Screening of suitable mooring systems

Barbara Zanuttigh
Luca Martinelli
Mirko Castagnetti

Deliverable D2.1
Screening of suitable mooring systems

by

Barbara Zanuttigh
Luca Martinelli
Mirko Castagnetti
Index

PREFACE .............................................................................................................................................. 4

1. INTRODUCTION .......................................................................................................................... 4

2. REGULATIONS AND NORMS ...................................................................................................... 5

3. FUNCTION REQUIREMENTS OF F-WEC MOORING ................................................................... 6

4. AN APPROACH TO DESIGN OF F-WEC MOORING .................................................................... 7

4.1 DESIGN PHASE .......................................................................................................................... 8

4.1.1 CHOICE OF MOORING SYSTEM TYPE ................................................................................. 8

4.2 GENERAL LAYOUT, SHAPE AND NUMBER OF MOORING LINES ............................................... 11

4.3 CABLE COMPOSITION ............................................................................................................... 12

4.3.1 VERTICAL LAYOUT ............................................................................................................... 12

4.3.2 THE CHAIN ............................................................................................................................ 14

4.3.3 THE CATENARY .................................................................................................................... 16

4.3.4 SYNTHETIC LINES ............................................................................................................... 17

4.3.5 WIRE ROPEs ........................................................................................................................ 20

4.3.6 COST OF THE LINE .............................................................................................................. 22

4.4 ANCHOR POSITIONING ............................................................................................................. 23

4.5 VERIFICATION PHASE ............................................................................................................... 25

4.5.1 EVALUATION OF FLOATING BODY MOVEMENTS ............................................................. 25

4.5.2 VERIFICATION OF LINE AND ANCHOR ............................................................................. 26

4.5.3 NUMERICAL MODELS ......................................................................................................... 28

CONCLUSIONS .................................................................................................................................. 29

REFERENCES ...................................................................................................................................... 30
Preface

Objectives of this report are to provide an overview of the mooring systems and specifically to answer the following questions:

- What are the needs? Function requirements of moorings for Wave Energy Converters (WECs).
- What is it? Description of mooring systems.
- Which software can be used. List commercial software to evaluate the real behavior of moored device under extreme wave loads.

1. Introduction

The loads acting on WECs are very high and at the same time difficult to compute a priori (Sannasiraj et al., 1998; Zanuttigh et al., 2009, Martinelli et al., 2008; Loukogeorgaki and Angelides, 2005). If the device is installed offshore, in deep water, it can convert a big quantity of energy, because a very little part is lost by friction with the seabed. Although nearshore devices may result competitive at the present state of development (Boccotti, 2003), offshore WECs are exposed to a stress undoubtedly greater than nearshore ones (Ruol et al., 2009). Extreme loads, to which the device must resist, are higher and are directly responsible for the costs of WECs (Masuda et al., 2002), while the energy to be sold is produced in ordinary load conditions (Falcão and Rodrigues, 2002).

Moreover, the offshore placement of WECs may result in lower attenuation of the waves approaching the shore. Such aspect represents an interesting investigation field to integrate energy conversion systems and coastal protection measures.

The mooring design has been known in engineering’s field for some years by the experience from offshore structures (Isaacson & Nwogu, 1987) and shipbuilding. Despite this fact, a relatively high rate of floating WECs have failed in their efforts because the mooring system was unable to anchor. Functional and structural inadequacy may affect also the efficiency of energy conversion (Martinelli et al., 2009). In fact, the moorings must ensure that the device remains close to the point where it was originally placed, but at the same time, they must allow the relative movement of the device to convert a sufficient quantity of energy.

There is no experimental database that allows systematic analysis of working conditions of WECs. Some large-scale prototype scale (see also www.pelamiswave.com,
www.oceanpowertechnologies.com, www/wavegen.co.uk) could provide in the coming years a significant deepening of construction technology through monitoring campaigns.

The existing models have not provided so far criteria for design, stability, durability and reliability of devices and moorings, so that field data based on physical model tests are required, in order to fully evaluate the device behavior.

More reliable devices and lower management costs would certainly result in more competitive energy production from wave energy market, leading to the benefits previously listed.

2. Regulations and norms

In the past, regulations, guidelines and norms have been provided by several authorities whose their specific aims were to ensure the station keeping to offshore gas and oil platforms under extreme environmental loads (waves, winds, currents):

- DNV (Det Norske Veritas): rules and regulations for the classification of ships, mobile offshore platforms and other floating marine structures were established (see also www.dnv.com). Classification and design criteria for mooring systems and their specific parts (chains, anchors, etc.):
  - DNV-OS-E301 - Position Mooring;
  - DNV-OS-E302 - Offshore Mooring Chain;
  - DNV-OS-E303 - Offshore Mooring Fibre Ropes;
  - DNV-OS-E304 - Offshore Mooring Steel Wire Ropes;
  - DNV-RP-E304 - Damage Assessment of Fibre Ropes for Offshore Mooring.

