Specialist Committee on Hydrodynamic Modelling of Offshore Renewable Energy Devices

27TH ITTC • Copenhagen

Committee Members

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Committee Meetings

The committee met four times:

• CNR-INSEAN, Rome	February 2012
• Australian Maritime College	December 2012
• University of Ulsan, Korea	November 2013
• Pennsylvania State University, USA	April 2014

Terms of Reference

1. Review and update the guideline on wave energy converters.
2. Develop guidelines for the physical modelling of wind and current/tidal renewable energy systems, both floating and bottom fixed structures.
3. Investigate and report on techniques for the modelling of power take-off (PTO) systems.
4. Review and report on techniques for the numerical modelling of renewable energy systems.
5. Investigate and suggest improvements for wind load modelling on wind turbine devices during physical model testing.
6. Identify the parameters that cause the largest uncertainties in the results of physical model experiments and the extrapolation to full scale.
7. Investigate and report on the correct modelling for renewable energy system arrays (farms).

Structure of Presentation

1. Overview: WECs, Current Energy, Offshore Wind
2. Guideline development
3. Power Take-Off (PTO) Systems
4. Numerical Modelling of Marine Renewable Energy Devices
5. Wind Load Modelling on Offshore Wind Turbines
6. Uncertainties in Physical Model Experiments and Extrapolation to Full Scale
7. Recommendations

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Wave Energy Converters (WECs)

- Wide Diversity of concepts and technologies;
- Over 1000 patents since 1799 – extensive studies in 1970s and from mid 1990s onwards
- Modelling challenges are different for different device types
- Three main types of device:

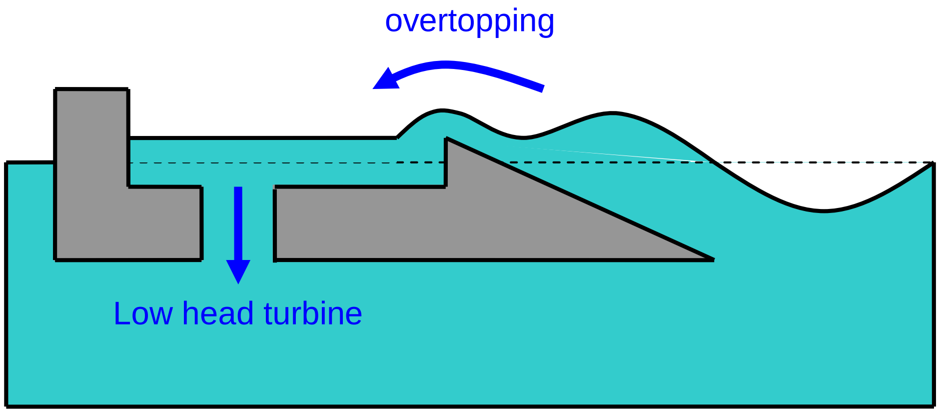
  Overtopping Devices

  Oscillating Water Columns (OWCs)

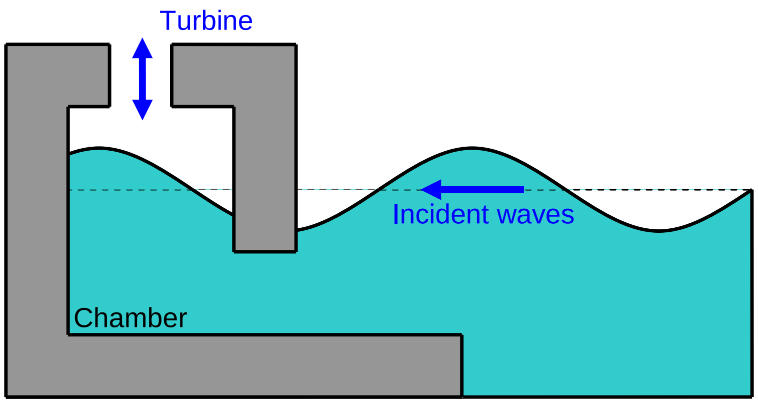
  Oscillating Bodies

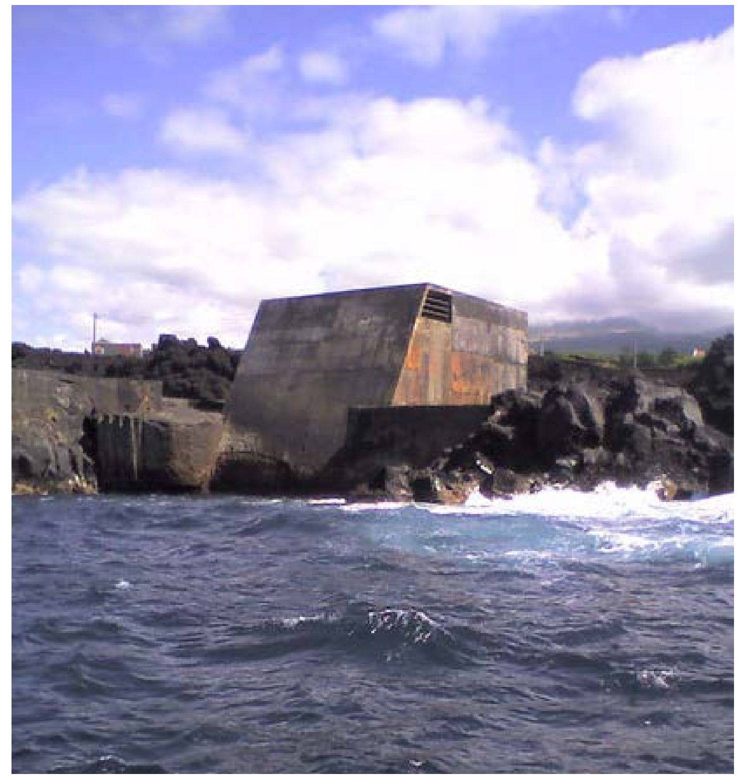
  (plus Others…)

WECs (1): Overtopping Devices:

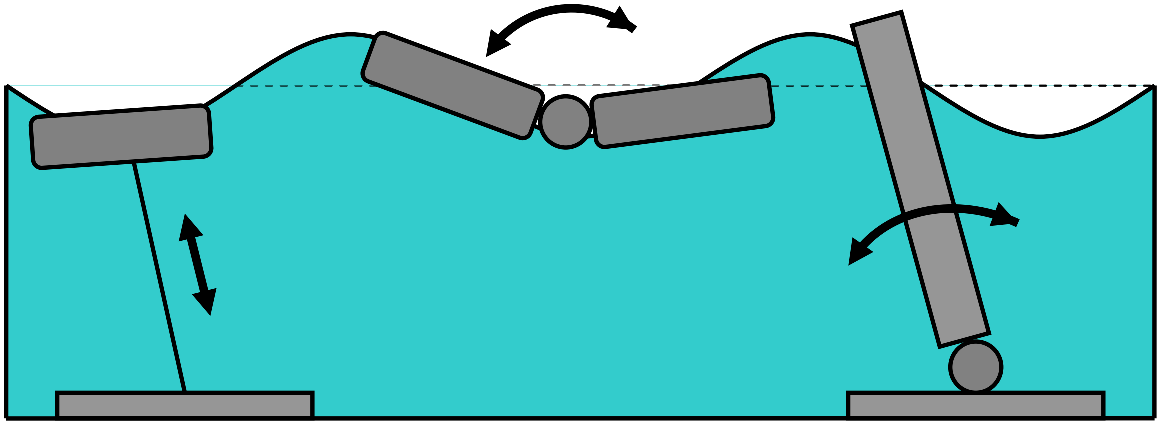


WECs (2): Oscillating Water Columns (OWCs)

