ITTC Quality System Manual

Recommended Procedures and Guidelines

Guideline

Practical Guidelines for Numerical Modelling of Wave Energy Converters

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Disclaimer

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Practical Guidelines for Numerical Modelling of Wave Energy Converters

1. PURPOSE OF THE GUIDELINES

The purpose of these guidelines is to provide a methodology to assess the fidelity of the numerical simulation for Wave Energy Converters (WECs) at different stages of development, to set up numerical calculations and to analyze the obtained results.

2. PARAMETERS AND MODELLING STAGES

It is not possible to draw general guidelines for all WECs because of their variety and of their very different development stages. In the following, the used classification of types, the energy capture techniques, the definition of the development stages, and the specific problems the WECs developments have to face will be specified.

2.1 Types of WECs

According to the classification in Falcao, 2010 and Babarit et al. 2015, a WEC can be classified according to its operational principle as oscillating water columns (OWCs), overtopping devices, oscillating bodies, floating and bottom fixed, and Oscillating Wave Surge Converters (OWSCs). The archetype of each of them is represented in Figure 1 (after Babarit (2015)).

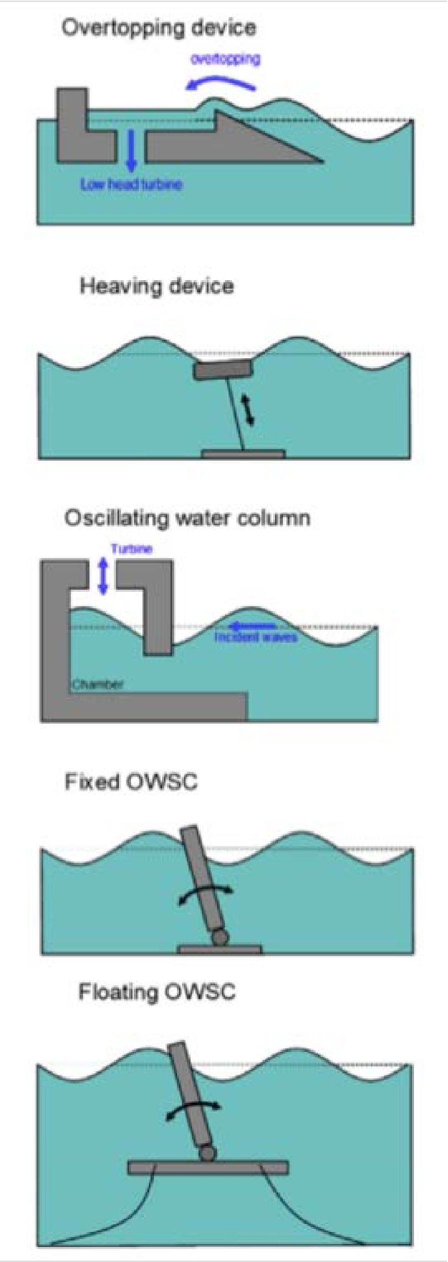

Figure 1: WECs classification (after Babarit (2015))

2.2 Energy capture

The wave energy is captured by the OWC devices trough the motion of the free surface in the internal chamber. The oscillations then drive an air flow through a turbine.

In the case of the overtopping devices the green water is recovered in a reservoir before passing through a turbine.

Heaving devices and OWSCs extract power by the relative motion of different parts of the WEC. Different mechanisms are then used to convert the motion into useful power such as hydraulic converters or linear motors.

2.3 TRL

The large variety of WECs is also characterized by a very large range of development. Here, the development stage of a technology is addressed using a 1 to 9 scale introduced by NASA in 1974. It is known as the Technology Readiness Level (TRL) and it goes from 1 that stands for basic scientific research to 9 where the actual system is proven in operational environment (see https://www.nasa.gov/topics/aeronautics/features/trl_demystified.html).

When the TRL becomes larger than 2, the WEC reliability and survivability have to be addressed.

