Best practice report - mooring of floating marine renewable energy devices

Deliverable 3.5.3 from the MERiFIC Project

A report prepared as part of the MERiFIC Project "Marine Energy in Far Peripheral and Island Communities"

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Executive Summary

This report is a deliverable of MERiFIC Work Package 3: *'Dynamic Behaviour of Marine Energy Devices'* involving the collaboration of IFREMER (Institut français de recherche pour l'exploitation de la mer) in France and the University of Exeter in the United Kingdom.

It is anticipated that the International Electrotechnical Commission's guidelines *Marine energy - Wave, tidal and other water current converters - Part 10: The assessment of mooring system for marine energy converters (MECs)* will be published by the end of 2013. Although there are several guidance documents in the literature regarding the mooring of marine renewable energy (MRE) devices, the IEC document is one of the first to be produced on this subject, with guidance also available in documents produced by Det Norske Veritas.

This document is intended to provide a concise introduction to mooring systems for MRE devices with reference given to guidelines and standards which may be applicable to the design of moorings for marine renewable energy (MRE) devices. The document begins by setting the scene to give background on the fundamental differences between conventional offshore equipment and MRE devices. In Section 2 design considerations are introduced, including cost, geometry and the importance of conducting risk analysis. Section 3 then gives an overview of moored system numerical modelling. Key findings of the report are then summarised in Section 4.

Contents

Introduction

The MERiFIC Project

MERiFIC is an EU project linking Cornwall and Finistère through the ERDF INTERREG IVa France (Manche) England programme. The project seeks to advance the adoption of marine energy in Cornwall and Finistère, with particular focus on the island communities of the Parc naturel marin d'Iroise and the Isles of Scilly. Project partners include Cornwall Council, University of Exeter, University of Plymouth and Cornwall Marine Network from the UK, and Conseil général du Finistère, Pôle Mer Bretagne, Technôpole Brest Iroise, IFREMER and Bretagne Développement Innovation from France.

MERiFIC was launched on 13th September at the National Maritime Museum Cornwall and runs until June 2014. During this time, the partners aim to

- Develop and share a common understanding of existing marine energy resource assessment techniques and terminology;
- Identify significant marine energy resource 'hot spots' across the common area, focussing on the island communities of the Isles of Scilly and Parc Naturel Marin d'Iroise;
- Define infrastructure issues and requirements for the deployment of marine energy technologies between island and mainland communities;
- Identify, share and implement best practice policies to encourage and support the deployment of marine renewables;
- Identify best practice case studies and opportunities for businesses across the two regions to participate in supply chains for the marine energy sector;
- Share best practices and trial new methods of stakeholder engagement, in order to secure wider understanding and acceptance of the marine renewables agenda;
- Develop and deliver a range of case studies, tool kits and resources that will assist other regions.

To facilitate this, the project is broken down into a series of work packages:

WP1: Project Preparation
WP2: Project Management
WP3: Technology Support
WP4: Policy Issues
WP5: Sustainable Economic Development
WP6: Stakeholder Engagement
WP7: Communication and Dissemination

Disclaimer:

It is the intention of this document to provide introductory guidance for mooring systems for marine renewable energy devices. Readers are actively encouraged to also seek guidance from certification agencies before embarking on the specification of mooring components and the design of mooring systems. The authors of this document cannot be held liable for any damage, loss or injury resulting from use of these guidelines.

Acknowledgement:

The authors would like to thank Det Norske Veritas for reviewing the document.

Related documentation:

As a result of the MERiFIC WP3.5 study *Dynamic behaviours of marine energy devices* the following documents have either been produced or are in preparation:

