Spar Buoy oscillating-water-column wave energy converter 6 DOF hybrid mooring non-linear model

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HYWEC  
Workshop Hydrodynamics of wave energy converters  
Bilbao, April 3-7, 2017

The way to see the future

www.sener.es
SENER Grupo de Ingeniería

SENER is a privately owned engineering and technology group, with growing international presence, founded in 1956. Since its beginnings, the company has been distinguished for developing excellent projects and innovative solutions.
SENER GROUP - FIGURES 2015

TURNOVER (M€): 1,356
STAFF: 5,558
SALES OUTSIDE SPAIN: 95%

DISTINCTIVE VALUES
Innovation
Quality
Independence

100% Privately Owned

SENER INGENIERIA Y SISTEMAS

Founded in 1956, SENER ranks as the largest privately owned engineering company in Spain.

It is particularly recognized for its capacity to deliver innovative and complex multidisciplinary projects.

ENGINEERING - FIGURES 2015

TURNOVER (M€): 650.5
STAFF: 2,410
**SENER INGENIERIA Y SISTEMAS: Strategic Business Units**

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<thead>
<tr>
<th>AEROSPACE</th>
<th>INFRASTRUCTURES &amp; TRANSPORT</th>
<th>POWER OIL &amp; GAS</th>
<th>MARINE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space</td>
<td>Metro, LRT, Tramways</td>
<td>Power Plants</td>
<td>FORAN System:</td>
</tr>
<tr>
<td>Aeronautics</td>
<td>High Speed Railways</td>
<td>Liquefied Natural Gas (LNG)</td>
<td>Global leader in Shipbuilding</td>
</tr>
<tr>
<td>Defense and security</td>
<td>Conventional Railways</td>
<td>Thermosolar Energy</td>
<td>CAD/CAE/CAM</td>
</tr>
<tr>
<td>New Markets; Science and Medical Systems and Solar CPV</td>
<td>Architecture and Urban Planning</td>
<td>Renewables</td>
<td>Ship design &amp; Engineering:</td>
</tr>
<tr>
<td>Guidance, Navigation Guiding and Control Systems</td>
<td>Transport Planning</td>
<td>Oil &amp; Gas</td>
<td>Concept, Contract, Detail and Production Technical Assistance</td>
</tr>
<tr>
<td>ISR Sensors and Applications (Intelligence, surveillance and reconnaissance)</td>
<td>Roads and Highways</td>
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</tbody>
</table>
## PRODUCT LINES (I)

### POWER PLANTS

#### Project Types
- Open Simple Cycle
- Combined Cycle
- Cogeneration
- Coal
- Nuclear

### LIQUEFIED NATURAL GAS (LNG)

#### Project Types
- Regasification Terminals
- FSRU
- Liquefaction
- Virtual Gas Pipeline
- Off-Shore LNG
PRODUCT LINES (II)

THERMOSOLAR ENERGY

Project Types
- Parabolic Trough (SENERTROUGH ®)
- Central Tower
- Molten Salts

RENEWABLES

Project Types
- Biomass Power Plants
- Waste to Energy
- Hydro
- Farm Waste Treatment

OIL & GAS

Project Types
- Oil Refining Units
- Petrochemical and Process
- Waste Oil Recycling
- Gas Treatment and Separation
- Gas Underground
SERVICES

SENER works in every and all stages of the project cycle
POWER PLANTS

“More than 20,000 MW installed worldwide guarantee SENER capabilities as E/EPC contractor in Power Plants”
THERMOSOLAR ENERGY

“SENER innovation & technology developments in Thermosolar Plants - determinant to be considered world leader in the field”

- **SPAIN**
  - Termosol 1 & 2 (Parabolic Trough Plants) 50 MWe
  - Andasol 1 & 2 (Parabolic Trough Plants) 50 MWe
  - Valle 1 & 2 (Parabolic Trough Plants) 50 MWe
  - Gemasolar (Central Receiver Plant) 19.9 MWe

- **USA**
  - Genesis 1 & 2 (Parabolic Trough Plant) 140 MWe
  - Noor I & II (Parabolic Trough Plants) 160 & 200 MWe

- **MOROCCO**
  - Noor III (Central Receiver Plant) 150 MWe

- **SOUTH AFRICA**
  - Bokpoort (Parabolic Trough Plant) 50 MWe
The way to see the future

RENEWABLES

“SENER experience in conventional power together with our technological developments lead our renewable projects to become unique, a world reference of efficiency and innovation”
WHY SENER

SENER, in Power, Oil & Gas is an **EPC Contractor** with the highest technological and innovation approach.