2.4 Fatigue

WECs are often designed to work in conditions close to resonance. This means that there is either a large body motion (floating or moving devices) or large motion of the free surface inside the OWCs. Both conditions make the device subject to continuous oscillating loads and can cause fatigue failures. This drawback has to be avoided in the lifetime of the WEC; thus requiring a survey and maintenance timeline for the different parts.

2.5 Survivability

As all the marine structures, WECs have to withstand sever sea conditions. Unlike classical offshore structures, they can be subject to very large body motions and the conditions that produce the largest loading on the structure, on the Power Take Off (PTO) system and/or on the mooring system are dependent on the kind of device and are not necessarily caused by the largest wave. For example, in the case of the floating OWSC, strong (but not extreme) waves in resonant conditions can cause the impact between the moving parts.

Nonetheless, performing runs in extreme conditions in survival or failure mode is still an important step to prove the structural strength of the device and of the mooring lines.

The return period of the extreme conditions and the sea state are to be considered in the deployment site and, where possible, balancing failure possibilities with costs.

2.6 Arrays

The configuration of WECs in arrays may lead to reduction of the capital cost per device by sharing parts among the devices such as mooring systems, PTO system and electrical infrastructure.

However, WECs development stage is still low, and the numerical analysis of array configurations is still limited. For this reason, it is not included in the current guidelines.

3. METHODS

3.1 Analytical models

When dealing with WECs, the involved problems are quite complex and often include significant nonlinearities of the flow and of the fluid-structure/PTO interaction. However, in some particular cases and in the early stages of the design, the WEC geometry can be simplified and the hypothesis of incompressible, irrotational, isothermal, inviscid fluid with small amplitude of oscillations of the body and of the free surface can be considered reliable enough. In such conditions, analytical solutions can be determined. They rely on the superposition principle so that the whole problem is divided into diffraction and scattering problems (Alves (2016), Budan *et al* (1975), Falnes *et al* (1985)). This allows the determination of both the free surface oscillation and the body motion. The equations can then be linked to a simplified model of the PTO to calculate the possible hydrodynamic extracted power.

This method allows the study of the problem in a very fast way and can be used in the very early stages of the design of WECs in order to define the gross dimensions of the device depending on the deployment site characteristics.

3.2 Potential flow (PF) models

As the design stage progresses and the shape of the body becomes more complex and assuming that the fluid can still be considered irrotational, isothermal and inviscid, potential flow theory can be applied and the velocity field can be written as the gradient of a potential function satisfying the Laplace equation. In cases where the losses due boundary layer effects, flow separation, vortex shedding and wave breaking are negligible, the potential flow solution represents an accurate and reliable tool of analysis.

The potential solution can be either linear or non-linear.

3.2.1 Linear solution

For the linear approximation of the equations, the free surface and the body oscillations around the equilibrium position are small, so that higher order effects are neglected. The linear solution can be obtained either in frequency or time domains with models usually based on a boundary element methods (BEM) or on finite element methods (FEM). Even though the former model requires only the discretization of the boundary surfaces, while the other requires the discretization of the whole computational domain, the computational load does not vary very much between the two. With the BEM method, a fully populated stiffness matrix has to be inverted, while the FEM method usually results in a larger but sparser banded matrix.

Frequency domain models assume that the excitation and responses to be simple harmonics, the time dependency of the solution can be removed and the superposition principle can be applied. These models are usually highly CPU efficient allowing for fast first-order optimization stage.

On the other hand, time domain solutions are more computational expensive but can be coupled with other potentially nonlinear algorithms such as those modelling PTO effects and mooring systems (see Hybrid Models Section). This makes the time domain solution more suitable when defining a higher level performance analysis and designing the control strategy for the PTO system. Moreover, the time domain solution allows taking into account other weakly nonlinear hydrodynamic properties, for example the body motion and free surface deformation can be directly used to calculate the body forces on the actual wetted surface at each time-step, commonly referred to as nonlinear Froude–Krylov forces (Gilloteaux *et al* (2007)). Furthermore, the body exact method can be used. With it, the exact body shape is used at each time step in conjunction with the linear free surface boundary condition. This allows all the nonlinearities associated with changing body shape and the above water portion of the hull to be taken into account.