- API (American Petroleum Institute): regulations and guidelines for offshore oil and gas platforms (floating and fixed) were provided. Issues as design and planning criteria for floating structures, materials, station keeping, mooring and anchoring systems, fabrication, installation and inspection, risk management, etc., are included into such regulations (see also www.api.org).


- ABS (American Bureau of Shipping): ABS offers practical standards for design, construction, operation and maintenance of offshore installations:
  - Rules for building and classing of single point moorings (1996)
Guidance notes on the application of synthetic ropes for offshore mooring (1999)

In general, the tolerable failure risk is much higher for offshore oil and gas installations rather than for F-WECs (they are usually unmanned, so that F-WEC failure does not lead to a loss of human life). However, redundancy, durability and reliability represent essential factors for a safe employing of such devices. The mentioned norms and guidelines can be also adopted for F-WEC mooring design.

More recently, Carbon Trust (2006) has provided recommended practices and a guide to assessment and application of engineering standards for F-WECs. In such publication, guidance on concept development, design, construction and life cycle processes during F-WECs in-service life are provided.

3. Function requirements of F-WEC mooring

Floating Wave Energy Converters (F-WECs) require a mooring system in order to ensure station keeping, and more specifically to limit the drift, ensure alignment of directional WECs with the prevailing wave conditions, avoid impact with other structures and excessive loads on the electric power umbilical.

In details the requirements are:

- to maintain the floating structure on station within specified tolerances under normal operating load and extreme storm load conditions, that is generally more severe and frequent than for normal mooring installations;
- the excursion of the device must not permit tension loads in the electrical transmission cable(s) and should allow for suitable specified clearance distances between devices in multiple installations; contact between mooring lines, or contact with the device itself must be avoided;
- the mooring system must be sufficiently compliant to the environmental loading to reduce the forces acting on anchors, mooring lines and the device itself to a minimum (unless the stiffness of the mooring itself is an active element in the wave energy conversion principle used);
- the mooring have to be sufficiently compliant to accommodate the tidal range at the installation location, and sufficiently stiff to allow berthing for inspection and maintenance purposes;
The mooring system should also require as little inspection and maintenance as possible over the in-service life of the device. It should be possible to remove the F-WEC from the site (or remove one F-WEC from energy farm), with easy re-installation, without damaging any components or reducing the service life of the system.

The system should limit the environmental impact as much as possible. Environmental factors to be considered include damage to the local environment, visual impact, and any effect on the local eco-system.

4. An approach to design of F-WEC mooring

The design process concerns the configuration of the individual lines, their interaction with the bottom (through drag embedded, pile, gravity, plate anchors), and the overall layout, i.e. the disposition of the lines that is responsible of the correct orientation of the F-WEC relatively to the predominant waves and of the possible weathervaning.

The design procedure can be articulated in design and verification phases (Fig.4.1).

![Figure 4.1 - Conceptual scheme of design procedure for F-WECs mooring systems](image)
4.1 Design phase

4.1.1 Choice of mooring system type

First, it is necessary to define a proper functional and geometrical classification for mooring types:

- **Functional Classification**
  - *Passive mooring*, if the station keeping is the only purpose and movements have a limited effect on the device efficiency.
  - *Active mooring*, if the system stiffness is an important factor for the dynamic response of the device. Such effects can offer resonance conditions in order to produce much more energy;
  - *Reactive mooring*, if the mooring provides a reaction force. They are suited especially when the Power Take Off (PTO) exploits the relative movements between the body and the fixed ground.

- **Geometrical Classification:**
  Mooring systems can be basically classified on the basis of the layout configuration in: Spread, Single Point and Dynamic Moorings.
  - *Spread mooring systems*. They consist of multiple mooring lines attached to the floating body (Fig.4.3.a) in order to limit horizontal excursions and allowing a large compliance. They do not allow the floating body to rotate about its hull, according to wind, wave and current prevailing directions. It comprises catenary, taut lines and composed multi-lines. Active mooring or dynamic positioning (propulsion) could be an expensive station keeping option.
  - *Turret mooring (internal or external)*. A catenary moored turret attached to a floating structure allows weathervaning around it (Fig. 4.3.b).
  - *Catenary Anchor Leg Mooring (CALM)*. The floating structure is linked to a catenary moored buoy and it is able to weathervane around such buoy (Fig.4.4.a).
  - *Single Anchor Leg Mooring (SALM)*. The floating structure is linked to a single anchored buoy and it is able to weathervane around it (Fig. 4.4.b).
- **Articulated Loading Column (ALP).** The floating structure can weathervane around a bottom hinged column, which has a swivel above the water line.