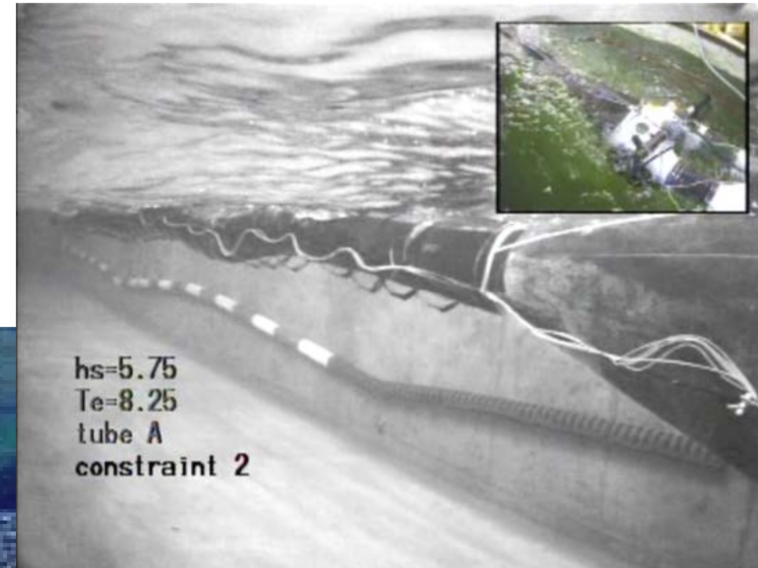




WECs (3): Oscillating Body devices



WECs (4): Other devices



Current Energy Devices

- Current energy devices considered here are designed to extract kinetic energy from tidal currents, ocean currents, or rivers
- Ocean current devices are designed for uni-directional flow; Tidal devices require to be bi-directional
- Main Device types are:

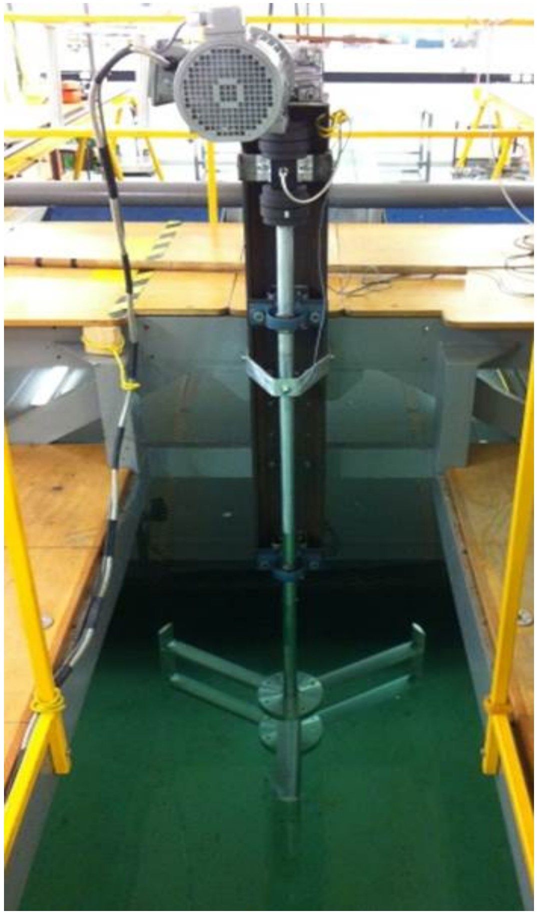
  Horizontal-axis turbines

  Cross-flow Turbines (including Vertical-axis Turbines)

  Non-turbine systems
- Turbines may be bottom-mounted, mid-water, or supported by floating structures

Current Energy Devices (1): HA Turbines

Current Energy Devices (2): Cross-flow Turbines



Current Energy (3): Non Turbine Devices

- Non turbine concepts include:
  - *VIV-driven devices*
  - *Tidal kites*
  - *Oscillating foil devices*

Bottom-Mounted Offshore Wind Turbines

- Divide into *Bottom-Mounted* and *Floating* wind turbines

- Bottom mounted foundations:

  Monopiles / Tripods / Jackets / Gravity bases

Floating Offshore Wind Turbines

Floating Offshore Turbines typically:

Spars / Semi-submersibles / Barges / TLPs

(ballast-stabilised / buoyancy stabilised / mooring stabilised)

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Guidelines: Background

- Proliferation of guidelines addressing development of Ocean Renewable Energy Devices
- Bodies generating guidelines include
  - *International Electrotechnical Commission (IEC)*

    TC88 (Wind Turbines) & TC114 (Marine Energy)
  - *International Energy Agency*

    Ocean Engineering Systems
  - *Research institutes and research projects*

    EMEC, Equimar, Marinet …

Guidelines generated by International Bodies

Organisation	Organisation Type	Title	Status (Reference)	Informal Liaison
International Electrotechnical Commission (IEC) Technical Committee TC114 (Marine Energy) TS 62600-103	International Standard-setting body	Guidelines for the early stage development of wave energy converters: Best practices & recommended procedures for the testing of pre-prototype scale devices	Under Development	Yes
International Electrotechnical Commission (IEC) Technical Committee TC88 (Wind Turbines) PT 61400-3-2	International Standard-setting body	Design requirements for floating offshore wind turbines	Revision under development to include Annex addressing tank testing of FOWTs	Yes
International Energy Agency (IEA) Ocean Energy Systems	Intergovernmental organization	Guidelines for the Development & Testing of Wave Energy Systems	Published 2011 http://www.ocean-energy-systems.org/oes_reports/annex_ii_reports/	No

Committee Work on Guidelines

- Substantial proportion of the effort of the committee was spent in:

- Revision of 7.5-02-07-03.7

  Wave Energy Converter Model Test Experiments

- Generation of two new guidelines:

  7.5-02-07-03.8 Model Tests for Offshore Wind Turbine

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

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Power Take Off (PTO)

- Presence of the PTO is most significant difference between Marine Renewable Energy devices and other ocean structures

- Behaviour of PTO influences

  power capture

  motions (rigid and/or hydroelastic)

  hydrodynamic loads

- Appropriate simulation of PTO essential to determine the performance of the system in small-scale model tests

WEC Power Take Off

- PTO typically extracts energy from

  relative motion between the device and the water

  relative motion between different parts of the device

- Strong coupling between energy extraction and device and fluid motions
- Key limitations due to size and scale of models
- Scale important due to impact of parasitic loading (e.g. friction)
- Size important due to requirement to fit simulated PTO in models whilst meeting geometry & mass constraints

Passive WEC Power Take Off systems

- Early tests typically use simplified / idealised passive systems

  Full-scale PTO typically not finalised

  Realistic PTO too complex for model-scale testing

- Typical passive systems:

  Orifice plates on OWCs

  Friction / pneumatic / hydraulic dampers - oscillating bodies

WEC Power Take Off: Measurements

- Power capture determined from

  measured force & velocity *(typically oscillating bodies)*

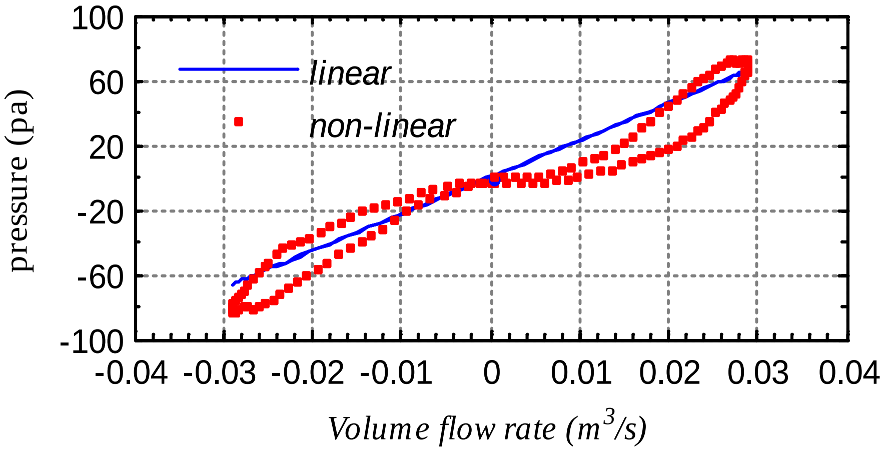
  pressure & flow rate *(typically OWCs)*

  potential energy of fluid *(overtopping devices)*

- Minimum requirement:

  repeatability – issues with friction-based passive systems

  characterisation – testing performance, linearity



Active WEC Power Take Off Systems

- Later stage tests may utilise active dampers using closed-loop control systems implemented using

  Digital drives

  Embedded controllers

  Programmable Logic Controllers (PLCs)

- Active systems can simulate

  idealised simplified models: *linear or quadratic damping*

  complex control strategies: *latching or reactive control*

WEC Power Take Off: Challenges

- Key challenge with oscillating body devices is to minimise impact of friction (static & dynamic)
- Component friction does not scale with Froude scaling and distorts relation in PTO between force and velocity
- Specialised components (e.g. air bearings) can be employed
- Generally beneficial to locate force measurement so that effect of mechanical friction is included in force measurements.