3.2.2 Nonlinear solution

In the time domain, Fully Non-linear Potential Flow (FNPF) algorithms can correctly model large wave amplitudes and large body motions with an eventual damping correction to take into account viscous effects on the WEC. (Fitzgerald (2016)). The solution to the fully non-linear problem can once again be based on either BEM or FEM. The remeshing of the computational domain at each time-step is however, usually required in order to take into account the deformation of the free surface. This and the necessity to invert a matrix at each time step cause a large increase in the computational requirement compared to linear models.

Recently, a Finite Difference Method (FDM) called Harmonic Polynomial Cells (Hanssen *et al* (2015)) has been used to describe floating bodies showing a very efficient solution of the FNPF.

However, even in the most advanced FNPFs, the viscous effects and the free surface breaking are neglected.

While performing fully nonlinear free surface calculations, wave breaking has to be delt with as it is going to be a problem even in small to moderate seas. There are several techniques to “fix” the free surface: artificial damping, peeling, etc. Unfortunately, none of these methods works in all cases and their application has to be carefully studied in order to get realistic post-breaking solutions.

3.3 Computational fluid dynamics (CFD)

In real sea conditions, both viscous effects and wave breaking can have non-negligible effects on the WEC behaviour and it is recommended that CFD solutions should be considered especially in high TRLs for the verification stage as well as survivability studies.

There is a wide variety of CFD methods that can be used to discretize the Full Navier-Stokes equations. The most classical ones are Finite Volume Methods (FVM) and Finite Difference Methods (FDM). However, new methods are becoming more often used in marine renewable energy applications such as the Smoothed Particle Hydrodynamics (SPH) methods and the Lattice Boltzmann Methods (LBM). All of them allow for large deformations of the free surface, wave breaking and turbulence modelling.

The high fidelity CFD solutions are computationally expensive. Their cost can be limited by coupling them with other more efficient PF methods as described in the next paragraph.

3.4 Hybrid Models

For a complete study of the WECs, the fluid dynamic models have to be coupled with external solvers:

1. to take into account Fluid Structure Interaction (FSI): in a simplified coupling, the fluid forcing is passed to the struc-tural solver that evaluates the strain on the structure and the fatigue acting on it (weak coupling); in the case where the frequency of the structural response is similar to the characteristic resonant frequency of the WEC, a two-way strong coupling can become necessary;
2. to take into account the mooring response: in fact, the mooring can strongly influ-ence the performance of the WEC;
3. to model the PTO system: either by a sophisticated software that can also im-plement the control strategy or by a more simplified elastic and damping model;
4. compensating the expensive computational time of the CFD solvers: the compu-tational domain can be reduced to the near-WEC region resolving the strong close field non-linearities; the CFD can then be coupled with lower-fidelity models on the far field; this coupling has to be strong to avoid undesired re-flection from the coupling boundaries.

3.5 Numerical Facilities

The computational costs of the different solvers are very different so that facilities to run the solvers vary from the laptop for both analytical and linear PF solutions, to workstations for the non-linear PF and simplified CFD calculations or hybrid PF-CFD solutions, to High Performance Computing (HPC) clusters and HPC cloud computing. The choice between the last two depends on the availability of a local cluster or not. In the case of the local cluster, there is the possibility of longer time storage of the data and of the source code. In the case where such a resource is not available, there is a large variety of servers that offer HPC cloud computing (i.e. Amazon, Microsoft Azure, SGI, etc.). They can be accessed on a pay-as-you-go basis and allow the choice of the most suitable hardware structure (for example the kind of processors can be freely chosen). Their drawback is the need to set up a docker, *i.e.* a software based on an Operating System virtualization that self contains the necessary structures to run the simulation without the need to compile the algorithm on the specific kernel of the HPC cluster. This makes the simulation as portable as possible (https://www.docker.com/).