- **Fixed Tower Mooring.** The floating structure is able to weathervane around the mooring point which is composed by an anchored tower into the seabed.

A more liable alternative is the introduction of configurations typical of flexible risers such as Lazy S, Steep S, Lazy Wave, Steep Wave or Pliant Wave could decrease the system stiffness thereby reducing the mooring loads. The use of these multi-catenary mooring configurations could provide flexibility in particular modes of motion required to improve the energy extraction for wave activated F-WEC designs.

The most economic option for the lines is the free hanging catenary configuration. Unfortunately this may not be able to allow for a sufficient extension without excessive loads when the tidal range is large. Another disadvantage of such a configuration could be the restraining stiffness affecting the F-WEC dynamic (Harris et al., 2004).

First and second classification can be combined to chose the best F-WEC mooring type. (Fig.4.2).

<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>

*Figure 4.2. – Comparison of the functional and geometrical classification.*

Selection of the of proper mooring can be done using traditional methods in case of the passive and reactive type. For active moorings, i.e. when the system stiffness is fundamental, the process involves many iterative steps. The overall efficiency needs to be evaluated and – if not correct - the design have to be reconsidered.

Fitzgerald (2009) proposes 3 examples of F-WECs and compares compliance and costs. From his research, there should be a tendency to keep large structures to maintain mooring and operational costs down. He also shows that costs of the mooring are quite essential in the F-WEC sector (see Fig. 4.5). It may be concluded that, during F-WEC design, a detailed analysis of the mooring system is fully justified.
Figure 4.3. – Spread mooring system (a) and internal turret mooring (b) (API, 1987).

Figure 4.4. – CALM (a) (Sagrilo et al., 2002) and SALM (b) (API, 2001).

Figure 4.5 Cost breakdown and relevance of mooring system for Oil floating platforms and for F-WECs (Fitzgerald, 2008).
4.2 General layout, shape and number of mooring lines

In this design step, the horizontal layout of mooring lines has to be chosen, considering the 2DH mooring system stiffness.

Line orientations are based on the hull geometry and on the prevailing directions of winds, waves and currents. Several schemes to moor floating structures are currently provided, but they can be ideally summarized as follows:

- symmetric layouts;
- asymmetric layouts.

Generally, the asymmetric mooring schemes are to be avoided, adopted only where strong winds or currents come from one direction only or for steep bed variations, whereas the symmetric ones are especially employed when the prevailing wind and current directions are very variable. The most commonly used patterns are the 30-60° eight line and the symmetric eight line (Fig. 4.6).
4.3 Cable composition

Lines are composed in general of a combination of metallic chains, metallic or synthetic wires. Chains (see SubSection 4.3.2) are typically the first choice due to low cost and reliability. Synthetic lines are used for special cases when low weights are required. It is frequently required that the fraction of mooring line at the touchdown point is formed by a chain, more resistant to wear.

4.3.1 Vertical layout

Each individual line may be formed by a composition of different parts made of chain or wire, with the addition of floats, clumps, or chain tails (drag chains) used as an alternative to a clump weight.

The lines may be displaced in several configurations, possibly in combinations with a spring buoy (e.g. surface buoy) which offer advantages such as reduced loads on F-WEC devices and increased vertical F-WEC clearance. Figures 4.7 - 4.11 show the possible chain configurations according to Fitzgerald (2009), which mainly differ for the horizontal/vertical load-displacement curves: it is evident that in some cases the vertical load depends on the displacement in a non-linear way (cases in Fig. 4.7 and 4.11), in other cases is almost negligible (Fig. 4.9 and 4.10) and on other cases it is important but essentially constant (Fig. 4.10).

The stiffness matrix, more precisely the mixed terms in the horizontal, vertical and rotational degrees of freedom (DOF), can significantly change due to different vertical adopted layouts.
**Figure 4.8 - Catenary mooring with added surface buoy (Fitzgerald, 2009)**

Anchor: Conventional drag embedded anchor - zero vertical loads permissible

Cable 2a: Polyester Parallel Strands

Cable 2b: Nylon Braided Strands

---

**Figure 4.9 - Catenary mooring with added surface buoy and clump weight (Fitzgerald, 2009)**

Anchor: Conventional drag embedded anchor - zero vertical loads permissible

**Figure 4.10 - Vertical loaded anchor with compliance using weights and buoys (Fitzgerald, 2009)**

Anchor: Vertically Loaded Anchor. (Drag-in plate or gravity anchor)
4.3.2 The chain