Our business model aims towards **self-performance** for all the Engineering, Procurement, Construction, Startup, Operation and Maintenance.

SENER provides **technological commitment** and **financial trustworthiness** towards our Clients and Financial Institutions. SENER is recognized as fully bankable for **Project Finances**.

SENER, under specific circumstances, can share with the developers part the **investment or financing** of the EPC contracts.
EXPERIENCE in MARINE ENERGY and COAST modelling
EXPERIENCE IN MARINE ENERGY: EMERGE

Project: EMERGE Offshore wind turbines

Emerge project is focused in the study of supporting structures for offshore wind generators, in deeper seas than considered up to now >50 (m). This leads to new studies of the structures and its behavior.

The study is divided in three stage:
- Conceptual design (State of Art, Conceptual design of three alternatives & Evaluation technical and economical)
- Basic engineering (Preliminary stability, Preliminary scantling & Budget)
- Detail engineering
EXPERIENCE IN MARINE ENERGY: OCEAN LEADER

Project: OCEAN LEADER Offshore wind farm

Consortium of companies with high research capacity.

The project is divided into six different activities (A1, AII....AVI), SENER takes part in two of these activities, AII and AV:

AII. Basic Design of different mix-generation devices

- Stability, structural and longitudinal resistance studies of three mix-generation devices, TLP, SPAR and Semisubmersible.

- Finite elements model for structure analysis.

- Selection of a device to be studied at the towing tank.
EXPERIENCE IN MARINE ENERGY: OCEAN LEADER

AV. Technology research and design of installation and maintenance ship.

- Analysis of the critical design factors
- Vessels characteristics:
  - Towing & Helideck
  - Equipment transportation, maintenance, installation
  - Anchors fixation & Cable laying
  - ROV operation and Diving equipment (from moon-pool)
  - DP3
  - Cranes: 1x 1,600 (T) and 1x 150 (T)
EXPERIENCE IN MARINE ENERGY: MTORRES

Project: MTorres

- Development of MTorres concept for a floating platform (Wind Turbine & Water-maker System).

- Based on MTorres concept. Dimensions optimization to fulfill the design requirements and obtain a stable system.

- System’s stability study.

- Study of the movements effects in the water-maker system (towing tank).

- Basic Design
EXPERIENCE IN MARINE ENERGY: OWA CONTEST

OWA contest: OFFSHORE WIND ACCELERATOR

- Conceptual design for CARBON TRUST public contest.
- SENER takes part in the contest of three possible developments:
  - Launch and Recovery system
  - Personnel transfer system
  - Equipment transfer system
EXPERIENCE IN MARINE ENERGY: BIMEP

Writing/supervision of technical and administrative specification for the four public work packages (subsea cable, connector, substation and marine aids to navigation).

Bidders evaluation and awardee selection of the different public work packages

Supplier supervision for the compliance of the specifications of the elements of the infrastructure

Project management and awardee coordination (construction management and support for the commissioning).
SENER MARINE and POWER software
FORAN

Integrated CAD/CAM/CAE system for the design and production of any naval ship and offshore unit. Currently licensed at more than 150 shipyards and design offices in 40 countries.

FORAN capitalizes on SENER’s engineering and ship design know-how, as SENER is the only company that offers services of this kind and that has also developed a marine design system.
SENSOL software supports the design, performance calculation and analysis of any solar plant.
ORIGIN: TECHNICAL - ECONOMICAL ASSESSMENT OF WECS

Many different technologies.

<table>
<thead>
<tr>
<th>Attenuator</th>
<th>Point Absorber</th>
<th>Surge Converter</th>
<th>Overtopping</th>
<th>Submerged pressure differential</th>
<th>Oscillating Water Column</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pelamis</td>
<td>OPT</td>
<td>Aquamarine</td>
<td>WaveDragon</td>
<td>AWS (Shell)</td>
<td>Oceanlinx</td>
</tr>
<tr>
<td>Inerjy (WaveTork)</td>
<td>Atmocean</td>
<td>BioPower</td>
<td></td>
<td>Oceantec</td>
<td>Oceantec</td>
</tr>
<tr>
<td>Martifer (FLOW)</td>
<td>Oceanic Power</td>
<td>(BioWave)</td>
<td></td>
<td>SENDEKIA</td>
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<tr>
<td>Dexawave</td>
<td>Fred Olsen</td>
<td>AW-Energy</td>
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<tr>
<td>Poseidon (FPP)</td>
<td>EWE</td>
<td>(WaveRoller)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hidroflot</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wedge Global</td>
<td></td>
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</tr>
</tbody>
</table>

Others

- PiSys (Pipo)
- Motor Wave
ORIGIN: TECHNICAL - ECONOMICAL ASSESSMENT OF WECS

Meetings with developers.
SENERWave. WAVE POWER CONVERTERS ASSESSMENT

WHAT?
Assessment and comparison of different technological families of WECs.