Table 1 shows in which conditions the different models can be used.

Table 1: Brief summary of the models applicability and features

Models	TRL	Objectives	Wave conditions	Non hydrodynamic features:			Facilities
				PTO	mooring	Fluid structure interaction	
Analitical solutionLinear PF	1-3	Concept validation	Regular waves irregular (long crested)	Linearized	Linearized	No	Laptop
FNPF/CFD	4	Concept design: Real sea performance	Short crested waves	Simplified	Simplified	No	Workstation / HPC / Cloud computing
Hybrid models	5-6	Concept rating: Power rating; Survivability	Deployment site features/extreme conditions	Advanced	Full	Coupled solution	HPC/Cloud computing

4. PRE-PROCESSING

4.1 Device geometry

Following the ITTC procedure 7.5-03-02-03, the geometry files defining the body should be checked for reasonable surface smoothness and for appropriate connections among the describing surfaces for a closed body. Unlike classical hull shapes, WECs can be characterized by joints or sliding parts. Their features have to be exactly specified: exact position, maximum and minimum excursion of the moving parts, eventual damping in the motion. Some devices are even characterized by deformable surfaces; their structural features have to be clearly stated.

In the case of OWCs, an artificial modification has to be imposed on the body to mimic the presence of the turbine whose fluid dynamic modelling is unfeasible.

4.2 Computational domain and boundary conditions

The size of the computational domain is to be determined to avoid as much as possible the interaction with the computational boundaries of the fluid domain.

The inlet boundary should be at least six wave lengths (6λ) in front of the device, the outlet should be at least 2λ downstream of the device unless it is close to the coastline and the coast delimits the actual domain boundary.

4.2.1 Bathymetry

The numerical representation of the bottom varies according to the water depth (Le Méhauté (1976)):

1. In deep water, the bottom limit of the computational domain can be chosen to be a wavelength below the WEC.
2. In finite-depth water conditions, the bottom exact position has to be taken into account; in the first stages of design, it can be approximated as a flatbed but, in later stages, the local bathymetry has to be represented especially if strong variations are found locally;
3. In shallow water, the exact bathymetry should be considered.

4.2.2 Atmosphere

In case of a multiphase CFD simulation, the computational domain has an upper limit in air. To reduce as much as possible the computational cost, while still maintaining the required accuracy, the upper boundary has to be higher than the maximum expected wave height. In the case of an OWC, there should be a region around the turbine exit to allow the correct alignment of the flow.

4.3 Environmental conditions

4.3.1 Wave inlet

The wave generation at the inlet can be achieved in several ways:

1. moving boundaries that mimics the presence of a wavemaker either flap or piston type: this technique is optimal when comparing with wave tank data, with the wavemaker motion being assumed equal to the physical one;
2. static boundary with Dirichlet boundary conditions: the use of this method is very delicate because it can lead to instability, and its accuracy depends very much on the numerical discretization of the convection terms; moreover, the choice of the correct analytical approximation of the incoming wave has to be considered according to the work by Le Méhauté (1976);
3. relaxation method: it is very similar to Dirichlet boundary conditions but the analytical solution is calculated on a region (usually equal to a wavelength) and relaxed through a function that smoothly matches it with the full numerical solution; it is advised that the relaxation length is at least equal to a wavelength λ.
4. other ways are available as the mass source method but they are cumbersome and their accuracy is still uncertain.

4.3.2 Wave absorption

Similar to the wave inlet, there are several choices for the wave absorption as described in Windt *et al* (2018):

1. The relaxation zone, with the solution smoothly damped to calm water conditions
2. The passive absorption, where the mesh stretching and/or a slope towards the outlet mimics the presence of a beach; this solution can be combined with the former to reduce the length of the domain;
3. The static boundary condition, where the outlet velocity is calculated to allow the waves to exit the domain without reflections; this method is cumbersome though and it can only be used in shallow water conditions where hyperbolic conditions take place;
4. Dynamic boundary conditions, as for the inflow conditions, a numerical wavemaker is positioned at the far ends of the domain and

acts as the absorbing wavemaker in wave tanks, however the accuracy of this method is not yet properly stated.