Conference and journal publications	MERiFIC deliverables
Weller SD, Davies P, Thies PR, Harnois V, Johanning L. (2012) Durability of synthetic mooring lines for ocean energy devices, Proceedings of the 4th International Conference on Ocean Energy, Dublin, Ireland	D3.4.2: Cross border laboratory and field test procedures
Thies PR, Johanning L, Gordelier T, Vickers A, Weller S. (2013) Physical component testing to simulate dynamic marine load conditions, Nantes, France, 9th - 14th Jun 2013, Proc. of 32nd ASME Int. Conference on Ocean, Offshore and Arctic Engineering (OMAE), Nantes, France.	D3.5.1: Testing of synthetic fibre ropes
Weller S.D., Davies P. and Johanning L. (2013) The Influence of Load History on Synthetic Rope Response. Proceedings of the 10th European Wave and Tidal Energy Conference, Aalborg, Denmark	D3.5.2: Guidance on the use of synthetic ropes for marine energy devices
Weller S.D., Davies, P., Vickers, A.W. and Johanning, L. Synthetic Rope Responses in the Context of Load History: Operational Performance. *In-review*	D3.5.3: Best practice report - mooring of floating marine renewable energy devices
Weller S.D., Davies, P., Vickers, A.W. and Johanning, L. Synthetic Rope Responses in the Context of Load History: The Influence of Aging. *In preparation*	
Harnois, V., Weller, S., Le Boulluec, M., Davies, P., Le Roux, D., Soule, V. and Johanning, L. Experimental and Numerical Investigation of a Small-scale Mooring Test Facility model. *In preparation*	

1 Terms

ABS: American Bureau of Shipping

ALS: Accident limit state

API: American Petroleum Institute

BEM: Boundary element method

BV: Bureau Veritas

CFD: Computational fluid dynamics

DNV: Det Norske Veritas

FEM: Finite element method

FLS: Fatigue limit state

GBS: Gravity-based structure

HMPE: High-modulus polyethylene

ISO: International Standards Organisation

MRE: Marine renewable energy

ROV: Remotely operated vehicle

SPM: Single point mooring

SWMTF: South West Mooring Test Facility

TLP: Tension leg platform

ULS: Ultimate limit state

WEC: Wave energy converter

2 Background

The purpose of an offshore mooring system is primarily to provide sufficient restraint to keep surface or sub-surface equipment on position and minimise the combined effects of wind, current and wave loads on the floating structure. This has particular importance for safety critical equipment (e.g. manned equipment such as oil and gas platforms, floating production, storage and offloading vessels and auxiliary equipment) where the consequences of failure could result in loss of life, environmental disaster or interruption of operations. In terms of size and mass there are some similarities with the mooring systems of MRE devices which have large support structures (e.g. floating wind turbines and proposed multi-purpose platforms, Figure 1). Unwanted and possibly damaging motions can be minimised by designing the moored system (comprising the floating structure and mooring system) to have natural response periods which do not correspond to the excitation frequencies of environmental loading, such as first-order or second-order wave excitation or other excitation forces (Figure 2).

Figure 1: MRE devices with supporting structures (*from left*) artist's impression of *WinFlo* concept (source: WinFlo), prototype of the *Poseidon Floating Power Plant* (source: Knud E Hansen A/S) and artist's impression of the *W2Power* concept (source: Pelagic Power)

In general MRE devices which are small compared to the incident wave length (i.e. wave energy converters or WECs) will dynamically respond to first-order and second-order wave loading as well as the combined effects of wind and currents. There is usually strong coupling between the device and mooring system responses [1,2] and hence complex motions can occur [3] which may be large if the system response is resonant. One particular class of devices; WECs are designed to either i) generate electricity or ii) be used to desalinate water. These devices are typically designed for optimal performance at first-order excitation periods (Figure 2) and therefore responses close to resonant are possible in one or more modes of motion. Clearly the possibility of resonant motions occurring will have implications for the load cases used in the design of MRE mooring system and the specification of mooring components.