WHY?
There are lots of different types of technologies to capture the energy from the waves, and it is not easy to “choose” one.

WHAT FOR?
Conclude which technology will be the successful (LCOE), compare it with other marine renewable technologies, and take decisions (Continue development?)

HOW?
Numerical Simulations based on coupled CFD and multi-domain dynamic systems has being used for the assessment of each technology.

7 different disciplines within SENER have participated in the Costs Estimations based on our EPC (Engineering, Procurement and Construction) experience LCOE calculation module incorporates financial ratios and allow to simulate wave farms of a Mean Power and for several years.
SENERWave. OVERVIEW

Developed in C++ using U++ open source BSD cross-platform library.

Windows based graphical user interface.

Multi OS: Windows, Linux.

Detailed metocean data handling.

Parametric cost model.

Internationalization.

User level security.
SENERWave. INPUTS

INPUTS

Wave Climate & Bathymetry
- Monochromatic & irregular waves, white noise
- Different spectrum (JONSWAP, Pierson-Moskowitz, TMA...)
- Currents
- Wind forces

Physics and Dynamics of the devices.
- 3D Geometry of floating and fixed devices and platforms
- Mooring Systems
- Pneumatic, hydraulic or mechanic conversion systems.

WAVE CLIMATE

Resource assessment
Import and maintain metocean register for different locations.
- Meteorological Summary
- Scatter Diagram
- Waves statistics.
- Energy Evolution in different periods (kW/m).

Wave propagation
Definition of frequential and directional wave components
SENERWave. OUTPUTS

PERFORMANCES
- Time domain Analysis
- Water surface tracking
- Water pressure over device surface
- Fluid velocities
- Body motions
- Loads on the mooring system
- Electrical production and Power Matrix
- Optimization of device production

COSTS AND LCOE CALCULATION

CAPEX
- Engineering and Purchasing
- Hull Construction
- Equipment
- Piping / Static Cable
- Offshore Works & Installation
- Indirect Costs

OPEX
- Operation an Maintenance
- Decommissioning

Calculation and Assessment
- Different devices.
- Different locations.
- Sensibility Assessments.
- Financial rates and Parameters.

Result & Post-process (report)
- Operational Data.
- Production and consumptions.
- Payback.
- LCOE
- Graphical Results.
SENERWave Modules. Climate database
SENER Wave Modules. Climate database
SENERWave Modules. Climate database
SENERWave Modules. Power Matrix database
SENERWave Modules. WEC Model
SENERWave Modules. WEC Simulation
SENERWave Modules. WEC Simulation
SENERWave Modules. Global parameters and functions
SENERWave Modules. Costs/Availability/Consumptions
SENERWave Modules. Results
SENERWave SOLVER: THE CHALLENGE

Simulation has to couple hydrodynamic and power take off interaction.

WEC design and optimization sensitivity analysis requires to simulate different cases to get the average power considering:

- **Wave resource:**
  - Different irregular wave height and period
  - Wave direction
  - Real spectrum
  - Tide height (nearshore, onshore devices)

- **WEC design**
  - General device hydrodynamic design
  - Design optimization to local wave conditions

- **WEC control**
  - Test and optimization of different control strategies
    - Power maximization
    - Optimum power and durability

(Please remember that a simulation case for power requires 30-60 min simulations)

In summary: **WEC ASSESSMENT REQUIRES WEEKS OF SIMULATION TIME.**
SENERWave SOLVER. THE DILEMMA

- Slow solver, low accuracy
- Much slower solver, better accuracy
SENERWave SOLVER. PTO AND FIRST HYDRODYNAMICS

Simulation had to couple hydrodynamic and power take off (PTO) effects.

From the first version simulation was in time domain.