Current Turbine PTO: Steady flow

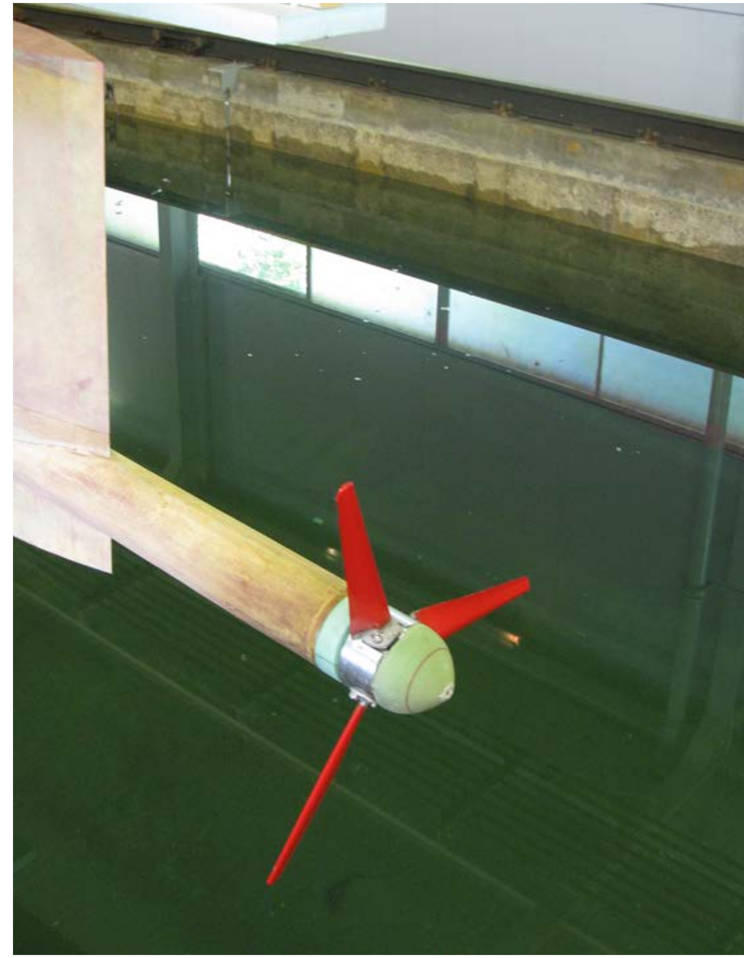
- PTO simulation in steady state generally less demanding for current devices than for WECs

- PTO typically represented by

  direct electrical power generation

  passive mechanical / hydraulic / magnetic loading

  active speed or torque control drive to control rotor RPM



Current Turbine PTO: Steady flow

- Measurement of rotational velocity and torque (also thrust)
- Friction losses must be carefully assessed
- For HA turbines challenges are associated with fitting PTO & instrumentation package inside turbine nacelle

Current Turbine PTO: Unsteady Flow

- PTO simulation in unsteady flow generally more demanding
- Strategy required depends upon details of test aims
- For characterisation of unsteady rotor hydrodynamics speed or torque control may be adequate
- Accurate prediction of full-scale performance requires simulation of dynamic response of generator

Offshore Wind Turbine PTO

- Requirements for PTO simulation generally less demanding than for wave and current devices
- Goal of hydrodynamic tests of offshore wind turbines is typically to examine structure motions and/or loads and possibly turbine control strategies, rather than to characterise the power capture performance of the turbine
- Power output generally not required
- Appropriate loading should ideally be generated by the rotor, to yield correct simulation of coupling between turbine and support structure

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Numerical Modelling of WECs

- Mathematical / numerical models of WECs including simulations of both the body hydrodynamics and the power take-off are usually called *Wave-to-Wire* models

- At early stages of device development, numerical models allow

  rapid estimates of the energy capture performance

  insight in the behaviour of novel device configurations

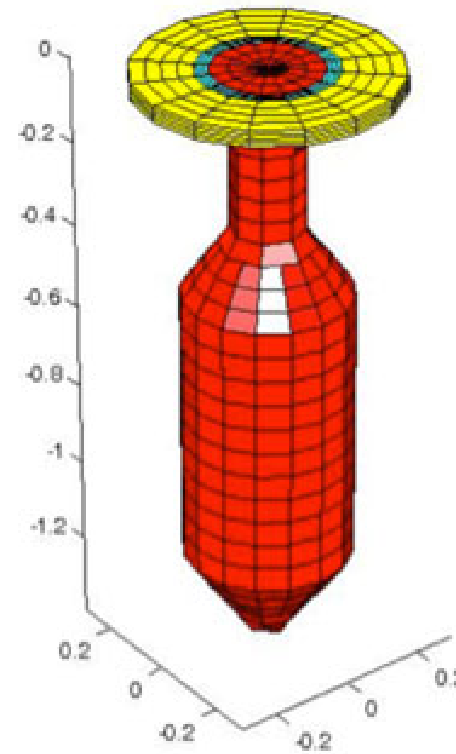
  extended parametric studies and optimization

Numerical Modelling of WECs

- Hydrodynamics of WECs consisting of rigid bodies are essentially no different to those for other marine structures

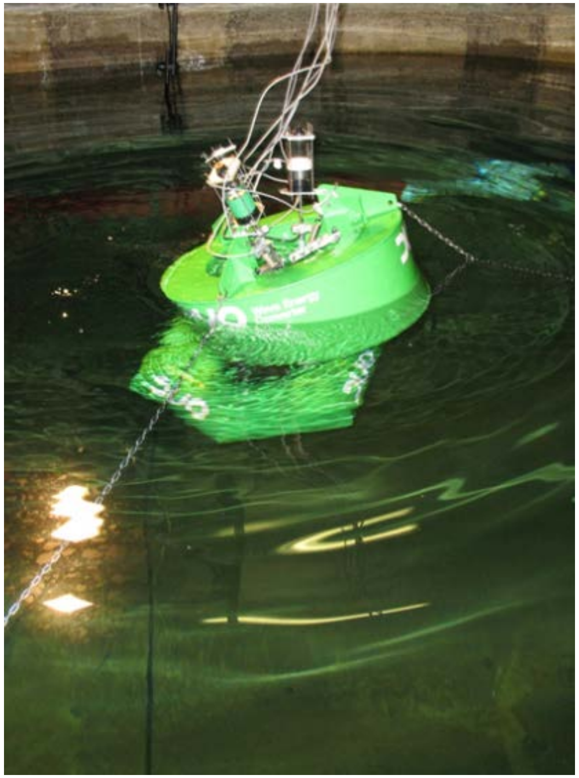
- Hence well-established tools (e.g. linear potential theory) are widely used to determine wave loading on many WECs

- One key difference between modelling of WECs and other marine structures is the need to model the PTO



Numerical Modelling of WEC PTOs

- PTO commonly assumed to behave as linear spring/damper system allowing frequency domain solution, & rapid computation
- Linear PTO model may be inaccurate for hydraulic PTOs; non-linear time-domain simulations may be required
- Non linear simulations required to investigate advanced PTO control strategies – e.g. latching and reactive control.