4.3.3 Current

The presence of currents in the proximity of the WECs alter wave steepness. It makes it milder if it moves in the same direction of the waves, and steeper on the opposite direction. The correct implementation of the boundary conditions both at the inlet and at the outlets, should be verified without the body in the fluid domain to check that wave current interaction is correctly achieved without spurious instabilities.

4.3.4 Turbulence

The flow regime for WEC operations should be identified using Reynolds and Keuleng-Carpenter Numbers, respectively written as:

$$Re = \frac{\zeta_{VF} L}{T\nu} \tag{1}$$

$$KC = \frac{\zeta_{VF} T}{L} \tag{2}$$

where, L is the characteristic length, ν the kinematic viscosity, ζ_{VF} amplitude of the wave flow oscillations and T the wave period.

However, there is no generally valid rule to state the values of Re and KC limiting the laminar-turbulent border. This border can depend very much on the problems that have to be studied (fixed/floating device, sharp/smooth edges). However, as a gross estimate, if the Reynolds number is larger than $5 \cdot 10^4$ and KC>1.0, it is likely that turbulence can play an important role.

Considering that Direct Numerical Simulations (DNS) are unfeasible, the models of turbulence are listed below from the lowest fidelity to the highest one:

1) *Reynolds Averaged Navier-Stokes (RANS)* models: the fluid properties are written as the sum of a fluctuating part and a time averaged one (Reynolds Averaged). This fluctuating part introduces a further shear stress that is added in the averaged equations as a turbulent viscosity. To derive this quantity, a closure to the NS equations is necessary, the most commonly used closures are:

    a. *k-ε models (Launder et al. (1974)):* two equations are introduced for the turbulent energy k and the dissipation rate of the kinematic energy ε. The main limit of this model is the poor accuracy in the near wall regions, this drawback is partially overcome with the following development of the *Realisable k-ε models (Shih et al., 1995)* and *Re-Normalisation Group (RNG) k-ε models (Yakhot et al (1992)).*

    b. *k-ω model (Wilcox (1988)):* where the equation for the kinetic energy dissipation rate is substituted with one for the turbulent frequency ω. Differently from the former model, this one is characterized by poor accuracy in the far field.

    c. *k-ω Shear Stress Transport models (Menter (1992)):* it combines the k-ω model in the near wall regions to a k-ε model in the far field.

2) *Large Eddy Simulation (LES):* The Navier-Stokes equations are filtered in space rather than averaged in time; the

sub-grid scale (SGS) that cannot be resolved on the computational grid are modelled with a SGS stress model (Versteeg et al., 2007). The limit of this model is the high computational cost as the model aims to resolve very small scales of turbulence.

3) *The Reynolds Stress Model (RSM)*: The RSM closes the NS equations with a more rigorous relationship between the stresses and the strains. This is obtained introducing six Reynolds stresses $R_{ij} = \overline{u_i' u_j'}$ besides the kinematic energy ε. The high computational cost and the difficulties in convergence of this method limits its application to the WECs problems.

5. COMPUTATIONS

5.1 Time and spatial discretization

The choice of the time and space discretization are usually made balancing accuracy and efficiency in the solution.

Faster solvers, such as the potential flow solver, are usually discretized with higher order accuracy compared to full CFD simulations. However, the features of the WEC problems, usually involving large resonant motion, require a strict analysis of the discretization steps.

As for the time schemes, first order schemes are usually favoured to reduce the computational time, however explicit schemes can cause instabilities and implicit ones can introduce damping. For these reasons, for long time series, it is important to rely on higher order schemes (at least second order) for the correct approximation of the incoming waves.