First solver version was based in Sundials IDA, a differential-algebraic equation (DAE) systems solver. The integration method in IDA is a implicit, variable-order, variable-coefficient BDF (Backward Differentiation Formula) derived from package DASPK.

Hydrodynamics was implemented using 2D Cummins equations. \[ \sum_{j=1}^{6} (m_j \delta_{jk} + m_k) + \int_{-\infty}^{t} K_{jk}(t-\tau) \ddot{x}_j(\tau) d\tau + c_{jk} x_j = f_k(t) \]

More complex PTO including compressible fluid flow, heat transfer and other effects were not possible to implement due to accumulation of numerical errors.

Algorithms (Pantelides) to lower system index were analyzed.

As the modularity was a must, to reduce the development time it was decided to use an established dynamic system solver: OpenModelica.

Hydrodynamic and PTO coupling was perfect, but Cummins simulation should have to be improved.
SENERWave SOLVER. SIMULATION OPTIONS

Slow solver, good accuracy

Faster solver, worse accuracy... improved with tank testing

- CFD
- Potential Flow
- Calibration
- Tank testing
SENERWave SOLVER. DualSPHysics

SPH Smoothed Particle Hydrodynamics.

Pros
- Fully non linear focus
- Meshless
- SPH particles adapt and interact easily with moving immersed boundaries

Cons
- Not enough fast for full time tests (... like other full CFD)
- Not very focus in marine problems (now improved)
- Unphysical numerical viscosity, difficult to calibrate based on model tank testing

We contributed to the project in areas like irregular wave generation, mooring and free surface pressure conditions (OWC).
SENERWave SOLVER. Potential flow

Pragmatism required faster options... Compass IS SeaFEM

3D potential flow equations solver in the time domain, using the finite element method on unstructured meshes.

1st and 2nd order multi-body wave diffraction and radiation model with irregular sea spectra.

Includes mooring solver and free surface pressure.
SENERWave SOLVER. Tank testing

However potential flow does not consider viscosity or turbulence.

Models need to be calibrated with tank testing.
SENERWave SOLVER. Scaling dilemma. Reynolds vs. Froude

Non-dimensional Navier-Stokes equation contains both Froude and Reynolds adimensional numbers.

\[
\frac{\partial \mathbf{u}^*}{\partial t^*} + (\mathbf{u}^* \cdot \nabla) \mathbf{u}^* = -\nabla p^* + \frac{1}{Re} \nabla^2 \mathbf{u}^* + \frac{1}{Fr^2} \mathbf{g}^*
\]

Considering that Reynolds effects are negligible, tank tests scale down device and events following Froude scaling rules.

However we would like to calibrate potential flow from tank testing.

How have to be scaled up properly viscous/turbulent/rotational effects?

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Dimension</th>
<th>Froude</th>
<th>Reynolds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometric</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length</td>
<td>L</td>
<td>(\lambda)</td>
<td>(\lambda)</td>
</tr>
<tr>
<td>Area</td>
<td>(L^2)</td>
<td>(\lambda^2)</td>
<td>(\lambda^2)</td>
</tr>
<tr>
<td>Volume</td>
<td>(L^3)</td>
<td>(\lambda^3)</td>
<td>(\lambda^3)</td>
</tr>
<tr>
<td>Rotation</td>
<td>(L^0)</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Cinematic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time</td>
<td>T</td>
<td>(\sqrt{\lambda})</td>
<td>(\lambda^2)</td>
</tr>
<tr>
<td>Speed</td>
<td>(LT^{-1})</td>
<td>(\sqrt{\lambda})</td>
<td>(\lambda^{-1})</td>
</tr>
<tr>
<td>Acceleration</td>
<td>(LT^{-2})</td>
<td>–</td>
<td>(\lambda^{-3})</td>
</tr>
<tr>
<td>Volumetric flow</td>
<td>(L^3T^{-1})</td>
<td>(\lambda^{2.5})</td>
<td>(\lambda)</td>
</tr>
<tr>
<td>Dynamic</td>
<td></td>
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<tr>
<td>Mass</td>
<td>M</td>
<td>(\lambda^3)</td>
<td>(\lambda^3)</td>
</tr>
<tr>
<td>Force</td>
<td>(MLT^{-2})</td>
<td>(\lambda^3)</td>
<td>–</td>
</tr>
<tr>
<td>Pressure</td>
<td>(ML^{-1}T^{-2})</td>
<td>(\lambda)</td>
<td>(\lambda^{-2})</td>
</tr>
<tr>
<td>Power</td>
<td>(ML^2T^{-3})</td>
<td>(\lambda^{3.5})</td>
<td>(\lambda^{-1})</td>
</tr>
</tbody>
</table>
SENERWave SOLVER FOCUS

Potential flow pragmatism tuned with tank testing and CFD.