Numerical Modelling of WECs: Key challenges

- *Large numbers of calculations needed to generate power matrices, especially if devices are sensitive to wave direction: hence rapid solution of linear hydrodynamics attractive…*
- … but *WECs are often designed to have large motion responses which violate the assumption of small amplitude motion in linear potential theory*
- *Articulated devices have many degrees of freedom and solvers must be adapted to deal with this feature*
- *Overtopping devices are intrinsically non-linear and are often modelled using empirical approaches*

Numerical Modelling of WEC arrays

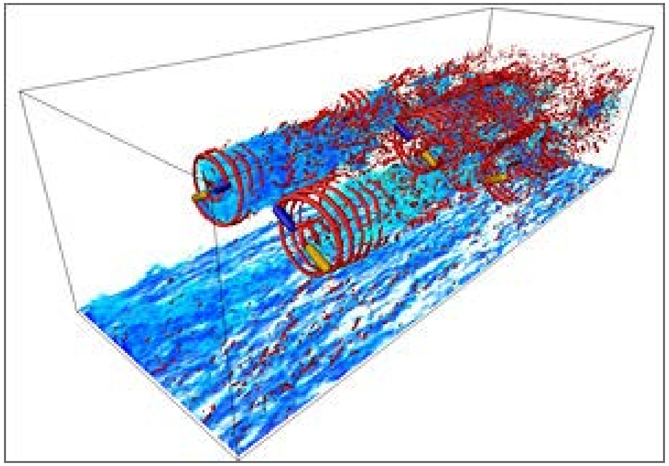
- WECs are expected to be deployed in arrays of many devices.
- The behaviour of devices can be different in the array from that found for isolated devices due to wave interactions
- Wave device arrays may also impact on local wave climate
- Potential-theory based models or wave propagation models may be used to address these issues.
- For wave propagation models, key issue is taking proper account of the disturbance generated by the WEC or array of WECs.
- For potential-flow solvers, the key challenges are related to the bathymetry and the computational time

Numerical Modelling of Current Turbines

- Computational methods for marine current devices are closely related to models used for wind turbine modelling, and to a lesser extent models used for ship propellers
- Aspects that cannot be reproduced by physical tests can be investigated by numerical simulations – e.g.

estimation of scale effects in lab tests carried out on small models

multiple device operations in arrays and the impact of energy capture on the environment



Global performance methods for Current Turbines

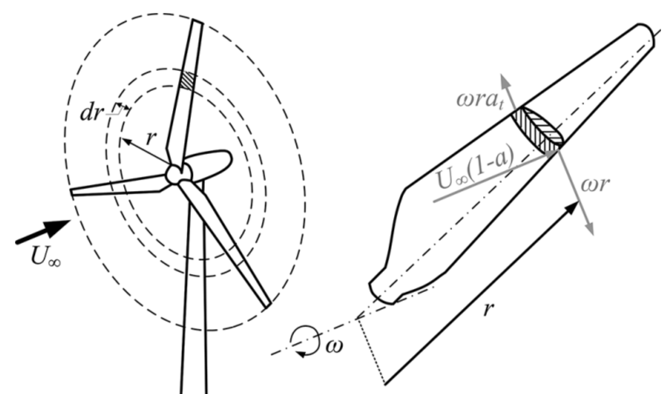
- Models divided into *global performance methods* & *flow-field models*
- *Global performance methods* estimate device power output by balancing momentum and energy of fluid through the device; e.g.

  Momentum theory

  Blade Element Method (BEM)

  Blade Element Momentum Theory (BEMT)

- Very fast predictions of global hydrodynamic performance can be obtained using basic representations of geometry and operating conditions



Flowfield models of Current Turbines

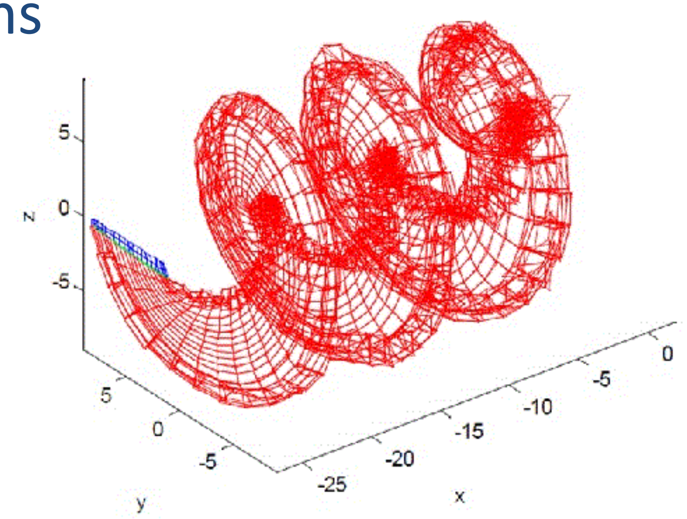
- Flowfield models describe the detailed hydrodynamic interaction between the device and the incoming flow by the numerical solution of mass and momentum equations

- Inviscid, irrotational methods include

  Lifting Line / Lifting Surface Methods

  Vortex Lattice Method

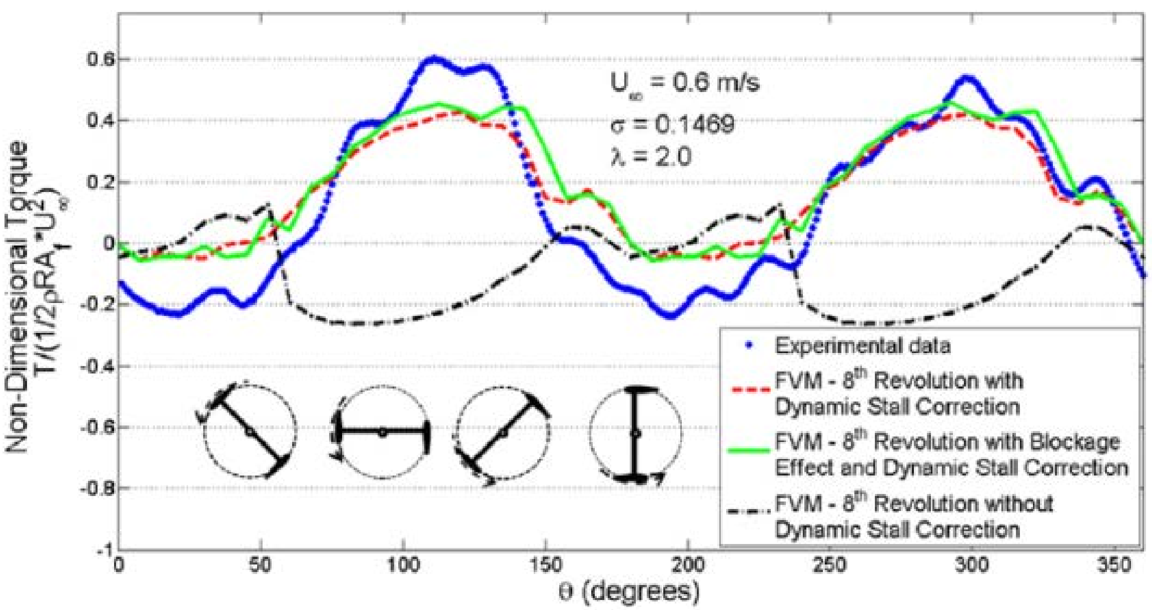
  Boundary Integral Equations Method



- Inviscid methods require viscous flow corrections to analyse blades at high angle of attack where boundary layer flow separation and static/dynamic stall impact on blade loads

