SDWED Project
WP2 - Moorings

State of the art

Copenhagen, Aug. 30th, 2010
Motivation
State of the art on mooring design
Examples
UniBo experience
Waveplane (floating OvT)
Norms

• Many guidelines and regulations: (DNV, API, ISO, Germanischer Lloyd, ..)

Wave Energy Converters (WECs) are usually unmanned and tolerable failure risk is much higher than for the offshore oil and gas industry. Nevertheless, redundancy, durability and reliability are essential factors.

• New specific guidelines are needed in order to integrate Carbon Trust (2006) that provides specific rules for WECs.
Objectives

• To present the state of the art of mooring design enhancing specific requirements of WECs installations;
• To present the experience of UniBo group;
• Enhance the importance of further research in this topic for next applications.
Requirements of moorings

Stiffness may be important for the WEC performance. The system must be

• Sufficiently compliant to:
  – reduce the forces acting on anchors & mooring lines
  – accommodate the tidal range

• Sufficiently stiff to:
  – allow berthing for inspection and maintenance purposes;
  – stationkeeping within specified tolerances;
  – maintain clearance distances between mooring lines, power cable or device itself - in every tide conditions.
Requirements of moorings

- design lifetime 30 years;
- removal of single devices of the park & removal of single lines for inspection and maintenance must be possible;
- replacement of particular components at no less than 5 years;
- the electrical transmission cable(s) must be integrated with the design.
Approach to design of WEC mooring

**DESIGN PHASE**

- Anchor positioning
- Cable Composition
  - Compliance
  - material
- General layout shape and n° of lines
- Choice of mooring system type

**VERIFICATION PHASE**

- Verification of behaviour
  - EFFICIENCY
  - Station keeping
  - Rigidity
  - Loads
- Verification of line and anchor resistance
**Geometrical classification**

- **Spread mooring systems**, consist of multiple mooring lines attached to the floating body, in order to limit horizontal excursions allowing a large compliance. It comprises:
  - catenary
  - taut line
  - multi-line

Spread moorings do not allow the floating body to rotate about its hull, according to wind, wave and current prevailing directions. (avoiding high environmental loads).

(API, 1987)
Geometrical classification

• **Single Anchor Leg Mooring (SALM)**, where floating structure is moored to a single anchored taut buoy and it is able to weathervane around the moored buoy.  
  (Harris et al., 2004)

• **Single Point mooring And Reservoir (SPAR)** allows the storage of a medium (oil, hydrogen) and a floating structure to weathervane around a mooring point.  
  (Harris et al., 2004)
• **Passive mooring**, if the only purpose is station keeping (OEBuoy, Wave Dragon, Pelamis, Leancon) and movements have a limited effect on the device efficiency.

• **Active mooring**, if the system stiffness is important for the dynamic response (Point Absorbers like DEXA, WaveBob, PowerBob) and may alter the resonance conditions.

• **Reactive mooring**, if the mooring provides a reaction force (Archimede Wave Swing), and the PTO exploits the relative movements between the body and the fixed ground.
Matching of functionale and geometrical classification

<table>
<thead>
<tr>
<th>Single Point</th>
<th>Passive mooring</th>
<th>Active mooring</th>
<th>Reactive mooring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spread mooring</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turret mooring</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Catenary Anchor Leg Mooring (CALM)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single Anchor Leg Mooring (SALM)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Articulated Loading Platform (ALP)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fixed mooring tower</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Examples

Pelamis spread mooring
Examples

Syncwave
power
resonator
spread
mooring
Examples

AquaBuOY mooring

Displacer – floating buoy

Reactor – water mass

Piston

Hose pump
Approach to design of WEC mooring

**DESIGN PHASE**

- Anchor positioning
- Cable Composition
  - Compliance
  - Material
- Choice of mooring system type
- General layout shape and n° of lines

**VERIFICATION PHASE**

- Verification of behaviour
  - EFFICIENCY
  - Station keeping
  - Rigidity
  - Loads
- Verification of line and anchor resistance
Horizontal layout

System stiffness in 2DH

- **Line orientations** are based on
  - geometry of the hull;
  - prevailing directions of winds, waves and currents;
- Asymmetric mooring pattern can be adopted where strong winds or currents come from one direction only;
- The most commonly used patterns are the 30-60° eight line and the symmetric eight line.
Vertical layouts

Stiffness matrix has different mixed terms in the horizontal, vertical, rotational DOF
Approach to design of WEC mooring

**DESIGN PHASE**

- Anchor positioning
- Cable Composition
  - Compliance
  - Material
- General layout shape and n° of lines
- Choice of mooring system type

**VERIFICATION PHASE**

- Verification of line and anchor resistance
- Verification of behaviour
  - Efficiency
  - Station keeping
  - Rigidity
  - Loads
Cable vertical layouts

