve economic trade-offs between cost and performance.

Accordingly, in this phase, all elements of the Type B uncertainty should be applied. In particular, manufacturers' specifications may be included for an assessment identifying the quality of the instrumentation needed for acquisition of the desired experimental results. In some cases, an uncertainty analysis indicates that the desired results cannot be achieved and that the experiment should be abandoned.

6. LISTING AND DISCUSSION OF THE SOURCES OF UNCERTAINTY

An important step in the flow chart in Figure 3 is to define all possible uncertainty sources. Considering the different uncertainty sources provided in ITTC Procedure 7.5-02-06-05 for hydrodynamic experiments, the uncertainty sources that might be encountered when testing a WEC are listed below.

- Inaccuracy of WEC model characteristics including: geometry/dimensions, mass, centre of gravity, GM, draft, moment of inertia, model orientation to the incoming waves, especially for wave–direction dependent devices such as terminator and attenuator devices, mooring lines anchoring points and inclination angle in case of taut mooring with multiple lines.
- Undesired facility related hydrodynamic effects including discrepancy between nominal and measured wave characteristics. Often, the measured waves are different from the desired condition (input to wavemaker), especially the wave height. In addition, due to wave–wave interactions, the generated waves are not homogenous/consistent throughout the tank which increases the uncertainty in the measured waves and highlights the importance of properly identifying the testing area in the facility, as well as the exact deployment location of the device together with the measured wave characteristics at that location. ITTC Recommended Procedures and Guidelines 7.5-02-07-04.1, “Testing and Extrapolation Methods Loads and Responses, Stability Model Tests on Intact Stability” states that wave elevation should be monitored at more than three locations covering the testing area with variations in wave height and period should be within 5% among the different measured positions. Furthermore, residual free surface oscillations in the testing facility (flume, tank or basin), especially if the waiting time between each run is insufficient. This affects the initial conditions for the following run, which in turn influences the testing device dynamics. The waiting time depends mainly on the facility and the testing conditions, and it is recommended to be specified using previous testing experience within the same facility. In addition, the tank width and bottom profile may impact the collected data.