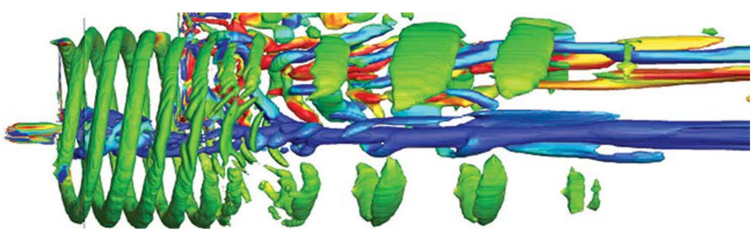
Dynamic Stall of Current Turbines

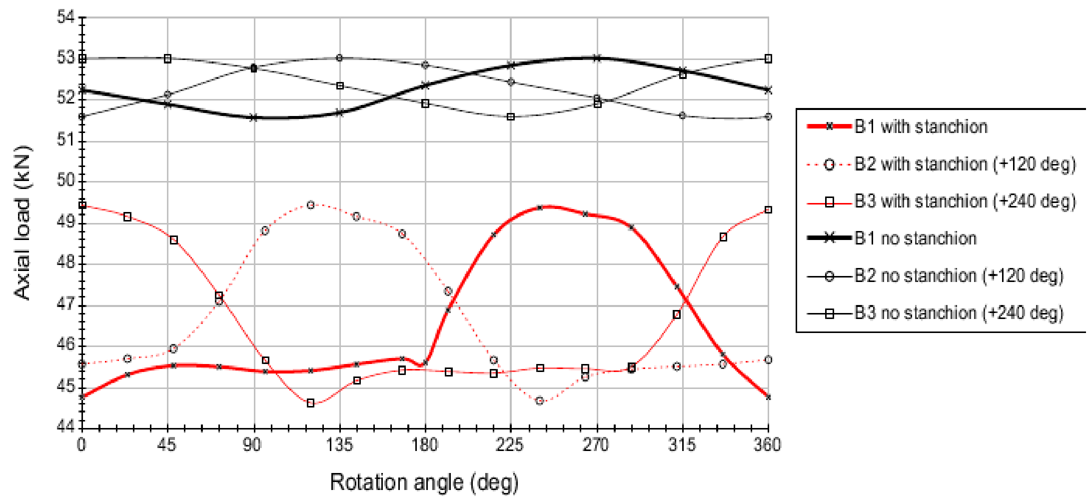
- Dynamic stall models adapted from helicopter aerodynamics especially relevant for cross-flow turbines or horizontal axis devices in unsteady flow



Viscous Flow Modelling of Current Turbines

- Viscous models are now widely implemented using RANSE, LES, and DES approaches
- Key challenges include capturing interaction between rotating parts (blades) and fixed parts (tower, support structure etc.), requiring fixed/rotating grids.
- Interactions between rotor and support can be significant





Numerical Modelling of Current Turbines

- Viscous models have been widely used for analysis of cross flow turbines, typically using 2D approximations
- Several studies have also used CFD to examine impact of ducts and diffusers
- Viscous methods have also been deployed to examine array effects

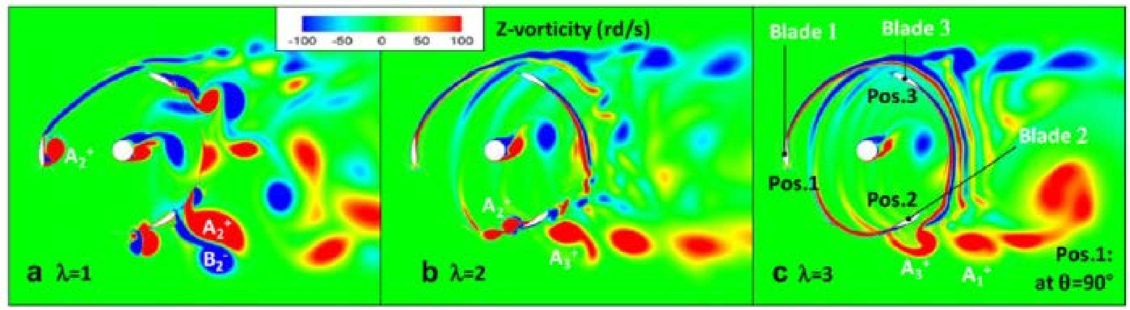
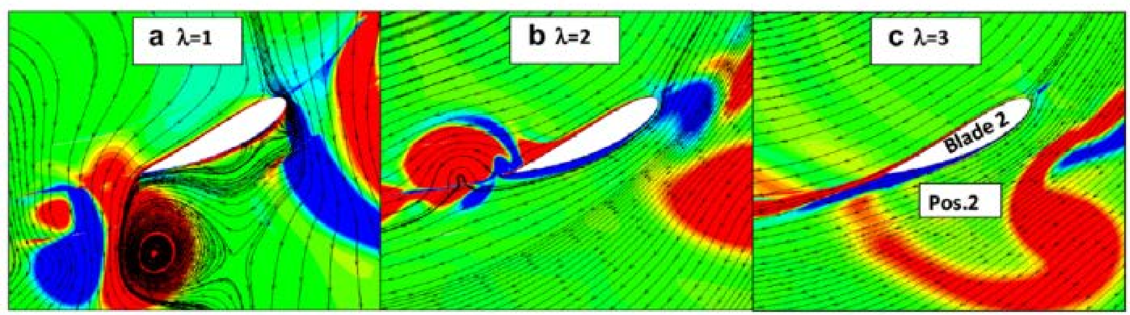


Fig. 18. Vortices structures (2D flow), for λ = 1, 2 & 3.



Numerical Modelling of Wind Turbines

- Codes involve complex coupling between different features
- Main focus is simulation of effects of wind inflow, aerodynamics, hydrodynamics, turbine control systems and structural elasticity:
- *aero-hydro-servo-elastic codes*

Table 1: Overview of offshore wind modeling tool capabilities

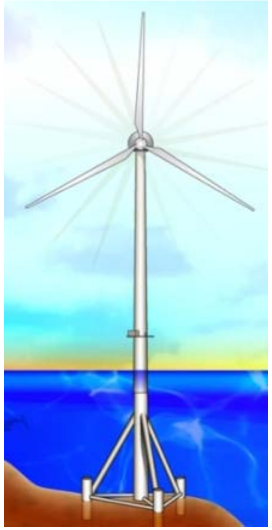
Code	Code Developer	OC4 Participant	Structural Dynamics	Aerodynamics	Hydrodynamics	Mooring Model
FAST	NREL	NREL, CENTEC, IST, Goldwind, CSIC	T: Mod/MB P: Rigid	(BEM or GDW)+DS	PF + QD + (QTF)	QS
FAST v8	NREL	NREL	T: Mod/MB P: Rigid	(BEM or GDW)+DS	PF + ME	QS
CHARM3D+ FAST	TAMU+ NREL	ABS	T: Mod/MB P: Rigid	(BEM or GDW)+DS	PF + ME + (MD + NA) + (IP + IWL)	FE/Dyn
OPASS+ FAST	CENER+ NREL	CENER	T: Mod/MB P: Rigid	(BEM or GDW)+DS	PF + ME	LM/Dyn
UOU+FAST	UOU+NREL	University of Ulsan	T: Mod/MB P: Rigid	(BEM or GDW)+DS	PF + QD	QS
Bladed	GH	GH, CGC, POSTECH	T: Mod/MB P: MB	(BEM or GDW)+DS	ME + (IWL+ IP)	QS
Bladed Advanced Hydro Beta	GH	GH	T: Mod/MB P: MB	(BEM or GDW)+DS	PF + ME + (IWL)	QS
OrcaFlex	Orcina	4Subsea	T: FE P: Rigid	BEM, GDW, or FDT	PF + ME	LM/Dyn
HAWC2	DTU	DTU	T: MB/FE P: MB/FE	(BEM or GDW)+DS	ME	FE/Dyn
hydro-GAST	NTUA	NTUA	T: MB/FE P: MB/FE	BEM or FWV	PF + ME + (IP)	FE/Dyn
Simo+Riflex+ AeroDyn	MARINTEK+ NREL	CeSOS	T: FE P: FE	(BEM or GDW)+DS	PF+ME	FE/Dyn
Riflex-Coupled	MARINTEK	MARINTEK	T: FE P: Rigid	BEM+FDT	PF + ME + (IWL)	FE/Dyn
3Dfloat	IFE-UMB	IFE	T: FE (co-rotated) P: FE	BEM+FDT	ME + (IWL)	FE/Dyn
SWT	SAMTECH	SAMTECH & IREC	T: FE+Mod/MB P:FE+Mod/MB	BEM or GDW	ME + (IWL)	FE/Dyn
DeepLinesWT	PRINCIPIA-IFPEN	PRINCIPIA	T: FE P: FE	BEM+DS	PF + ME + (MD + QTF/NA) + (IP + IWL)	FE/Dyn
SIMPACK+ HydroDyn	SIMPACK	SWE	T: Mod/MB P: Rigid	BEM or GDW	PF + QD	QS
CAsT	University of Tokyo	University of Tokyo	T: FE W: FE	BEM	ME	QS
Wavec2Wire	WavEC	WavEC	T: N/A P: Rigid	N/A	PF + QD	QS
WAMSIM	DHI	DHI	T: N/A P: Rigid	N/A	PF + QD	QS