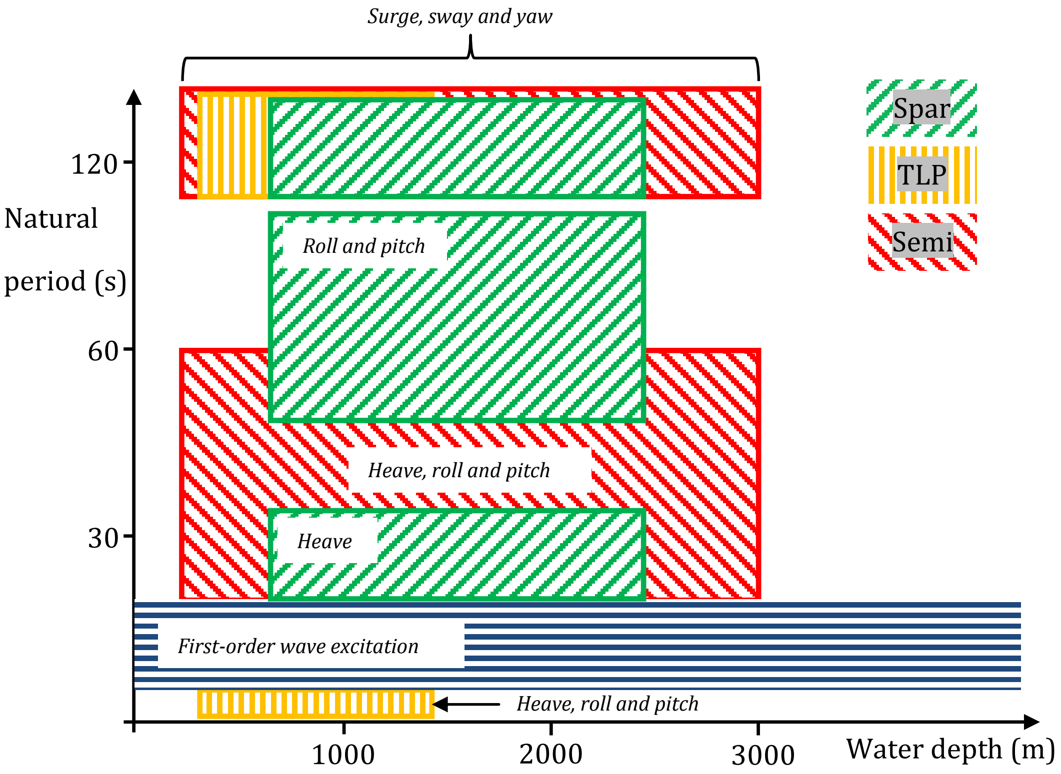

Figure 2: Indicative natural periods of offshore structures (natural periods and operational water depths from [4-6]. Spar platform water depths taken from Technip online information[1]). First-order wave excitation periods which may be relevant to MRE devices are also indicated

In addition to providing station-keeping (to avoid large displacements which could lead to collision with adjacent devices), a WEC mooring system must also permit motions in one or more degrees of freedom for wave energy extraction. For certain WEC systems the mooring system is an integral part of the power take-off system of the device (i.e. Carnegie Wave Energy's *CETO* device[2]), providing a link between a rigid foundation (and power take-off system) and floating body. The mooring system may not be the only form of device restraint. In large (and possibly damaging) sea states, the power take-off of the device may be capable of providing active motion control to restrict device motions. Passive control through particular geometrical features of the floating body may also be used [7].

Although similar mooring geometries have been proposed for MRE devices, there are fundamental differences between this new application and conventional offshore equipment (as listed in Table 1). It is therefore not a straightforward matter to apply existing offshore guidelines or practices to this emerging industry. Certification agencies such as Det Norske Veritas have started to produce more relevant guidelines (see Section 2.4.1) but currently

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[1] http://www.technip.com/en/our-business/offshore/floating-platforms

[2] www.carnegiewave.com/

these are mainly based upon existing offshore guidelines (e.g. [8,9]). A more coherent approach is therefore required to the design and lifecycle analysis [10] of MRE devices and associated mooring components

	Existing offshore equipment	**MRE devices**
Water depth	Deep and ultra-deep *Semi-submersible* (60m to 3km) *Spar platform* (down to 2.4km, e.g. Perdido platform in the Gulf of Mexico)	Near-shore, intermediate and deep *Pelamis* (greater than 50m) *AWS-III Wave Swing* (around 100m) *WinFlo* (greater than 40m)
Design natural period	Less than 4s or greater than 20s (avoiding first-order wave periods)	WECs tuned to first-order wave periods Platforms supporting MRE devices are designed with a similar approach to existing equipment
Mooring system footprint	Large[3] *Catenary system* (e.g. 2.8km radius in 1.2km water depth) *Taut moored system* (e.g. 1.7km radius in 1.2km water depth)	Relatively small due to water depth (e.g. a catenary system may have a 75m radius footprint in 30m water depth)
Number of mooring lines	Many (e.g. 16 may be used for catenary or taut-moored systems)	Typically 3-4, although single point moorings have also been proposed

Table 1: Discernible differences and similarities between existing offshore equipment and MRE devices in the context of mooring systems

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[3] Examples taken from [5].