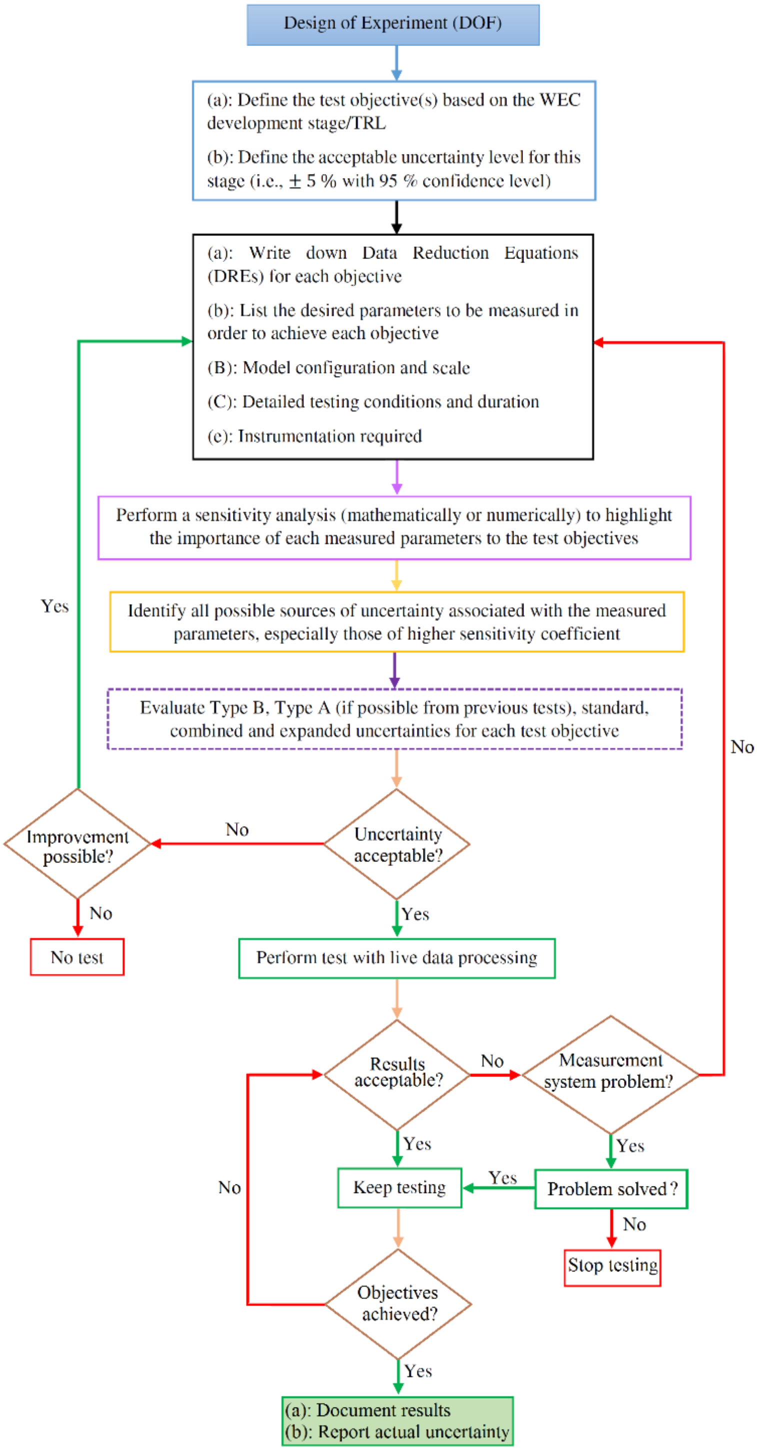

Figure 3: Flow chart of experimental process, indicating decision points and information sources. Adapted from ITTC Procedure 7.5-02-01-02.

- Errors in PTO system control equipment parameters such as size of orifice, turbine propeller rate of rotations, copper loss (resistance in the electric circuit of the PTO system), etc.;
- Disturbance from test arrangement of the model such as using signal cables for wave probes and pressure sensors attached to the model as in floating Oscillating Water Columns (OWCs);
- Measurement inaccuracies due to calibration or improper installation of instruments such as misalignment in an Acoustic Doppler Velocimetry (ADV), laser sheet for Particle Image Velocimetry (PIV), laser displacement sensors and potentiometers, etc.

7. ENERGY CAPTURE PERFORMANCE AT DIFFERENT TRLs

7.1 TRLs 1-3

As previously mentioned, the current procedure focuses principally in the experimental proof of concept tests to early “Wave to Wire” numerical model calibration and validation tests. A PTO simulator may or may not be included in these experiments.

For the numerical model calibration and validation tests, the uncertainty analysis of the quantities to be compared need to be performed for both the experimental and numerical model results. A guideline for the numerical modelling of wave energy converters can be found in ITTC guideline 7.5-02-07-03.18 and an example for numerical modelling uncertainty analysis (CFD in this case) can be found in ITTC guideline 7.5-03-01-01.

If a PTO simulator is considered, the Energy Capture Performance is usually represented by the capture width as described in the ITTC guideline 7.5-02-07-03.7 “Wave Energy Converter Model Test Experiments” as the quotient of the WEC hydrodynamic power absorbed and the wave energy flux (input wave power). The capture width can be derived from regular wave as well as irregular wave tests.

A preliminary power matrix can also be considered where the expected power absorbed or capture width of the device is reported in a matrix type table for a set of irregular sea states. The sea states in the table are defined by their peak period (rows) and significant wave height (columns). Depending on the targeted type of deployment sites (open sea or fetch limited area) Bretschneider or JONSWAP unidirectional wave spectra can be used but the choice must be mentioned. The power matrix can be developed from a series of experiments with irregular incident waves or it can be reconstructed using the regular wave results using the wave superposition principle. The later can only be developed if both the incident waves, WEC responses and PTO system behaviour can be considered linear. In any case, the combined uncertainties need to consider the uncertainties of both the hydrodynamic power absorbed and the wave energy flux.

The Froude number (the ratio between inertia and gravity forces) is usually used to scale tank testing. However, other numbers rule the behaviour of the flow, (Reynolds number, Cauchy number, Euler number, Strouhal number) which cannot be scaled at the same time. Furthermore, strong nonlinearities are usually present in WEC behaviour and due to the sparsity of full WEC development stages at multiple scales, uncertainties on the scaling method has not yet been fully investigated. This is a reason why testing at the highest scale possible is usually favoured.