As for the spatial discretization, the kind of computational grid varies according to the used computational model. For BEMs, only the body surface and computational boundaries have to be represented. In this case the body surface has to be panelled taking care that: 1) the panels are refined where there are abrupt pressure changes and high fluid flows, 2) adjacent bodies should not touch throughout the computation, 3) panels should have a low aspect ratio and small skewness; the mesh size should vary gradually along the body, 4) the mesh size in the longitudinal direction should be smaller than □□□□□□where □□is the wave length (however convergence tests have to be performed), 5) in the case of non-linear PF, with free surface deformation and body motion, refining is necessary to resolve the wave profile. Also, some type of numerical methods may be necessary to handle wave breaking (see note at the end of section 3.2.2).

In the case of full CFD computations, the computational grid can be body fitted or represented through an Immersed Boundary (IB) or a Cut Cells (CC) method.

In the first case, the body surface should be represented with the same first three constraints of the BEM but the mesh size along the wave direction should be smaller than □□□□□□ and in the case of irregular waves, there should be at least 20 points along the minimum wave length.

In the cases where the IB or the CC methods are used, the requirement of the mesh size remains unaltered and refinement should take place in the region of high curvature of the body. In all cases, in the direction normal to the body, the mesh size should satisfy the requirements of the model used to take into account the viscous effects.

In proximity of the free surface, CFD simulations require that the mesh size is refined to avoid numerical viscous effects, so the number of cells per wave height should not be lower than 20.

As for the discretization schemes, the most commonly used schemes for the advection term are based on second-order discretization using a flux limiter, the accuracy and stability issues introduced by this discretization have to be addressed on a case by case basis.

The link between time step and spatial discretization is through the Courant-Fredikson-Levy (CFL) number that is defined as the maximum value of $\frac{u\Delta t}{\Delta x}$ on the grid points. It indicates how far the information travels in the time step Δt relatively to the mesh size Δx. For explicit time integration schemes, CFL should be strictly lower than 1. In case of implicit time integration schemes, the CFL can be larger than 1 because there is no issue with scheme instabilities, but convergence and accuracy should be checked (Hirsh, 1988).

5.2 Device response

For floating WECs, the device moves as a result of the wave action, the effect of gravity, the action of eventual mooring lines and of the PTO. This means that, once all the forces are calculated, the equations of motion for the solid body have to be solved; acceleration, velocity and displacement of the WEC have to be updated.

In case of a mesh based calculation, the grid can deform, in the case of large motion of the WEC regridding could be necessary if some cells become characterized by high skewness. In the case of overlapping grids, IB or CC methods, this is not necessary, but the mesh should be dynamically refined close to the position of the body, or the part of the boundary fitted grid has to be remapped on the background mesh at each time step.

Depending on the discretization schemes and on the method used to let the grid follow the body motion, the calculated forces can be affected by numerical oscillations. In such cases, a suitable filtering or relaxation method has to be implemented to avoid instabilities in the body motion calculation.

5.2.1 Mooring system

The mooring lines contribute to the total force influencing the WEC motion. Depending on the design, the mooring lines can be considered: 1) passive, used for the station keeping, with influence only on the slow drift motion and with limited effect on the WEC performance; 2) active, directly influencing the WEC motion and performance; 3) reacting, that directly takes part into the power extraction.

Depending on their use, the mooring lines can be neglected or not and have to be modelled with lower or higher fidelity. The easiest way to take them into account is to substitute for them with a spring. However, in the verification stage or in case they are active or reacting, more sophisticated models have to be integrated into the fluid-dynamic simulation.

5.2.2 PTO, hybrid systems

The importance of the PTO system in the wave energy conversion would require its nonlinear modelling. Unfortunately, no study can be found to include it into a wave-to-wire modelling. Currently the PTO is represented in a very simplified way; for example, in the studies of OWC devices, normally the PTO is represented with an orifice that assures a pressure jump similar in behavior to the actual turbine. Practically, the PTO effect is represented with a linear damping force. The same rule is also used in the case of a pure electrical PTO system (Babarit *et al* (2012)) and a Coulomb damping force represents the hydraulic ones. However, since very few devices have been working for a long time at high TRL, the code development of sophisticated PTO representations with all its elements is premature. Only a few papers with more articulated representation of the PTO system in OWC devices are available, (Henriques *et al* (2016)). They take into account the response of the turbine at different air fluxes, the air compressibility and eventual mechanical losses.