**Cable type 1:** Simple Catenary mooring

- **Anchor:** Conventional drag embedded anchor - zero vertical loads permissible

**Cable type 2:** Adding a surface buoy

- **Anchor:** Conventional drag embedded anchor - zero vertical loads permissible
  - Synthetic, L = d
  - **Cable 2a:** Polyester Parallel Strands
  - **Cable 2b:** Nylon Braided Strands

**Cable type 3:** Adding a clump-weight

- **Anchor:** Conventional drag embedded anchor - zero vertical loads permissible
  - Chain, L = 2.5d
  - Steel Rope, L = 0.9d
  - Synthetic Braided Nylon, L = d

**Cable type 4:** Vertically Loaded Anchor with compliance using weights and buoys

- **Anchor:** Vertically Loaded Anchor. (Drag-in plate or gravity anchor)
  - Steel Rope, L = 1.2d
  - Steel Rope, L = 0.7d
  - Steel Rope, L = 0.9d

(Fitzgerald, 2009)
Cable material

Chain

- there are essentially two types:
  - open link
  - stud link

- stud links usually tend to get entangled less than open links;

- failure process can be due to:
  - cathode corrosion;
  - joint crackings;

- chain integrity is also limited by relative rotation of the links, due to excessive abrasion.

(ABS, 1999a)

<table>
<thead>
<tr>
<th>Designation</th>
<th>Description</th>
<th>Nominal Dimension of the Link</th>
<th>Minus Tolerance</th>
<th>Plus Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>Link Length</td>
<td>6d</td>
<td>0.15d</td>
<td>0.15d</td>
</tr>
<tr>
<td>b</td>
<td>Link Half-Length</td>
<td>a*2</td>
<td>0.1d</td>
<td>0.1d</td>
</tr>
<tr>
<td>c</td>
<td>Link Width</td>
<td>3.6d</td>
<td>0.09d</td>
<td>0.09d</td>
</tr>
<tr>
<td>e</td>
<td>Stud Angular Misalignment</td>
<td>0 degrees</td>
<td>4 degrees</td>
<td>4 degrees</td>
</tr>
<tr>
<td>R</td>
<td>Inner Radius</td>
<td>0.65d</td>
<td>0</td>
<td>---</td>
</tr>
</tbody>
</table>

Notes:
(1) Dimension designation is shown in above figure
(2) d = Nominal diameter of chain
(3) a* = Actual link length
Cable material

**Synthetic ropes**

- Typical fibre ropes:
  - Polyester;
  - Aramid;
  - HMPE;
  - Nylon;
- weight is almost null;
- re-tensioning can be required in a long-term installation;
- They can be threatened by:
  - slacking phenomena;
  - hysteretic heating;
  - extreme storm condition;
  - fish bites;

  (Harris et al., 2004)

---

6-Strand Rope (non-load-bearing core)
7-Strand Rope (load-bearing core)
18-Strand Rope ("wire rope" construction)
8-Strand Rope ("Plaited") (ABS, 1999b)
Cable material

Wire ropes

- available wire ropes:
  - *Spiral Strand*;
  - *Six Strand*;
  - *Multi-Strand*;

- wire ropes have high elasticity and can be used in tensioned mooring applications;

- extreme bending must be avoided.

(Harris et al., 2004)
Comparison for costs of mooring line materials

- Steelite Xtra / Superline
- Polyester / Superline
- Spiral Strand / Lubrication + zinc coating + plastic jacket
- Spiral Strand / Lubrication + Al-Zn coating (Bezirfel)
- R4
- R3S
- R3

Note:

Synthetic rope: Prices obtained from Marlow Ropes which were purely budgetary, requiring confirmation with regard to end termination and suitable packaging. The prices quoted would attract a discount assuming large quantities and require a more detailed costing.

Chain: Prices obtained from Sanmar Ltd, Glasgow which were based on a 100m length stainless steel chain to grade R3, R3S and R4.

Wire rope: Prices obtained from ScanRope AS, Norway which were only indicative if large quantities of one type of strand would be ordered and are based on a 100m long rope. Ropes are terminated at each end with sockets whereby the price for the sockets was also based on a large quantity order. Additional cost not included would occur from the transport reels. The cost for the transport reels is a large variable depending on rope diameter and length and could contribute a significant part to the total cost.
Cable material

- **Chain systems**
  - have more durability in offshore applications;
  - have better resistance to bottom abrasion;
  - contribute significantly to anchor holding capacity.