The scaling of the capture width or power matrix results from small scale experiments to full scale needs to be handled with care as large uncertainties are certainly present. They should not be used for other purposes than the general TRL 1-3 objectives as defined in the ITTC guideline 7.5-02-07-03.7 "Wave Energy Converter Model Test Experiments".

7.2 TRLs 4-5

The power extraction tank testing of the device at medium TRLs needs to consider the power matrix of the actual extracted electrical power by including the PTO system and its control strategy. All sub-components such as the mooring system should be included in the tests. More realistic directional spectra need to be considered and spectra shape sensitivity tests performed. Current, wind and tide can also be considered.

Developing a full uncertainty analysis for such experimental tests becomes quite difficult where each of the WEC sub-component as well as the environmental parameters (wave, current etc.) uncertainties need to be independently developed and then combined.

It is advised that a numerical uncertainty model be created using numerical methods such as the Monte Carlo Method. Similar models can also be used in the survivability tests. A comprehensive example of the Monte Carlo method for deriving the uncertainties in a WEC experiment at small scale can be found in Orphin et al. (2021).

7.3 TRLs 6-9

Tests in the system validation stage (TRL 6-7), and the prototype and demonstration stage (TRL 8-9) are typically carried out at sea at large or full scale where real sea conditions including current, wind, tide interactions are investigated. Using these results, the mean annual energy production for a targeted site is usually developed.

Additionally, from further developing the model from TRLs 4-5, the uncertainty model needs to take into account the uncertainties of the uncontrolled environmental measurements of the test site and the resource assessment uncertainties of the targeted deployment site. An example of uncertainty in wave resource assessment can be found in Mackay et al. (2010).

8. EXAMPLE OF UNCERTAINTY ANALYSIS APPLIED TO AN OWC TYPE WEC EXPERIMENTAL TEST

8.1 Introduction to the experiment

A 1:50 model–scale of a fixed offshore OWC–WEC is considered in this section to quantify the loads and the OWC chamber pressure uncertainties in the physical measurements under regular incident wave conditions.

The dimensions of the device are illustrated in Figure 4. The OWC chamber extends from the length of the device and centred with a width of 200mm. The chamber is partially submerged (200mm) and fully opened in the downward direction to allow the action of the waves. A 50mm diameter orifice is located at the top of the chamber to constrict the air flow so as to modelized the effect of the PTO system.

The experiment was performed in the 100 m long, 3.5 m wide, 1.5 m deep towing tank of the Australian Maritime College (AMC), University of Tasmania, Australia (see Figure 5). The tank is equipped with a flap–type wavemaker at one end and a wave–absorption at the other end.

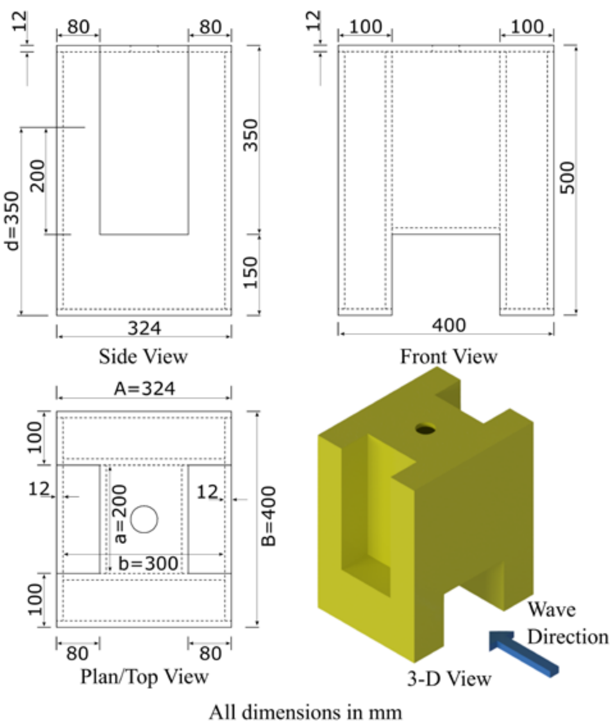

Figure 4: 1:50 offshore–stationary OWC dimensions

Figure 5: A general view of the AMC towing tank showing the OWC model installed in the tank, looking towards the beach.

In order to monitor the wave envelope resulting from the wave–OWC hydrodynamic interactions, six custom made resistive–type wave probes WP (names as WP_0 – WP_5) were installed along the tank as shown in the experiment layout in Figure 6 (a). WP_0 measured the incident waves, WP_1 – WP_3 were used to resolve the incident and reflected waves (energy), WP_4 measured the waves (energy) transmitted on the model's leeside and WP_5 (phase WP) was employed to provide information regarding the incoming waves approaching the model's front wall.