The chain has shown durability in offshore operations. It has better resistance to bottom abrasion and contributes significantly to anchor holding capacity. Moreover, the chain provides a good catenary mooring stiffness to comply horizontal and vertical excursions. It is also particularly suitable for long term mooring systems but it requires periodic inspections and maintenance to keep it clean from bio-fouling that can increase the weight per unit and also damage the chain due to excessive abrasion, caused by relative rotation of the links (API, 1999). Moreover, cathode corrosion represents a possible threat for chain integrity. Possible methods to avoid cathode corrosion can be essentially divided into active or passive methods. Active ones include the possibility to use an external cathode which focuses the corrosion over it. Passive ones consist of an outer chain cover by a polymeric layer (jacket) that isolates the chains from undesired electric currents. Nevertheless, passive cathode protection tends to be infrequently adopted, since the outer polymeric layer will be quickly removed due to relative movements of the chain elements (Harris et al., 2004).

At present, two types of chain are commonly employed:

- open link (Fig. 4.12.a);
- stud link (Fig. 4.12.b)

Studless steel chains are usually used, being reliable also in terms of fatigue, although stud link chains tend to get entangled less than open links.

Chains can be obtained in several grades, which are characterized by a different proof tensile strength (Tab. 4.1). In general, three grades (RQ3, RQ3S and RQ4) are provided for offshore operations.
mooring systems, whereas grade RQ5 is characterized by the highest proof tensile strength (ABS, 1999.a). Oil Rig Quality (ORQ) or RQ3 chain has been sold in large quantities industry wide and has generally performed well.

![Diagram of mooring system components](image)

**Figure 4.12 – Chain types (ABS 1999,a)**

<table>
<thead>
<tr>
<th>Designation(1)</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>$a^{w}/2$</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  
$a^{w}$ = Actual link length

**Figure 4.13 – Chain standard dimensions (ABS 1999,a)**

**Tensile Requirements for Chain, Accessory and Material**

<table>
<thead>
<tr>
<th>Grade</th>
<th>Yield Strength(1) minimum in N/mm² (kgn/mm², ksi)</th>
<th>Tensile Strength(1) minimum in N/mm² (kgn/mm², ksi)</th>
<th>Elongation in 5D minimum in percent</th>
<th>Reduction of Area minimum in percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>RQ3</td>
<td>410 (42.59)</td>
<td>690 (70, 100)</td>
<td>17</td>
<td>50(3)</td>
</tr>
<tr>
<td>RQ3S</td>
<td>490 (50, 71)</td>
<td>770 (78, 112)</td>
<td>15(3)</td>
<td>50(3)(3)</td>
</tr>
<tr>
<td>RQ4</td>
<td>580 (59, 84)</td>
<td>860 (87, 125)</td>
<td>12(3)</td>
<td>50(3)(3)</td>
</tr>
</tbody>
</table>

**Notes:**
(1) The aim value of yield to tensile ratio is 0.92 maximum  
(2) For cross-weld tensile tests these properties are to be reported for information only; the stated requirements do not apply.  
(3) For cast grade RQ3 and RQ3S accessories the reduction of area requirement is 40 percent minimum.  
(4) For cast grade RQ4 accessories the reduction of area requirement is 35% minimum.

**Figure 4.14 – Chain quality grades (ABS 1999,a)**
4.3.3 The catenary

An idealized hanging chain or cable in static conditions when supported at its ends and acted on only by its own weight assumes a catenary shapes. Such curve is the graph of the *hyperbolic cosine function*, and has a U-like shape, superficially similar in appearance to a parabola (though mathematically quite different).

![Figure 4.15. Catenary formulation](image)

First of all, a general formulation of the catenary equations has to be provided (Fig. 4.15). In such formulation, it is assumed that the catenary is hanging in points A and B. The point V accounts for the lowest point of the catenary, whereas a generic point P on the arch between V and B is taken. Horizontal and vertical forces in P are then are considered, respectively \( t \) and \( a \).

A relation between \( p \) and \( t \) by means of \( \tan \varphi \) can be given through Eq. [1]:

\[
p = t \tan \varphi = t \frac{dy}{dx}
\]  

[1]

At the same time, \( p \) can be written as the weight of VP arch, considering a constant linear density \( \lambda_0 \):

\[
p = g \lambda_0 \int_{x_v}^{x_p} \sqrt{1 + \left( \frac{dy}{dx} \right)^2} \, dx
\]  

[2]

By matching Eq.s [1] and [2], the following equation can be obtained:

\[
t \frac{dy}{dx} = g \lambda_0 \int_{x_v}^{x_p} \sqrt{1 + \left( \frac{dy}{dx} \right)^2} \, dx
\]  

[3]

By deriving first and second member along \( x \) axis, Eq. [3] becomes:

\[
t \frac{d^2y}{dx^2} = g \lambda_0 \sqrt{1 + \left( \frac{dy}{dx} \right)^2}
\]  