- **Wire systems**
  - are more lightweight than all-chain system;
  - provide more restoring force in deep water;
  - requires lower pretensions;
  - much longer line length is required to prevent anchor uplift;
  - the abrasion between wire rope and a hard seafloor can sometimes become a problem.
  - need more maintenance.
  - corrosion due to lack of lubrication or mechanical damage could cause mooring failure. (API, 1987)
Cable material

• Chain-wire systems
  o offer the advantages of low pretension requirement, high restoring force, added anchor holding capacity, and good resistance to bottom abrasion.
  o are the best system for deepwater operations;
Approach to design of WEC mooring

**DESIGN PHASE**
- Anchor positioning
- Cable Composition
  - Compliance
  - Material
- Choice of mooring system type
- General layout shape and n° of lines

**VERIFICATION PHASE**
- Verification of behaviour
  - EFFICIENCY
  - Station keeping
  - Rigidity
  - Loads
- Verification of line and anchor resistance
Anchor positioning

• Based on planimetric layout of mooring lines, the anchor positioning is chosen;

• Many types of anchor is given
  o **Gravity Anchor** Dead weight provides friction between seabed and anchor.
  o **Drag-Embedment Anchor**: Horizontal holding capacity is generated by the embedment of the anchor in the ground.

(Harris et al., 2004)
Mooring system components

• **Driven Pile/Suction Anchor**: Horizontal and vertical holding capacity is generated by forcing a pile mechanically into the ground, providing friction along the pile and the ground.

• **Vertical Load Anchor**: Horizontal and vertical holding capacity is generated due to a specific embedment anchor, allowing loads not only in the main instalment direction.

(Harris et al., 2004)
Patented anchoring device

Bio Wave mooring
Approach to design of WEC mooring

**DESIGN PHASE**
- Anchor positioning
- Cable Composition
  - Compliance
  - material
- General layout shape and n° of lines
- Choice of mooring system type

**VERIFICATION PHASE**
- Verification of behaviour
  - EFFICIENCY
  - Station keeping
  - Rigidity
  - Loads
- Verification of line and anchor resistance
Overall behavior

Modelling of moored structure by AQWA™ software

1) Geometric modelling of the floating body and of the mooring system
2) The solution for diffraction/refraction problem is given, in terms of:

- diffracted and radiated wave fields;
- RAOs for all 6 degrees of freedom;
- Stiffness matrix of mooring system;
- External dumping matrix of mooring system;
- Added mass matrix of mooring system.
3) **Dynamic analysis of mooring lines**, in terms of:

- Element tensions
- Relative motions
- Node tensions
- Node velocities
- Node positions
- Cable energy

**Modelling of moored structure by AQWA™ software**

**Overall behavior**
Approach to design of WEC mooring

DESIGN PHASE

- Anchor positioning
- Cable Composition
  - Compliance
  - Material
- Choice of mooring system type
- General layout shape and number of lines

VERIFICATION PHASE

- Verification of behaviour
  - EFFICIENCY
  - Station keeping
  - Rigidity
  - Loads
- Verification of line and anchor resistance
In case of "snatching/snapping" phenomena, impulsive tensions in the cable become critical → field of research.

Dynamic stress on all parts of the system can be computed after the WEC movements are determined. Different external load conditions of loads must be considered, including possible loss of 1 cable.

(Fitzgerald, 2009)
Physical model experience

“Deep water” wave basin of Aalborg:
- Length 15.70 m
- Width 8.50 m
- Max depth 1.50 m
- 10 paddle wavemaker

Wave Basin at Padova University
- Length 39 m
- Width 1.00 m
- Max depth 0.60 m
- 1.4 m wide wave paddle

Wave Flume at Padova University
- Length 39 m
- Width 1.00 m
- Max depth 1.50 m
Model characteristics:
- Scale 1:20
- Length 2.10 m
- Width 0.85 m
- Weight 22 Kg
Tested turret mooring
Results: RAOs
Results: loads

OE_90_S_CC_016_RA_040_110.lvm

- Measured load, front
- Quasi-static load, front
- Measured load, back
- Quasi-static load, back

T (s) vs. N

0 0.5 1 1.5 0.8 1 1.2 1.4 1.6 1.8 2

0 0.5 1 1.5 2

0 0.8 1 1.2 1.4 1.6 1.8
Experience with phisical models on floating breakwaters since 2005

Tested moorings in Flume and Basin:
- Spread mooring with “different water level” and “different compliance with same water level”;
- Piles;
- Layout and load along connections.
Spread mooring
Piles
2-D wave flume tests
Effect of chain pretension
(maximum loads vs. initial loads)

\[ y = 8.1x + 1.5 \]
\[ y = 4.6x + 1.5 \]
\[ y = 4.8x + 1.5 \]

Initial load [kg]

Maximum load [kg]

$T_p = 1.00\, s$
$T_p = 0.87\, s$
$T_p = 0.72\, s$
Effect of wave height

COMMENT: maximum loads on chains increase much more than proportionally with Hi (and Ti)
Wave Basin tests