3 Mooring System Design Considerations

3.1 Cost

According to the *Accelerating Marine Energy* report published by the Carbon Trust and Black & Veatch in July 2011 the station-keeping systems of floating MRE devices typically represent less than 10% of overall capital costs [11], with studies based on individual designs estimating higher costs (i.e. up to 30% for the *Seabreath* device [12]). Utilising a different metric; cost of energy, the *Technology Innovation Needs Assessment (TINA): Marine Energy Summary Report* produced in August 2012 puts the figure at approximately 10% for both wave and tidal (Table 2, [13]). The report also estimates possible reductions in levelised costs for wave and tidal mooring systems of up to 50% and 40% respectably by 2020 and 85% and 60% by 2050. Whilst the assertion that *'Floating wave devices use conventional mooring systems with arguably little direct cost reduction potential. However, savings are nevertheless expected to stem from improved deployability'* is feasible in the short-term, it incorrectly assumes that there will be no further innovation in this area. One such example is a study conducted by Tension Technology International and Promoor (summarised in [11]) which demonstrated significant cost of energy reductions (5% to 10%) through using lightweight nylon mooring ropes instead of steel cables.

	Cost of Energy [13] (Wave, Tidal)
Foundations and moorings	10%, 10%
Installation	10%, 35%
O&M	25%, 15%

Table 2: Approximate costs of foundations and moorings in relation to installation, operations and maintenance costs

Cost savings made through informed component choices may be completely negated if the installation, maintenance and decommissioning of equipment is costly. The 10% estimate listed in Table 2 are likely to be for equipment only and not the inspection, operations and maintenance costs attributable to the foundations and moorings. The risk of bottlenecks occurring can be reduced by adequate planning and reducing the reliance on costly procedures (e.g. dive teams).

3.2 Geometry and Components

There are two main types of mooring system which are applicable to MRE device systems; catenary and taut-moored systems (illustrated schematically in Figure 3). The main mooring and foundation components used in these mooring systems are summarised in Table 3. In addition, several mooring system variants exist; indeed arrays of closely spaced devices are likely to share common mooring attachment points [14].

Component	Function	Design considerations
Foundations: gravity, suction, sand/rock screws, piles	To provide a secure fixing point when an embedment anchor would not be suitable (i.e. due to seabed or loading conditions). Can be used for catenary and taut-moored systems.	Suited to vertically loaded systems. May have limits on horizontal loading. Durability and application of grouting systems Impact of sediment scour Use dependent on site characteristics
Anchors: drag embedment, plate	Provides secure fixing point for mud and silt seabed types. Drag embedment anchors are usually recoverable using a vessel, but are suitable for catenary mooring systems only. Plate anchors provide a more permanent attachment point and are installed using several different methods	Site survey required to determine suitability Drag embedment: Limits on vertical loading, and mooring line angle. Requires ground chain and significant mooring system footprint
Mooring lines: wire rope, chain, synthetic, hybrid	Link between foundation (and anchor) and MRE device. The range of commercially available materials offer a wide range of characteristics (e.g. stiffness, weight, fatigue performance)	Subject to peak and fatigue loading conditions Durability with aging mechanisms and usage Ease of handling and installation, cost and performance considerations
Additional components: shackles, swivels buoys, weights	Provides a means of connection between the device, mooring line and anchor or foundation. Buoys and weights may be used for surface buoy or floater and sinker systems	Durability of components with aging and fatigue loading