The OWC was fitted with three WPs: one at the centreline of OWC's front wall to measure the wave run–up (WP_6) and the other two (WP_7 – WP_8) installed inside the OWC's chamber for averaging the measured water level elevation (η) and the free surface vertical velocity ($d\eta/dt$). In addition, two pressure sensors, Honeywell–TruStability–001PD TSC Series (P_1 and P_2) for averaging the chamber's differential air pressure ($\Delta P(t)$), were installed on the OWC's top plate (see Figure 6(b)). Having defined the free surface vertical velocity and assuming incompressible air for the small scale used in the experiment, airflow rate ($Q(t)$) can be calculated as in Equation (12) and then the time–averaged extracted pneumatic power (P_{WEC}) and the overall hydrodynamic non-dimensional capture width (ζ) are calculated from Equations (13) and (14), respectively.

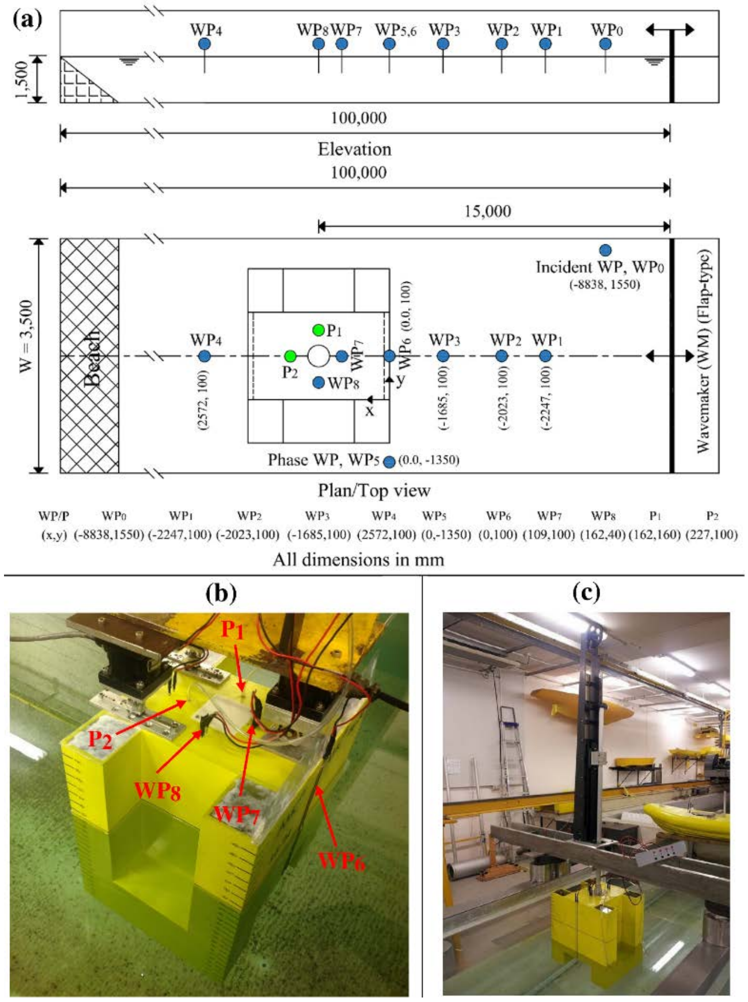

Figure 6: (a) Experiment layout (not to scale), (b) OWC wave probes and pressure sensors, and (c) OWC wave probes calibration procedure

$$Q(t) = \frac{d\eta}{dt} ba \left[\frac{m^3}{s}\right] \quad (12)$$

where b and a are the chamber's length and width, respectively (see Figure 4).

$$P_{WEC} = \frac{1}{T}\int_0^T \Delta P(t) Q(t)\, dt \; [W] \quad (13)$$

where T is the wave period.

$$\zeta = \frac{P}{aP_W} [-] \quad (14)$$

where P_W is the incident wave energy flux (power) per unit width that is defined as the product of the total (potential and kinetic) wave energy (E) per unit ocean surface area and the group velocity (c_G) (Dalrymple and Dean, 1991):

$$P_W = \frac{1}{8}\rho g H_W^2 c_G \left[\frac{W}{m}\right] \quad (15)$$

where (H_W) is the incident wave height measured from pick to trough using the incident wave probe WP_0.