Tank testing validates CFD.

CFD calibrates different design options in potential flow.
SENERWave SOLVER. Detailed studies

In addition to power production different phenomena can be studied.

Waves interference

Wake effects
SENERWave SOLVER. Mooring

Fast time domain non linear solver.

To easily define mooring layout and calculating initial conditions.
SENERWave SOLVER SUMMARY

It couples 2 different solvers to simulate floating and fixed devices and structures in sea conditions:

A fluid dynamic solver devoted to simulations of 3D multi-body radiation and diffraction problems:

- Potential flow equations in the time domain.
- Finite element method on unstructured meshes.
- Interface to enter device geometries.
- Regular, irregular and user defined wave conditions.
- Quasi-static and dynamic mooring solver

A modular equation based language to model complex physical systems:

- Mechanical
- Electrical
- Electronic
- Hydraulic
- Thermal
- Control
SENERWave SOLVER. ECN VALIDATION

To increase the confidence in the power production obtained by SENERWave solver, the Ecole Centrale Nantes LHEEA Research Laboratory in Hydrodynamics, Energetics and atmospheric environment leaded by Aurélien Babarit and Alain H. Clément did a due diligence review of the modelling including tank testing calibration.

Prof. Clément and Babarit have a long experience WEC hydrodynamics in general and in potential flow solvers in special like ACHIl3D, AQUAPLUS and NEMOH.

Tests included fixed and floating OWC setups. The OWC design chosen was a basic Spar buoy design.

Coupled SENERWave linear hydrodynamic laboratory calibrated + non linear PTO model was validated by ECN researchers, including a procedure for proper hydrodynamic model calibration.
COLLABORATION WITH INSTITUTO SUPERIOR TÉCNICO
COLLABORATION WITH IST

The IST Instituto Superior Técnico is one of the world most active researchers in wave energy. The team leaded by Emeritus Prof. Falcão and Prof. Gato have a more than 30 years experience in OWC from Pico Plant, to CORES OEL OE Buoy turbine. Actually they are the developers of biradial turbine that will be installed in OCEANTEC Marmok A-5 device.
COLLABORATION WITH IST

As a part of a collaboration between IST and SENER in the development of a high fidelity numerical model for the Spar Buoy, the following slides describe the hydrodynamic, mooring and PTO models used in the device simulation.

In addition the definition of the feedback control law is described as well as the choice of the optimal turbine size.

Numerical results are presented for device’s performance in irregular waves.
The Spar buoy is possibly the simplest concept for a floating oscillating water column (OWC) wave energy converter.

It is an axisymmetric device consisting basically of a submerged vertical tail-tube-fixed to an axisymmetric floater that oscillates essentially in heave.

The air flow displaced by the water motion inside the tube drives a self-rectifying biradial air turbine.

Pioneer Yoshio Masuda (1925-2009) developed navigation buoys powered by wave energy, equipped with an air turbine, which would later be known as oscillating Water columns (OWCs).

These buoys have been Commercialized in Japan since 1965 until present.

http://www.ryokuseisha.com/eng/product/beacon/light_buoy/oogata.html
The reliability and performance of the oscillating-water-column (OWC) have made it one of the most studied wave energy converter options [1].

The Spar buoy with biradial turbine is a simple and powerful concept developed by IST for more than 15 years with extensive tank testing until 1:16 scale and turbine testing until 1:3 scale.

IST has developed a procedure to choose the optimal turbine size and a feedback control law to get the maximum power per sea state.

In actual stage IST Spar buoy has a TRL of 4-5.
TURBINE DEFINITION

Turbine and generator curves have been defined from laboratory testing and simulation.

In top plot are depicted dimensionless flow rate $\Phi$, dimensionless power coefficient $\Pi$ and efficiency $\eta$ as functions of the dimensionless pressure head $\Psi$ for the biradial turbine used in the numerical simulations.

Bottom plot includes generator efficiency curve.
OPTIMAL TURBINE SIZE

To obtain optimal turbine size and feedback control law, WEC simulations for different JONSWAP sea states and turbine rotational speeds were launched.

By joining maximum power points the control law is obtained, choosing the turbine that generates maximum power for standard generator speeds.