Table 3: Summary of relevant mooring and foundation components

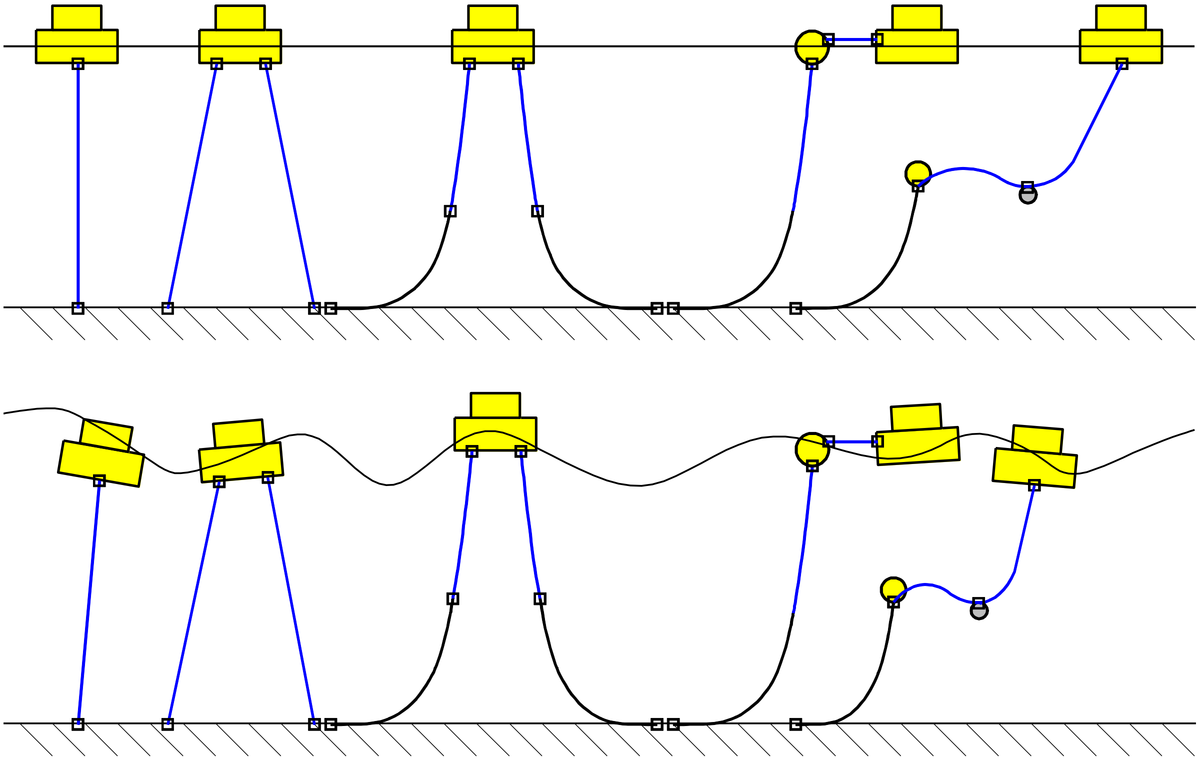

Figure 3: Schematic of possible mooring arrangements for a single MRE device (*from left*) taut-moored systems with single and multiple lines, basic catenary system, catenary system with auxiliary surface buoy and lazy wave system with subsea floater and sinker. Illustrative device displacements due to passing waves are also shown

A catenary mooring system is suitable for applications in which station-keeping is required and device motions are permitted in several degrees of freedom. Horizontal and vertical restoring forces are provided by the single or multiple mooring lines which have a catenary geometry due to the hanging weight of the mooring system. Steel mooring chains or wires can be used for the entire line but for reasons of cost and due to the favourable properties of alternative materials, it is likely that synthetic ropes will be used for the mid or upper sections (i.e. from the fairlead) of MRE mooring systems. Further information regarding the use of synthetic mooring ropes for MRE devices is available in literature (e.g. [15]), including the MERiFIC deliverable, *D3.5.2: Guidance on the use of synthetic ropes for marine energy devices.* In this case 'rider' or ground chains are used for the lower sections of the mooring system to provide sufficient tension in the lines. The lower sections of mooring chain are spread radially out from the device to transfer horizontal and vertical mooring loads at the fairlead to horizontal loads at the anchor. Floater and sinker components can be used to provide a 'lazy-wave' mooring geometry for increased horizontal compliance and hence may reduce mooring loads.

The compliance of a catenary mooring system will allow a connected device to move in several degrees-of-freedom in response to wave, current and wind forces. The allowable magnitude of displacement and mooring forces must be quantified during the design stage. Whilst large device motions in one degree-of-freedom (i.e. heave for a WEC point absorber) may be desirable (i.e. for power absorption), a mooring system which is too compliant may lead to large horizontal device motions and the possibility of collision with adjacent devices. In calm conditions the lower section chains will rest on the seabed and are lifted if the mooring loads from energetic device motions are sufficiently high. For drag embedment anchors, loads applied at shallow angles from the seabed are permitted (typically up to 30° for the Danforth fluke anchor shown in Figure 4). Larger angles, as would be the case if the entire chain is lifted, will cause the anchor to pull out and partial (or total in the case of single line systems) loss of the mooring system. Clearly the interaction of the chain with the seabed will have an impact with marine species located in the vicinity of the mooring system.

Figure 4: (*left*) 1.1 Tonne Danforth fluke anchor prior to deployment with the South West Mooring Test Facility[4], (*right*) vertically loaded Delmar OMNI-Max anchor (source: Delmar Systems Inc.)