[4]
or alternatively:

$$\frac{d^2y}{dx^2} = \frac{g\lambda_0}{t} = k$$

By solving the differential equation [5], the catenary formulation also for mooring lines can be given:

$$\frac{z}{c} = \cosh\left(\frac{x}{c}\right) - 1$$

$$\frac{s}{c} = \sinh\left(\frac{x}{c}\right)$$

$$c = \frac{F_h}{w}$$

where:

- $z =$ vertical coordinate [m]
- $s = $ line coordinate [m]
- $x = $ horizontal coordinate [m]
- $F_h = $ the constant horizontal force [N]
- $w = $ weight per unit length [N/m]

In actual practice, the chain is generally subject to other loads beside the weight, such as those due to the direct wave action and the fairlead is connected to a moving body. In short, the line does not behave like a pure catenary. The design should therefore account for at least the following additional loads:

- the inertia forces due to the chain accelerations;
- drag and inertia forces due to the different velocity of the moving chain with respect to the adjacent water, generally a combination of irregular wave with a coherent vertical structure but quite variable in time and currents usually stratified in the vertical direction but rather constant in time.

### 4.3.4 Synthetic lines

In order to minimize the vertical load on F-WECs, the alternative solution to chains are synthetic line. Most common materials are nylon, polyster, polipropilene, kevlar, high density
polyethylene (Dyneema). Conversely from chains, where the resistant force is due to their weight, the synthetic lines offer a resistance which depend on their elastic characteristics.

The weight and elasticity properties of the ropes make them more common for very deep water tether applications. Axial compression and hysteretic heating may reduce the initial rope resistance (although considerable change in axial stiffness after installation could require one or more re-tensioning). Fish bites can represent a serious problem (Harris et al, 2004). Therefore, fibre rope segments in mooring lines are normally protected by an outer jacket, which has an adequate resistance to hydrolysis, chemical corrosion, creep phenomena, fish bites, friction and shear, with a proper flexibility at minimum exposure temperatures in order to meet the requirement to protect the rope core.

![Figure 4.16 - Structure of a synthetic line](image)

A synthetic line results from the assembly of different components in a hierarchic structure which follows the production line, starting from the fibre that composes the line (Fig. 4.16).

The elastoplastic response of the line is very complex: a first permanent deformation occurs at the first loading, which stretches the fibers for the first time; an important non-linear elastic response is present at each successive loading, mixed to a plastic deformation or creep which is due to a microscopic re-aligning of the fibers and that dissipates energy.

Such behavior can be described by the axial rigidity $EA [N]$, which gives the proportionality constant in the stress-strain $\sigma$–$\varepsilon$ relation. $E$ is the elastic modulus and is not constant and, as explained above, depends on the past load history (Fig. 4.17).

The design of the line section is carried out on the basis of the minimum breaking load (MBL). Fig. 4.18 shows a comparison of MBL for different lines Vs diameter, for different materials: polyester, steel and special polyester with high rigidity (HMPE), similar to that of steel itself.

Examples of typical rope construction are given in Fig. 4.19.
Figure 4.17 - Qualitative stress-strain curve for a mooring line.

Figure 4.18 - MBL function of line diameter, for different materials
4.3.5 Wire ropes

Wire ropes are characterized by an high elasticity, so that they are usually used in tensioned mooring applications (Chaplin 1998). In general, wire ropes provide more restoring force in deep water than chains and require lower pretensions. Moreover, they are significantly more lightweight than chains.

Failure modes for wire ropes can be numerous, but the most important ones are:

- **excessive abrasion** between them and a hard seabed: it usually results in more frequent maintenance operations.
- **corrosion** due to lack of lubrication or mechanical damage to the wire ropes.
- **cathode corrosion**: it can be avoided by adopting passive or active measures against corrosion, covering the wires with an outer polymeric jacket.
- **extreme bending**: wire ropes have to have sufficient bending flexibility to not compromise the wire resistance properties, which strongly depend on the rope construction modes. In other
terms, wire section shape is very important to ensure an adequate resistance to the bending and torsion.

The most common used wire ropes are:

- **Spiral Strand** (Fig. 4.20.a) is the simplest of rope constructions. It consists of concentric helical layers of wires. The outer layers of a spiral strand, which constitute the bulk of the cross section, generally have wires of the same diameter, disposed in opposite helical senses and with the same or similar helix angle. The outer surface is cylindrical, so that it facilitates the cover by polymeric jacket to provide long-term protection. Moreover, spiral strands offer high strength and stiffness for a given diameter and wire grade.