T = turbine P = platform Mod = modal MB = multi-body FE = finite element N/A = not applicable	BEM = blade-element/momentum GDW = generalized dynamic wake DS = dynamic stall FDT = filtered dynamic thrust FWV = free-wake vortex	PF = potential flow theory ME = Morison eq. MD = mean drift QTF = quadratic transfer function NA = Newman's approximation IP = instantaneous position IWL = instantaneous water level QD = quadratic drag	QS = quasi-static Dyn = dynamic LM = lumped mass

Code-to-code comparisons for Wind Turbines

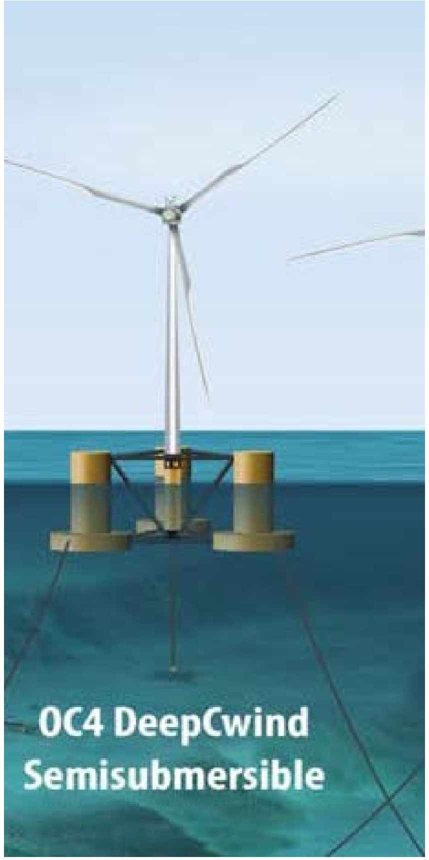
- International Energy Agency has developed a series of research tasks to verify & validate the available codes by code-to-code comparison

- *Offshore Code Comparison Collaboration (OC3)* addressed monopiles with different foundation conditions & water depths and a floating spar structure



Numerical Modelling of Wind Turbines

- *Offshore Code Comparison Collaboration, Continuation* (OC4) project extends study to jacket foundation and tri-floater semi-sub
- Series of studies continues with OC5: *Offshore Code Comparison Collaboration, Continuation, with Correlation* examining correlation for three structures from both tank test and full-scale results



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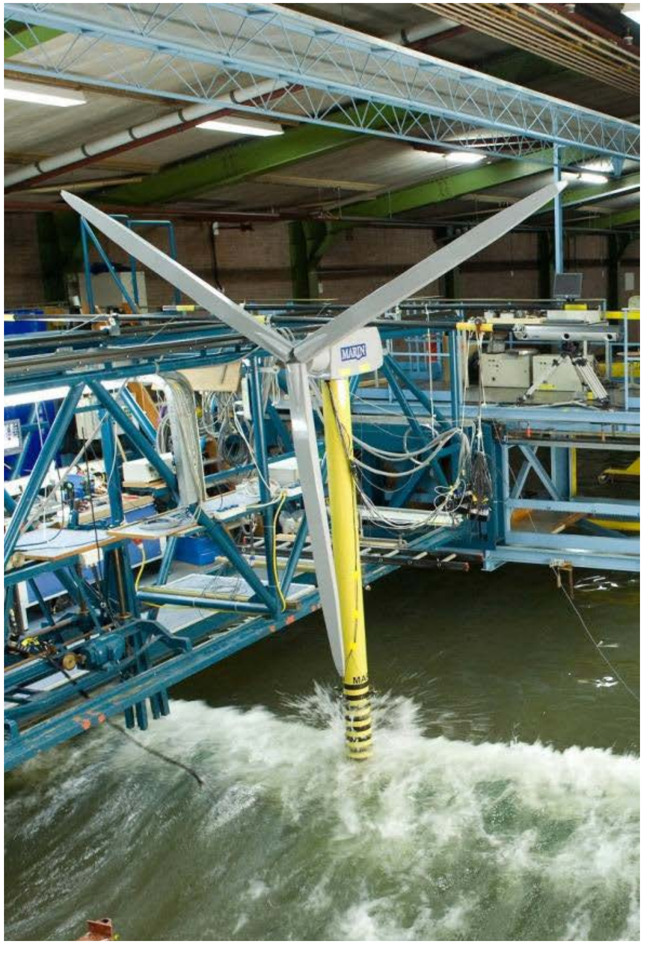
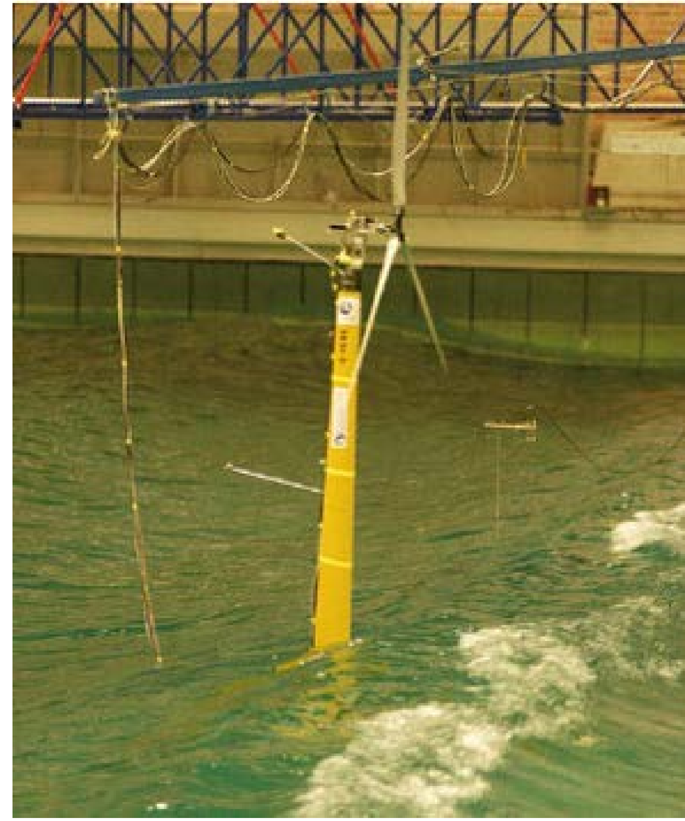
Wind Load Modelling on Wind Turbines: Uncoupled Tests

- For bottom-mounted OWTs focus is often on hydrodynamic loads & hydroelastic behaviour of support structure
- This may be considered to be independent of aerodynamic load on rotor, especially in extreme conditions
- Hence simulation of wind loads may not be necessary



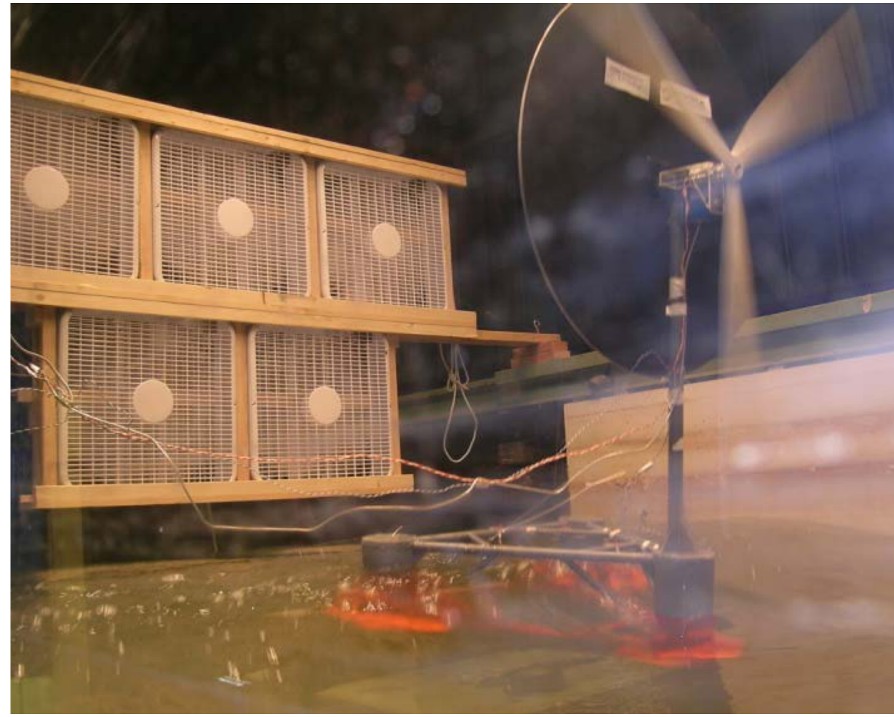
Wind Load Modelling on Wind Turbines: Coupled Tests