Time-averaged turbine power output $P_{turb}$ for each sea-state $n$ as function of the rotational speed, for different turbine rotor diameters are shown. The dots are maximum power output for each spectrum and the broken line is the exponential curve that interpolates the maximum power output for each spectrum.
SPAR BUOY MODEL IN SENERWAVE
WEC MODELLING. PTO

Original PTO model was directly programmed in C++ including PTO non linear equations model, hydrodynamic and solver in the same code.

\[
F[5] = (\text{CONST}_\text{OMEGA} ? 0.0 : T_t - T_g);
\]
\[
F[6] = \frac{P_t}{tt};
\]

Model was converted first in a Modelica code defined as equations

\[
der(\text{omega})*P_t = (T_t - T_g);
\]
\[
P_t = T_t * \text{omega};
\]
WEC MODELLING. PTO

In a last step equations were arranged modularly so it is simple to change components, for example replacing a Biradial turbine with a Wells turbine, just by connecting a model. Modelica connectors join for example:
- Air mass flow including mass flow (kg/s) and enthalpy (J/s)
- Shaft torque including shaft angular position (and all derivatives) and torque.
WEC MODELLING. MOORING

Full Spar buoy model include three heterogeneous main mooring lines composed by three lines with buoy and clump weight.

This layout permits to reduce mooring loads with smaller footprint.
WEC MODELLING. MOORING

Buoy simulations demonstrated that it can capsize because a low righting torque due to a reduced distance between center of buoyancy and gravity.
Spar buoy frequential response without PTO was analyzed.

Using simpler heave models hides effects like the pitch response.
WEC MODELLING. FREQUENTIAL RESPONSE

Spar buoy frequential response with PTO was analyzed.

As expected PTO changes device frequential response.

This effects are not possible to analyze with simpler hydrodynamic models without PTO.
WEC MODELLING. FREQUENTIAL RESPONSE

Many other effects can be analyzed.

In this case the moorings remove the pitch resonance in frequencies close to normal operation.
WEC MODELLING. NAREC TANK TESTING

IST Spar buoy 1:16 model was tested in NAREC wave tank (National Renewable Energy Centre, Blyth, UK).
The model was built from steel plate having these main characteristics:

- Weight: 700 kg
- Height: 4 m
- Mooring line horizontal projection: 16x2 m
WEC MODELLING. NAREC TANK TESTING

Video

TÈCNICO LISBOA

SPAR-BUOY OWC
LARGE WAVE FLUME
NAREC, UK
October 2012
WEC MODELLING. NON LINEAR EFFECTS

Spar buoy model experiments were reproduced with full CFD.

CFD model served to calibrate SENERWave potential flow solver for fast production simulations.
WEC MODELLING. NON LINEAR EFFECTS

General base size: 8 m
Domain length: 320 m
Spar buoy height: 64 m

Free Surface Refinement:
- X size: 1.2 m
- Z size: 0.064 m

Overset base size: 0.48 m

Surface control:
- Target Surface size: 20 %
- Minimum Surface size: 7.5 %

2,500,000 hexahedral cells
POWER PRODUCTION

Plots column depicts annual averaged results as function of the constants a and b of the generator control law. Top figure reports the pneumatic power, middle the turbine power output, and lower the electrical power output. The dot shows the optimal values of a and b for the generator control law.
POWER PRODUCTION

Top plot depicts results for annual averaged electrical power output, as function of the energy period $T_e$ and significant wave height $H_s$.

Bottom plot presents the corresponding dimensionless electrical capture width.
POWER PRODUCTION

An Atlantic deployment site off the western coast of Portugal has been characterized by a set of 12 sea states.

Each sea-state is described by a JONSWAP spectrum without wave spreading with $T_e$ and $H_s$ presented in table.

Simulations were launched for these states including spar 6 degrees of freedom, hybrid mooring including clump weights and buoys, and variable speed turbine feedback control.

Averaged power results are shown in table. Estimated yearly energy production has been estimated and included in device SENERWave database to obtain cost of electricity.

<table>
<thead>
<tr>
<th>n</th>
<th>$H_s$ [m]</th>
<th>$T_e$ [s]</th>
<th>$P_o$ [%]</th>
<th>$P$ [kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.1</td>
<td>5.49</td>
<td>7.14</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>1.18</td>
<td>6.5</td>
<td>12.53</td>
<td>8</td>
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<tr>
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<td>7.75</td>
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REFERENCES

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