- **Six Strand** (Fig. 4.20.b). This is a wire rope type widely used for general engineering purposes, especially for offshore installation, as a component of mooring systems. Six or eight strand ropes can be twisted around a core to form the strands (fibre or wire rope cores are commonly used). For any given ultimate breaking load, this six strand wire rope tends to be the cheapest of all. Despite this fact, since the outer layer are not cylindrical, it is not possible to cover it with a polymeric jacket, so that these ropes are not generally selected for very long term exposure to seawater. This rope has also good resistance to torsion loads.

- **Multi Strand** ropes (Fig. 4.20.c) have two or more layers of strand, that are sometimes compacted to improve the outer profile of the rope and the strand to strand contact stresses. These ropes are commonly used offshore for applications requiring bending flexibility and high tensional and torsion resistance. Such ropes have smaller outer wires than other ropes of comparable strength, so that they tend to have lower corrosion resistance. Moreover, since the contact area between the strands in different layers is much greater than other ropes, fatigue damages tend to develop internally without any externally visible sign, leading to unexpected strength loss and consequently to the mooring failure. Multi Strand ropes are more expensive than conventional six strand ropes of similar strength.

*Figure 4.20 – Typical wire ropes (Chaplin 1998)*
4.3.6 Cost of the line

Figure 4.22 is the product of the SUPERGEN project. Companies were asked to provide price information for chain, wire and fibre ropes. In Figure 4.23 the price per metre length is plotted against the minimum breaking load. From the figure it can be seen cost differences between chain, wire ropes and synthetic ropes are negligible: the choice for a mooring line material would be more likely to be based on physical attributes and technical issues rather than cost. Assuming that the mooring system is safe, costs are to be further related to instalment, maintenance, dismissal.

Fibre ropes require high safety factors since long term experience is not yet available, with the result of higher installation costs.

The polymeric jacket protecting wire ropes should provide ideal long term mechanical properties and higher maintenance periods. Chains have the advantage of ideal bending properties and good seabed abrasion qualities, with predictable maintenance intervals and inherent costs (Harris et al, 2004).
Figure 4.22 – Cost of different types of cable (Refer to Marlow Ropes, Sanmar Ltd. and ScanRope AS for details).

4.4 Anchor positioning

The location and the use of a specific mooring configuration or mooring line material often requires a specific anchor type (Musial et al, 2004):

- **Gravity anchor**. Horizontal holding capacity is generated by one or more dead weights providing friction force between seabed and anchor. The raw material is inexpensive but massive amounts are needed to achieve the desired capacity in case of WECs.

- **Drag-Embedment Anchor**. Horizontal holding capacity is ensured in the main instalment direction by the embedment of the anchor in the seabed. Such anchors are suitable for applications where anchor movements over time may not be critical. The weight of the chain attached to the shank causes line tension to drive the fluke deeper. It is one of the lowest cost anchor types and may be suited for catenary moored systems where placement precision is of the order of a few meters and horizontal mooring forces do not exist.

- **Driven Pile/Suction Anchor**. Horizontal and vertical holding capacity is generated by forcing a pile mechanically or from a pressure difference into the ground, providing friction reaction along the embedded length of the pile. Driven pile are the most commonly used anchors for offshore oil production units, since many years of experience has proven that piles are very reliable and can achieve high load capacity. Driven piles are installed vibrating the pile into the
seabed. Suction anchors, shown in Figure 4.23.b, are a commonly used alternative to the driven-pile embedment anchor. The mooring line is directly attached to the upper part of the pipe. Suction anchor is suited for catenary and taut mooring lines.

- **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. These anchors are designed to carry high vertical loads and can be more suitable for anchoring F-WECs which have a dynamic response to environmental loads that characterize high vertical excursion.

- **Drilled and grouted anchor.** Horizontal and vertical holding capacity is generated by grouting a pile in a rock with a pre-drilled hole. The pile is similar in size and shape to a driven pile. Drilled and grouted piles are more reliable and can achieve higher vertical loads than driven piles, but are more expensive because they require heavy installation equipment.

- **Driven Anchor plate.** The principle of this system is quite similar to that of the suction anchor. One of the key advantages is that when tension loads are applied to the plate, it rotates in the soil, allowing to involve a much larger wedge of soil with respect to suction anchor. Driven plates can absorb very high vertical loads and they are particularly suited for taut mooring lines.

![Figure 4.23](image)

*Figure 4.23* a) Drag embedment anchor; b) suction anchor; c) driven pile; d) driven plate anchor all from Musial et al, 2004; e) drilled pile anchors (from united states patent, June 1979)
4.5 Verification phase

This phase aims at evaluating the position and the stress on the mooring lines. Main line loads are related to the movements of the fairlead of each line that are strongly dependent from the movements of the floating body.