The six wave probes along the tank were calibrated daily, whereas OWC wave probes and pressure transducers were calibrated before and after completing the experiment. All OWC wave probes were calibrated at the same time as illustrated in Figure 6 (C). All measurements were sampled at 200 Hz.

8.2 Measurement uncertainty analysis

The two uncertainty types described in Section 4 are calculated as follows:

8.2.1 Type B uncertainty

The calibration procedures for the pressure sensors and wave probes were performed by an in-situ end-to-end calibration with the same data acquisition system and software used during the tests as advised by ITTC Recommended Procedures and Guidelines 7.5-02-07-02.1, "Seakeeping Experiments". This procedure characterises the sensor/instrument's uncertainty as it includes many of the possible Type B uncertainties in the calibration procedure so that details of uncertainty analysis of signal conditioning and data acquisition system is not necessary. Following the calibration process, the curve fitting's standard Type B uncertainty (u_B) is estimated using the standard error of estimation (SEE) 1.5 given in Equation (16).

$$u_B = SEE = \sqrt{\frac{\left(y_j - \widehat{y_j}\right)^2}{M-2}} \tag{16}$$

where M is the number of calibration samples/points, y_i and $\widehat{y_i}$ are the calibrated data point and the fitted value from the linear regression analysis, respectively.

8.2.2 Type A uncertainty

As discussed in Section 1.4, Type A uncertainty (u_A) depends on the experiment repeatability and this uncertainty is estimated as the standard deviation of the mean given by Equation (8). Examples of the experiment repeatability in time series are shown in Figure 7 for two tested conditions of $H_W = 0.05$ m, T = 1.2 s and $H_W = 0.10$ m, T = 1.2 s.

8.2.3 Standard uncertainty

After evaluating Type A and Type B uncertainties for each load cell component, the standard uncertainty (u) that combines both uncertainty types are calculated by (2).

8.2.4 Combined uncertainty

The chamber's differential air pressure is the average of two pressure sensors (P1 and P2). Similarly, the chamber's free surface oscillation is the average of WP7 and WP8. Accordingly, the combined standard uncertainties in air pressure ($u_c(P_{AVG})$) and free surface oscillation ($u_c(\eta_{OWC})$) are computed via the law of propagation of uncertainty described in 1.2 (and shown again below in Equation (17)) as given in Equations (18) and (19), respectively (ITTC Procedure 7.5-02-01-01):

$$u_c^2(y) = \sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i) \tag{17}$$

$$u_c(P_{AVG}) = \sqrt{\left(\frac{u(P_1)}{2}\right)^2 + \left(\frac{u(P_2)}{2}\right)^2} \tag{18}$$

where $u(P_1)$ and $u(P_2)$ are the standard uncertainty for pressure sensors P_1 and P_2, respectively.