5.2.3 Control

The need to demonstrate the power output potential of WECs has pushed researchers to improve the control systems.

The most commonly used strategies for the control systems are the reactive control and the latching control (Greave *et al* (2018)). The former is based on a representation of the PTO system as an elastic part in parallel with a damper. These parts are added as external forces to the hydrodynamic restoring and damping forces of the WEC system. The absorbed power is obtained through the damping (resistive) part, in phase with velocity, while the spring force component gives reactive power with an average zero contribution to the power. The aim of the reactive control system is to change the damping and elastic parameters of the PTO system in order to maximize the extracted power or decrease device loads in survivability mode.

The PTO reactive control is usually highly demanding in terms of resolution of the force control and PTO system size in order to handle high reactivity for power optimisation.

The latching control is easier. It aims to have a velocity in phase with the excitation force to maximize the extracted power. When this does not happen naturally, as soon as the velocity becomes zero, the position of the floating part of the WEC is locked for a time interval T_L long enough to reach this objective see figure (2). This control strategy was first introduced in Budal *et al* (1980), and it is applicable when the resonance frequency is higher than the wave frequency.

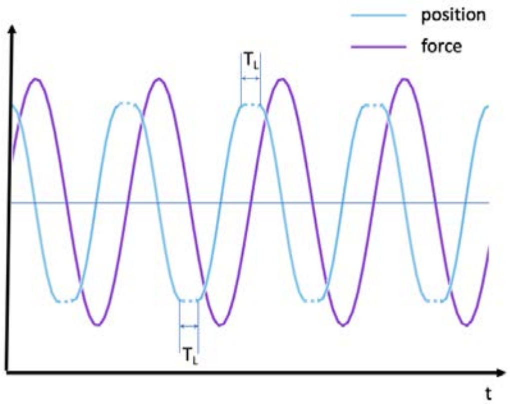

Figure 2: Latching control to put position and force in phase.

These control strategies are mainly based on Cummins equation (Cummins (1962)), where the hydrodynamic parameters are determined using linear potential flow solvers. Practically, they are based on the assumptions that the variations with respect to the equilibrium conditions are small. This hypothesis is far from true for wave energy converters, so in Davidson *et al* (2015), the parameter for the linear models where determined using the results of nonlinear calculations in the numerical wave tank and inserted into an adaptive receding horizon pseudo-spectral controller. It is one of the first examples of work to evaluate the control strategy in a nonlinear environment.

5.2.4 Loads

For a WEC design moving towards high TRL, the correct estimation of the loads is fundamental in the case of: 1) a WEC with separate moving parts, 2) if the PTO is sensitive to local loads as for piezoelectric or dielectric materials or 3) to evaluate extreme loads in extreme sea conditions and survival mode. In these cases,in order to get the correct estimate of the loads, viscous effects and possible wave breaking must be taken into account, and the use of full CFD calculations will be necessary.

6. POST-PROCESSING

6.1 Data collection

Results of the computational analysis in the frequency domain should be summarized in the RAO of the WEC in terms of body motion and extracted power.

In the time domain, the results should be presented as time histories of:

1. wave height along the numerical wave tank to verify the incoming wave;
2. wave height close to the body to calculate the effect of diffracted and radiated waves (where available, in the same position as the experiments);
3. Pressure on the body and in the compression chamber for OWCs;
4. Forces on each of the separate parts of the WEC;
5. Body motion;
6. Extracted power;
7. Forces acting on mooring lines and their eventual elastic deformation.

6.2 Data analysis

The procedure for the analysis of results in regular and irregular waves can be found respectively in the ITTC recommended Procedures 7.5-02-07-03.2 and 7.5-02-07-02.1.