4.5.1 Evaluation of floating body movements

The evaluation of the body displacements $\xi$ can be studied by the classical Equation of motion. For instance, in the frequency domain, the equation is:

$$[-\omega^2 (M + A) + i \omega (B + B^E) + C + K] \cdot \xi = f$$

where:

- $M$ is the mass matrix;
- $A$ is the added mass matrix;
- $B$ is the dumping matrix;
- $C$ is the hydrostatic matrix;
- $K$ is the stiffness matrix of mooring system. This matrix can be provided by catenary equations.
- $f$ is the vector of acting forces on the floating body;
- $B^E$ is the external dumping matrix, which is affected by external causes like drag, dumping and viscous effects on mooring lines.

While $M$, $C$ and $B$ matrixes can be easily found, numerical models based on potential theories have to be employed to provide the matrixes $A$, $B^E$ and vector $f$.

Finally, specific numerical codes provide the solution to Eq. [9]. In particular, the floating body movements are expressed in terms of Response Amplitude Operators (RAOs):

$$RAO_i = \frac{\xi_i}{a}$$

where $a$ is the amplitude of incident waves.

From $RAOs$, the maximum excursion of the body and the effectiveness of the mooring system in terms of station keeping can be accomplished. Should the requirements not be fulfilled, a different mooring system is required.
4.5.2 Verification of line and anchor

The equation of motion of a cable is given by:

\[
\rho \frac{\partial \mathbf{v}(t,s)}{\partial t} = \frac{\partial}{\partial s} \left( T(t,s) \cdot \mathbf{t}(t,s) \right) + \mathbf{f}(1 + \varepsilon) \tag{11}
\]

where \( t \) is the time variable, \( s \) is the curvilinear abscissa, \( \mathbf{v} \) is the velocity vector, \( \mathbf{t} \) is the tangential vector, \( L \) is the length of the unstretched cable, \( \rho \) is mass per unit length of unstretched cable, \( T \) is tension, \( \varepsilon \) is strain and \( \mathbf{f} \) is the sum of external forces (per unit length of unstretched cable) acting on cable. By introducing the position vector \( \mathbf{r} \), we get

\[
\mathbf{t} = \frac{1}{1 + \varepsilon} \frac{\partial \mathbf{r}}{\partial s} \tag{12}
\]

so that

\[
\rho \frac{\partial^2 \mathbf{r}}{\partial t^2} = \frac{\partial}{\partial s} \left( \frac{1}{1 + \varepsilon} \frac{\partial \mathbf{r}}{\partial s} \right) + \mathbf{f}(1 + \varepsilon) \tag{13}
\]

and applying Hooke’s law, Eq. [13] leads to:

\[
\rho \frac{\partial^2 \mathbf{r}}{\partial t^2} = \frac{\partial}{\partial s} \left( \frac{E A_0 \varepsilon}{1 + \varepsilon} \frac{\partial \mathbf{r}}{\partial s} \right) + \mathbf{f}(1 + \varepsilon) \tag{14}
\]

where \( E \) is Young’s modulus and \( A_0 \) is the cross-sectional area of the unstretched cable.

Dynamic stress on all parts of the system can be computed after the F-WEC movements are determined.

In general, a full dynamic analysis has to be performed and the equation of motion of the body Eq. [9] can be coupled to the Eq. of the line dynamics (Eq. [14]).

In order to solve Eq.[14] the line may be divided in a finite number of elements (Fig.4.24.a). For each element, constrains and DOFs are considered (Kreuzer et al., 2003). Element and node tensions, relative motions, node positions and velocities and cable energy can be evaluated by the implementation of the equation of motion for each element (Figure 4.24.b).

Snatching phenomena for mooring cable have to be avoided. Cable “snatching” can occur when a cable is excited dynamically. Here, as the attachment point undergoes motion down and/or horizontally towards the anchor, the slackening cable falling through the viscous fluid reaches a terminal velocity and zero tension and a “slack” condition results (Fitzgerald, 2009). As the attachment point then moves back up and/or horizontally away from the anchor, the falling cable mass may stop and reverse its velocity, resulting in rapid accelerations of the cable mass and corresponding impulsive tensions in the cable (Fig. 4.25). The impulse loads can be very high and
their magnitude are partly dependent on longitudinal elasticity of the cable, a property which can slow down the impulsive accelerations (Fitzgerald, 2009), and partly on the cable kinetic energy (Martinelli et al., 2009), so that infinitely large Young modulus is still associated to a finite load.

Finally, different external load conditions may be considered, including possible loss of one or more cables, in order to assess also the reliability of the mooring system.

Fig. 4.24 Subdivision of mooring line into a finite number of elements (Kreuzer et al., 2003).