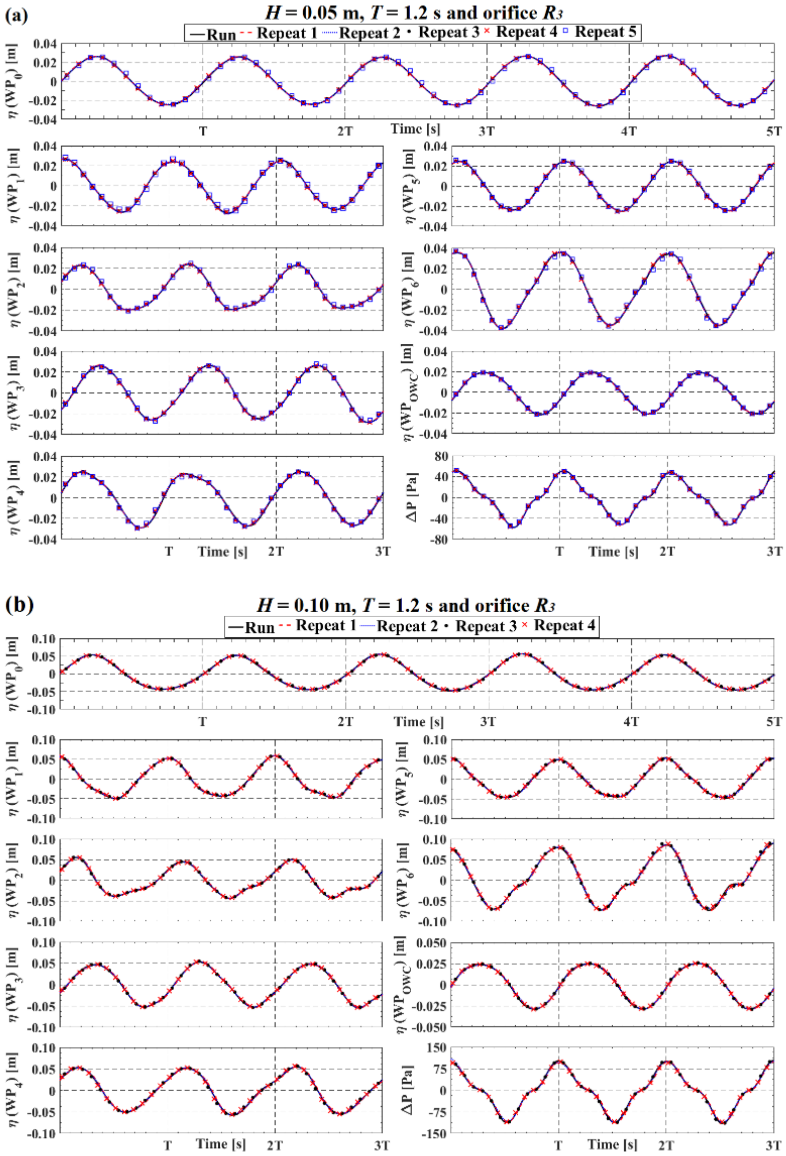

Figure 7: Experiment repeatability. (a) $H_W = 0.05$ m, $T = 1.2$ s, orifice R3 and (b) $H_W = 0.10$ m, $T = 1.2$ s and orifice R3 (radius = 17.84 mm)

$$u_c(\eta_{OWC}) = \sqrt{\left(\frac{u_{WP7}}{2}\right)^2 + \left(\frac{u_{WP8}}{2}\right)^2} \qquad (19)$$

where u_{WP7} and u_{WP8} are the standard uncertainty for WP_7 and WP_8, respectively.

8.2.5 Expanded uncertainty

The different general uncertainties (Type A, Type B and u) for each of the wave probe elevations and pressure measurements, the combined uncertainties (u_c) for the average pressure and free surface elevation inside the OWC chamber as well as the related expanded uncertainties (U) are summarized in Table 2 for two different incident wave heights used: H_{50} = 50 mm and H_{100} = 100 mm. The expanded uncertainties (U) is calculated with a 95% confidence. As only five runs were performed for each of the wave heights, the coverage factor (k) was taken from the T-Distribution tables with a value of k = 2.776.

Table 2: Experimental uncertainties

Instrument	Standard uncertainty					Expanded uncertainty (U)	
	Type A (u_A)		Type B (u_B)	u, u_c			
	H_{50}	H_{100}		H_{50}	H_{100}	H_{50}	H_{100}
WP_0 [mm]	±0.08	±0.09	±0.50	±0.51	±0.51	±1.42	±1.42
WP_1 [mm]	±0.13	±0.19	±0.36	±0.38	±0.41	±1.05	±1.14
WP_2 [mm]	±0.14	±0.18	±0.38	±0.40	±0.42	±1.11	±1.17
WP_3 [mm]	±0.14	±0.55	±0.35	±0.38	±0.65	±1.05	±1.80
WP_4 [mm]	±0.24	±0.07	±0.90	±0.93	±0.90	±2.58	±2.50
WP_5 [mm]	±0.20	±0.47	±0.41	±0.46	±0.62	±1.28	±1.72
WP_6 [mm]	±0.29	±0.67	±0.55	±0.62	±0.87	±1.72	±2.42
WP_7 [mm]	±0.08	±0.32	±0.54	±0.55	±0.63	NA	NA
WP_8 [mm]	±0.07	±0.21	±0.84	±0.84	±0.87	NA	NA
η_{OWC} [mm]	NA	NA	NA	±0.50	±0.54	±1.39	±1.50
P_1 [Pa]	±0.30	±2.06	±4.20	±4.21	±4.68	NA	NA
P_2 [Pa]	±0.30	±2.08	±3.90	±3.91	±4.42	NA	NA
P_{AVG} [Pa]	NA	NA	NA	±2.87	±3.22	±7.97	±8.94

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