The collected data should always be compared with experimental data where available. In particular the accurate modelling of the incident wave should be assured.

Where experiments are available, the wave evolution around the body, the forces on the WEC and the extracted power should be compared to validate the solution.

Then the numerical simulations should be run in full scale, for several wave conditions and the real site bathymetry to estimate the extracted power in the lifetime of the WEC.

A non-dimensional Capture Width Ratio (ζ) should be identified with

$$\zeta = \frac{P_{WEC}}{P_W L} \tag{3}$$

the ratio between absorbed wave power P_{WEC} (in kW) and the wave resource P_W (in kW/m) multiplied by the characteristic length L (in m) of the WEC. For more details see section 1.8 in the ITTC procedure 7.5-02-07-03.7.

In case of TRLs larger than 5, when possible, the Levelized Cost Of Energy (LCOE) should be indicated. Following Astariz et al. 2015, it is obtained as the ratio between Present Value (PV) of the costs C_t and of the electrical outputs O_t, over a period t, with a discount rate r on the renewable energy.

$$LCOE = \frac{PV(Ct)}{PV(Ot)} = \sum_{t=1}^{n} \frac{C_t/(1+r)^t}{O_t/(1+r)^t} \tag{4}$$

where the present value of cost is calculated adding investment, construction, operation and maintenance and decommissioning costs.

An FFT of the wave loads should be carried out so as to obtain the amplitude of loads on the structure and on the mooring system and their frequency. The results of this analysis should be passed to the structural solver to identify points that are subject to fatigue to schedule the service inspections and to state the most suitable materials for the WEC construction.

Moreover, in the numerical solution, the extreme values of the wave loads on the structure, on the mooring lines and the extreme conditions for the PTO system should be pointed out in both survival and failure modes. This should help to design the device to survive the extreme conditions that can be foreseen in the deployment time.

Comparison with linear calculations should point out the limit of the use of linear approximation for the control strategy and eventually give corrections parameters.

6.3 Verification and validation

The ITTC procedure 7.5-03-01-01 furnishes an exhaustive analysis of the verification and validation technique. For WECs, it is advised to quantify exactly the order of convergence in order to estimate errors and uncertainty particularly related to mesh generation and to the simplifying assumptions for the PTO and mooring effects. In cases where experimental data are available, the uncertainty of the experiments and the model should be taken into account in the process of validation of numerical results. An example for numerical modelling uncertainty analysis (CFD in this case) can be found in ITTC guideline 7.5-03-01-01.

When comparing with the experimental data, the same experimental conditions should be used for the validation. However, the experimental limits should be overcome with the numerical results both in terms of blockage effect and scaling effects.

6.3.1 Blockage

The experimental set up is limited by the tank width. The aim is to obtain the largest possible scale, particularly in array configurations. At times the ratio between the WEC and the tank width can exceed 1/5 which in turn causes large blockage effects. However, experimental limitations due to blockage effects and scaling issues can possibly be overcome by numerical studies.

6.3.2 Scaling

As already pointed out, WECs modelling involves different problems each of them characterized by a non-dimensional number. The Froude number (the ratio between inertia and gravity forces) is usually used to scale tank testing. However, other numbers can also govern the flow:

- Reynolds number (ratio between inertia and viscous effects) for WECs with sharp corners or large movements such as OWSCs, where vorticity is released and shed in the flow and for OWCs in the air chamber;
- the Cauchy number (ratio between inertia and elastic forces) for taut mooring lines and elastically deforming PTOs;
- The Euler number (ratio between pressure and inertial forces) for the compressible effects in the air chamber of OWCs;
- The Strouhal number (ratio between temporal inertia forces and convective inertia forces) for turbulent oscillations of the flow over immersed turbines in the case of the overtopping devices.

All these numbers cannot be scaled at the same time in experiments, but they can in the numerical simulations. The numerical results should be used to understand the effects of these features and different scale experiments should be used to check if each effect has been properly modelled.

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