---

**Extreme Dynamic Loading**

Tension due to a 6m radius orbit of the attachment at $T = 7$ sec

Fig. 4.25 Dynamic tensions and “snatching” of simple chain catenary cable with attachment point orbiting at a radius of 6 m at a period of 7 seconds in 50m water depth and for 3 scopes. The scope is defined as the ratio of cable length to the water depth, $d$ (Fitzgerald, 2009).
4.5.3 Numerical models

The assessment of the moored device behavior, in terms of mooring loads, mooring stiffness, station keeping, is usually performed through experimental tests and/or numerical modeling. In particular, experimental data are very useful to calibrate numerical models, in order to provide a better description of the acting loads, cable stresses and line movements.

Numerical codes can be divided in two types, each focusing on one of the steps of the complete analysis:

- *Model based on the irrotational wave theory* to determine added masses, damping and wave forces on F-WECs, i.e. the loads acting on floating bodies;
- *MSD models*, solving the dynamic equations for a possibly large number of degrees of freedom. They evaluate the joint dynamic behavior of the F-WECs and the mooring systems, i.e. all the lines, the floaters and the clump weights.

In this section, an overview of the currently available numerical codes is provided.

**WAMIT** is a software that belongs to the first type of numerical codes. It implements the linear and second-order potential theory to analyze floating or submerged bodies under ocean waves. The BIEM method (Boundary Integral Equation Method) is used to solve for the velocity potential and fluid pressures on the submerged surfaces of the bodies and simultaneously accounts for the diffraction and radiation effects. Through such analysis, hydrodynamic parameters like added-mass, damping coefficients, exciting forces, fluid pressure, fluid velocity and RAOs can be easily established.

Another (free) software that is included into first type is **SHIPSIM** (available from [www.shipsim.com](http://www.shipsim.com)).

**ORCAFLEX** is included into second type of software. The full tridimensional modeling of floaters and mooring systems can be performed using a finite element model with 6 DOFs. First and second order wave theories are implemented to define acting wave loads on floaters. It has a very broad range of applications and carries out very effective analysis, firstly for mooring system (jetty mooring systems, turret moored systems, single point moorings, oceanographic and aquaculture mooring systems), for buoy systems (catenary anchor leg mooring buoys, SPAR buoys, Metocean buoys) and above all for F-WECs (wave power systems, offshore wind farm installation, wind turbine modelling and power cable take-off).

**MSC** software, especially Ariane-3D, provides a complete time and frequency domain analysis for mooring systems, including a nonlinear time domain dynamic analysis of individual lines. This
software is also suitable for shallow water mooring problems and for non-linear and multi-elasticity component of mooring systems.

Finally, Ansys AQWA is a complete software package that includes both a first and a second type numerical code. By implementing the first type code an engineering analysis of wave effects, winds and currents on floating (buoys, ships, platforms, and still F-WECs) or fixed structure can be performed. By implementing the second type code (Cable Dynamics) an analysis capabilities for global performance of moorings and connecting systems subject to random sea loads, by static or dynamic simulations, in the frequency and time domain can be carried out.

Figure 4.26 shows an AQWA application to the DEXA wave energy converter.

![Figure 4.26 Example of application of AQWA to the DEXA wave energy converter.](image)

Conclusions

Every mooring system is strongly site and device specific. Design requires knowledge on a vast variety of different configurations. This report presented the most relevant mooring types for the point of view of the floating wave energy converters. Unfortunately, the practical experience relative to mooring of WECs is limited (and not published), so that knowledge in this field is still limited. Reference was made to mooring systems of ships and floating oil and gas platforms, that have slightly different characteristics and requirements. For instance, requirements of F-WECs mooring systems are not only to maintain the device station keeping, but also to be sufficiently compliant to reduce the WEC movements and reduce tension loads on the umbilical. A complete list of characteristics is given above.
The design process has been described, as a cyclic procedure articulated in two phases: design and verification. The procedure needs to be repeated since it must integrate to the design of the hydrodynamics, the PTO and electrical control, and the wave by wave prediction.

In the design phase a selection was provided of the most suited mooring system among a broad variety of types, which can be basically classified on the basis of geometrical and functional aspects. Mooring materials (chains, synthetic ropes, wire ropes), 2DV (catenary, taut line) and 2DH line configurations (symmetric or asymmetric disposition) have to be chosen to define the global mooring system stiffness. Finally, basing on the acting forces on attachment point, the anchor type is designed.

The second phase includes the static and dynamic analysis of the line movements and stresses, in order to describe mooring behavior and, at the same time, identify the critical points of the mooring system and possible failure modes that have to be avoided. Such analysis can be performed by implementing governing equations into numerical codes. At present, most of these codes are developed into commercial software, briefly recalled.

References

API (American Petroleum Institute), 1987. Recommended Practice for the Analysis of Spread Mooring Systems for Floating Drilling Units, RP 2P.
DNV, 2005. Guidelines on design and operation of wave energy converters, Commissioned by the Carbon Trust and carried out by DNV.