- The forces and moments generated by the rotor are partly aerodynamic and partly due to gyroscopic effects
- Tests of floating platforms should include at least simplified modelling of the rotor due to the strong coupling present between the platform dynamics and the rotor-generated forces and moments.



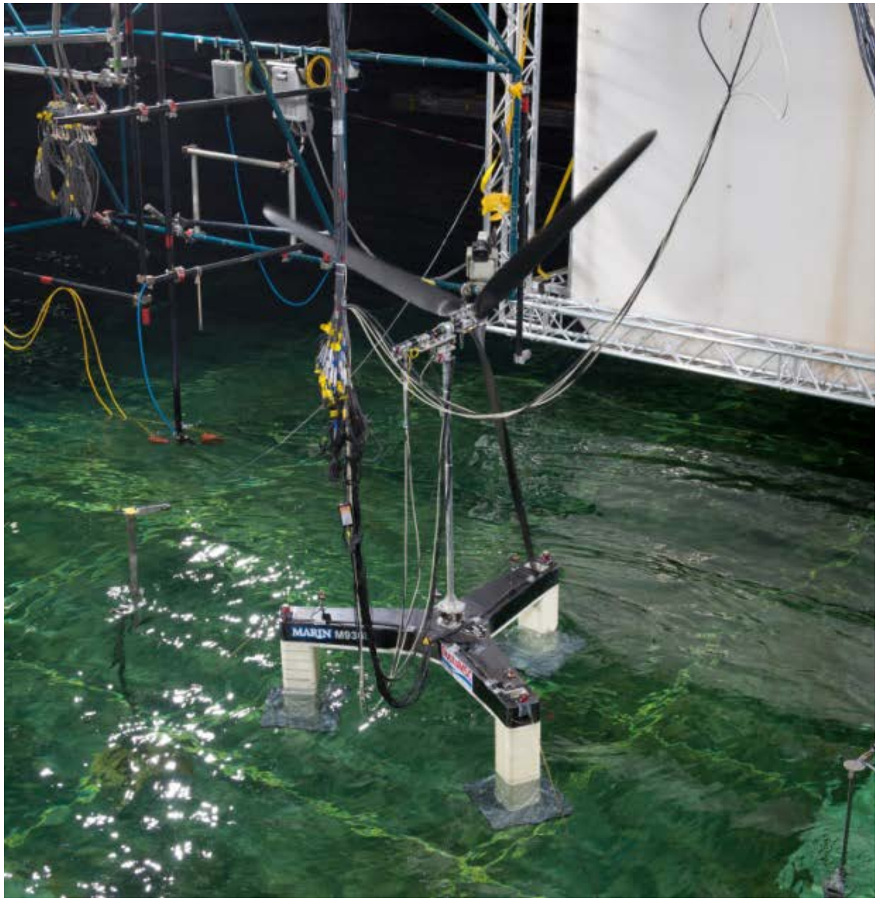
Simplified Simulations with & without wind

- Most simplified approach uses lightweight line attached at hub tensioned with a weight
- Rotor can be used as a fan rotating in stationary air.
- Alternative simplified approach with wind uses solid or porous disc in place of the rotor
- Rotating mass can be used to represent gyroscopic loads



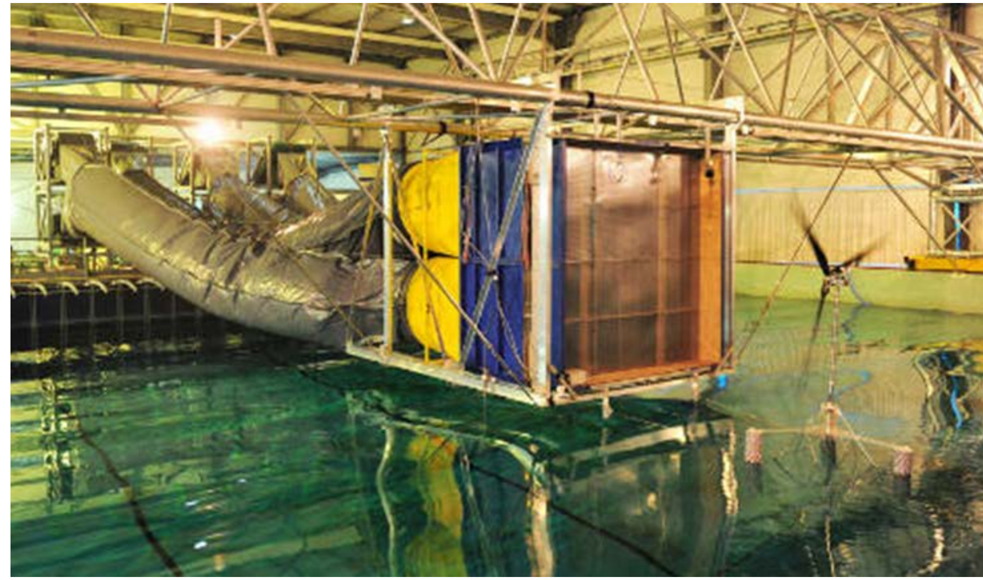
Direct Simulation

- Direct modelling exposing FOWT with working rotor to a wind field generated by a battery of fans
- Allows for the most accurate modelling of real conditions of rotor operation
- Rotor rpm and spatial variation of wind speed should be carefully calibrated prior to the main experiments



Direct Simulation: Challenges

- *Generation of wind field over large volumes*
- *Generation of wind close to wavy water surface*
- *Generation of correct steady and unsteady aero-dynamic behaviour at low Reynolds No.*



- *Active research ongoing in design of “equivalent” blades*
- *Manufacturing lightweight blades e.g. blades > 1000mm c140g*
- *Simulation of complex mechanisms for pitch and yaw control*