Laboratory at University of Padova
Mooring forces

- $0^\circ \ T_p < T_n$
- $0^\circ \ T_p > T_n$
- $30^\circ$
- $60^\circ$
- $L$

$\frac{F_{1/100}}{(\rho \ g \ H_{si} \ d)}$ vs. $\frac{H_{si}}{F_r}$
Numerical modelling

Available numerical models

• Commercial software:
  – Aqwa

• Developed:
  – FEM (cable dynamic) + FEM (added masses, Potential flow) + Matlab (Mass-Spring-Dashpot) + Matlab (Virtual world)
  – FEM (Viscous flow, Navier Stokes)
Ansys AQWA™

...work in progress

Geometric model of DEXA device, to be solved by programs in AQWA™ suite
Dynamics of synthetic lines
Flexible truss model

Dynamics of Chains Lumped mass model

Usually umbelicals are not subject to dynamic forces, whereas wires are always significantly loaded.
Numerical models of floating devices
Virtual world simulation of rigid body movements
2-way interaction problem, where free surface and body position is updated at each time step.

Fluid: Navier Stokes, no pressure at the surface, no friction at the boundaries.
Floating body: rigid body allowed to move in the vertical direction.
Moving grid approach

The mobility of the mesh is limited.

Points on the free surface and at the 2 immersed corners of the body are constrained to remain there.

Points on the side of the body cannot cross nor reach the body corners ..... they can “slide” but they should not leave or deform the body!!
Generation of waves from an internal source allows for a better description of the reflected waves, propagating toward the generation area.

Some stabilisation techniques (e.g. Petrov Galerkin pressure stabilisation) assume zero divergence and they cannot be used unless they are adapted.
Conclusions pre SDWED

- Mooring of some floating WECs failed thus rising the attention to the design problem.
- Design of mooring systems has an old history in the off-shore industry and some typologies are suited to WECs.
- On the base of physical model tests it was found that mooring compliance has a strong effect on performance → need for wave2wire model
- Modelling of mooring system requires enhancement due to the additional degrees of freedom of the system.
Introduction to WP2

• General problems related to moorings (enhanced in presence of WECs, usually subject to many high oscillations):
  – Reliability (FEMA, FEMCA, …)! 
  – Fatigue! 
  – Economic issues
• Mooring design problems specifically posed by floating WECS:
  – The WEC has more degrees of freedom than a ship (movable parts, water inside chambers) → the radiation problem is more complex
  – Wave non-linearity is much greater than for consolidated off-shore engineering design praxis (effects ?)
Basic need

• Propose suitable layouts:
  – in accordance with regulations, norms, environmental issues, ..;
  – weathervaning;
  – assuring WEC stability;
  – neutral (or positive 😊 ) performance;
  – possible displacement in farms;
  – avoid interference with umbilical;
  – easy installation and maintenance.
WP2 Aim

• The objective of WP2 are:
  – to propose reliable design of mooring systems for WECs;
  – to deliver knowledge and software to be able to calculate response from these moorings;
  – to give accurate estimates on lifetimes related to the designs.
Work tasks

• 2.1 Screening suitable systems
• 2.2 Non-linear force-displacement performance
• 2.3 Deployment methods
• 2.4 Reliability

Participants: Unibo, Sterndoff Engineering
Table 7.1 Gantt chart

<table>
<thead>
<tr>
<th>Project plan</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
</tr>
<tr>
<td>Project stages</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Project startup</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basic research</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Implementation / integration</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dissimination and feedback</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Project closure and evaluation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Management</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steering committee meetings</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Project meetings, all partners</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Advisory board meetings</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dissimination</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Symposium, The plan - industry feedback</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Symposium, Results WP1-3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Symposium, Wave to wire model, Reliability</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ph.D. course, visiting lecturers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conference presentations</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Journal papers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WP Research item</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 Moorings</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1 Screening suitable systems</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.2 Non-linear force-displacement performance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.3 Deployment methods</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.4 Reliability</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Interactions with other WTs

• WP1 (Hydrodynamics):
  – Long and short term wave climate is needed;
  – is the load on the structure provided as well?

• WP3 (PTO):
  – Feedback for interaction between performance and mooring/movements.

• WP4 (Wave2wire):
  – Agree simple mooring model.

• WP5 (Reliability):
  – Guidelines for design practice.
Expected results

- A simple (matlab) module that will be part of the wave2wire model providing mooring loads;
- best practise for design and certification of WECS moorings;
- methodology to perform a risk analysis of a WEC mooring system.
Luca Martinelli, Barbara Zanuttigh, Mirko Castagnetti
Università di Bologna
Dipartimento di Ingegneria Civile, Ambientale e dei Materiali
l.martinelli@unibo.it, barbara.zanuttigh@unibo.it, mirko.castagnetti2@unibo.it
www.unibo.it