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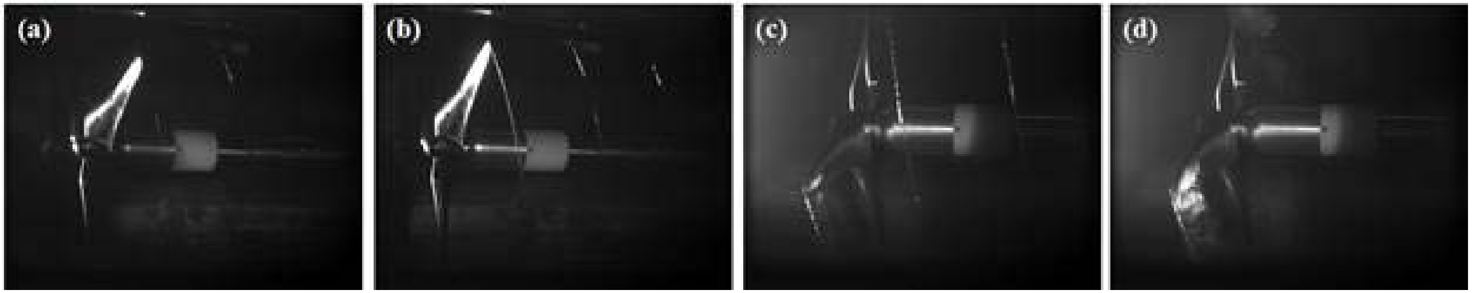
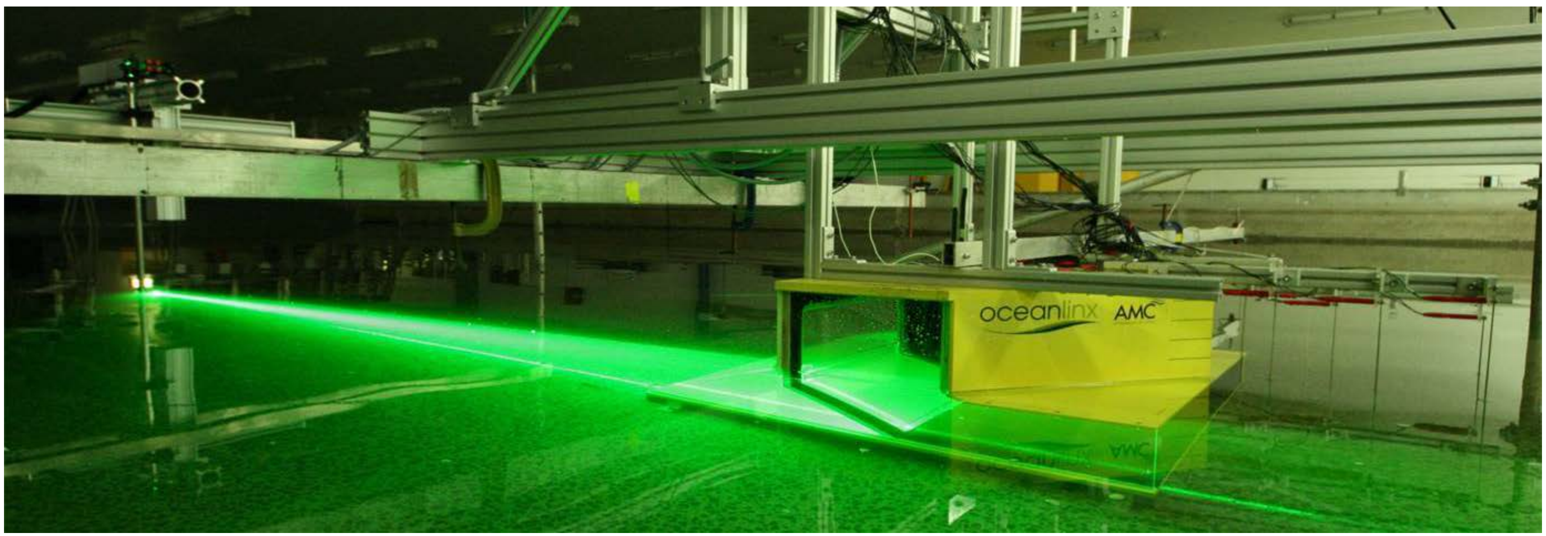
Uncertainties in Physical Model Experiments

- Relatively few examples in literature of thorough uncertainty analyses of hydrodynamic tests and/or extrapolation to full-scale.
- Some aspects of UA for renewable devices may be inferred from existing ITTC procedures
- Key area requiring consideration is power prediction for WECs
- Some studies show model-scale uncertainties in power capture of up to 8-10% for single test reducing to 2-3% for multiple tests



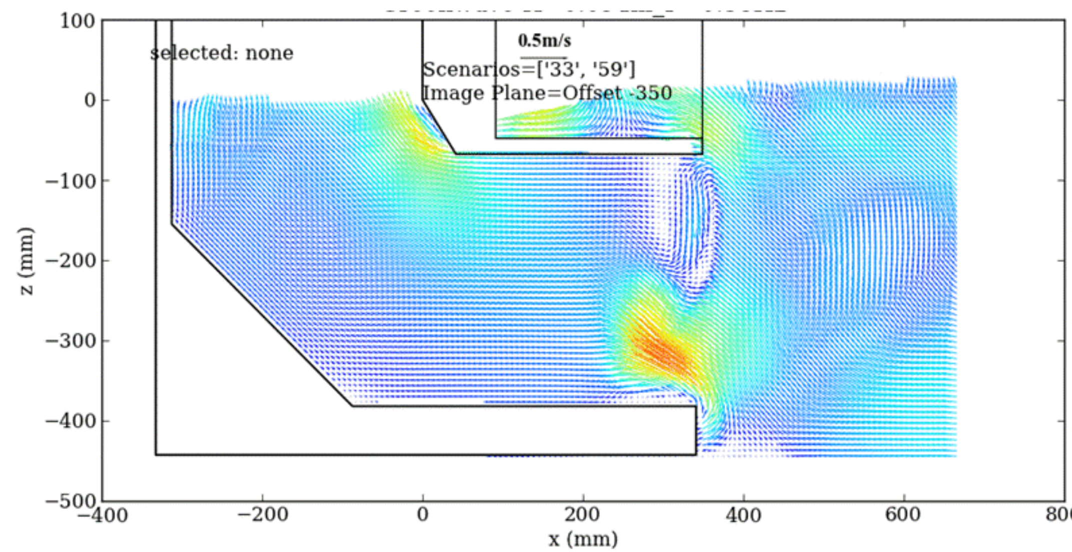
Quantification of Uncertainties in Offshore Renewable Energy Tests : Challenges at Model Scale

- Lack of knowledge of full-scale PTO at time of test
- Quantification of uncertainty of model-scale PTO behaviour
- Lack of understanding of facility bias issues



Quantification of Uncertainties in Offshore Renewable Energy Tests : Challenges

- Limited knowledge of site conditions at time of test
- Uncertainty resulting from extrapolation of model-scale results to full-scale, where multiple scaling ratios are relevant (e.g. OWC, floating current turbines, FOWT)
- Lack of public-domain large-scale open-sea data for validation of model-test and extrapolation procedures



Hydrodynamic Modelling of Offshore Renewable Energy Devices

1. Overview: WECs, Current Energy, Offshore Wind
2. Guideline development
3. Power Take-Off (PTO) Systems
4. Numerical Modelling of Marine Renewable Energy Devices
5. Wind Load Modelling on Offshore Wind Turbines
6. Uncertainties in Physical Model Experiments and Extrapolation to Full Scale
7. **Recommendations**

Recommendations to Conference

- The committee has made a major revision to the existing guideline *7.5-02-07-03.7 Model Testing of Wave Energy Converters*. The committee recommends that the conference adopts the revised guideline.
- The committee recommends that the conference adopts the new guideline *7.5-02-07-03.8 Model Tests for Offshore Wind Turbine*
- The committee recommends that the conference adopts the new guideline *7.5-02-07-03.9 Model Tests for Current Turbine*

Recommendations For Future Work: WECs

- Develop guidelines for uncertainty prediction for WECs.
- Monitor and report on developments in power take-off (PTO) modelling both for physical and numerical prediction of power capture.
- Review and report on the progress made on the modelling of WEC arrays.
- Review and report on challenges associated with the performance of WECs in irregular wave spectra, particularly as it relates to physical modelling.
- Check willingness of participants for a “round-robin” test campaign.
- Review and report on integrated WEC simulation tools based on multi-body solvers which are in development.

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Recommendations For Future Work: Current Turbine

- Develop specific uncertainty analysis guidelines / example for horizontal axis turbines
- Report on development in physical and numerical techniques for prediction of performance of current turbines, with particular emphasis on unsteady flows, off-axis conditions, and other phenomena which offer particular challenges to current devices.
- Report on the progress made on the modelling of arrays.
- Report on progress in testing at full-scale and moderate scale in-sea test sites.

Recommendations For Future Work: Wind Turbine

- Review Wind Field Modelling including Froude/Reynolds scaling challenges for the turbine in cooperation with the Specialist Committee on Modelling of Environmental Conditions
- Review the impact of control strategies and other features on full-scale devices on global response to allow improved understanding of the impact of simplifications adopted in model tests.
- Report on integrated tools for simulation of floating wind turbine including platform, mooring, turbine and control system.
- Report on developments in full-scale demonstrators of floating wind turbines.

Thanks for your attention!

We will be happy to discuss any questions…