The restoring forces provided by a taut-moored system are a result of axial stretching rather than geometric changes of the entire mooring system. This type of mooring requires the utilisation of anchors which can withstand large vertical forces and hence drag embedded type anchors are not suitable. Common types of anchors for taut moorings include large weights, sand screws, rock bolts, piled foundations or specialist anchors (e.g. Figure 4). Particular anchors may also be used for catenary or semi-taut mooring systems if the seabed conditions do not allow for drag embedment anchors to be used. The possibility of large and potentially damaging peak loads occurring should be considered for dynamically responding MRE devices restrained by a taut mooring system comprising non-compliant components (i.e. chains or wires).

Incorporating compliance into a taut-moored system through the use of synthetic ropes is one way to reduce peak loadings, with polyester, aramid and HMPE ropes particularly suited for floating platforms in deep and ultra-deep water depths [17]. The mean tensile loading of taut fibre ropes will lead to time-dependent elongation due to creep. Additional loading due to variations in tide height will result in cyclical variations in load, contributing to rope creep as the tide floods and conversely allowing relaxation as the tide ebbs. Because the displacement of a taut-moored device will be limited by the compliance of the mooring

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[4] Further details of the South West Mooring Test Facility can be found in Johanning, L. et al. (2010) [16].

line and rotational capability of end terminations, the device will become submerged in large waves or at locations with significant tidal ranges[5]. To avoid large wave forces on the sea surface, several WEC designs with taut-moored systems are permanently submerged (e.g. *CETO* and the *New Bristol Cylinder* [19]) and for surface devices, studies have been conducted into the feasibility of using certain geometrical features to limit displacement in large amplitude storm conditions [7].

3.3 Risk Analysis

The consequences of mooring system failure for MRE systems are likely to be less severe (e.g. leakage of internal fluids, beaching or collision of devices/other marine craft) than for large vessels or oil and gas exploration equipment, even if the station-keeping ability of the mooring system has been lost. The consequences of mooring component failure will depend on the device location, proximity to other equipment or water-users and if redundancy has been built into the system[6]. The current lack of specific mooring system guidance for MRE devices, in particular WECs and floating tidal stream devices necessitates the application of existing offshore guidelines to provide a conservative framework for certification. The design attributes that are required to satisfy the criteria outlined in guidelines designed for large offshore equipment are likely to be unnecessarily onerous, particularly for MRE devices which are largely unmanned[7]. Paredes, G. M. et al. highlighted in [20] the possible relevance of guidelines produced for marine fish farms (e.g. NS 9415. E:2009) for MRE device mooring systems. As has been mentioned in Section 2.1, mooring systems currently represent a significant proportion of the capital cost of the device and this is in part due to the use of conventional design approaches. In respect to the revenue generated from the sale of energy, there is a smaller margin for absorption in comparison to a fully operational oil or gas platform.

The counter argument to this is that the largely unproven use of commercially available mooring system components for this new application incurs uncertainties and risks which must be accounted for. To-date examples of catastrophic mooring system failure in the MRE sector are few, for example *Oceanlinx*[8] in May 2010 and the *Wavedragon* prototype in January 2004 [21], although this may in part be due to the lack of MRE devices deployed or the short duration of deployments. Both of the cited failures occurred in storm conditions and whilst it is not clear why *Oceanlinx's* mooring system failed, a broken load cell on a

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[5] A compliant-moored device will be subjected to both low frequency and wave frequency load excitation (predominantly due to wind, waves and currents). In addition taut-moored devices may be subjected to high frequency 'ringing' excitation and a taut mooring lines may be experience cyclic loading from vortex induced vibration or vortex induced motions [18]. The latter mechanism is briefly introduced in the MERiFIC deliverable *D3.5.2: Guidance on the use of synthetic ropes for marine energy devices.*

[6] Higher safety factors are typically specified for systems which do not have redundancy.

[7] For MRE devices this will only be the case during installation, maintenance and recovery operations which would be conducted during favourable weather windows (i.e. during calm conditions); hence the percentage of time that a device will be manned will be extremely small.

[8] http://www.abc.net.au/news/2010-05-17/huge-swell-sinks-wave-energy-generator/829282 (accessed online: 03/10/2013).

single mooring line led to the *Wavedragon* prototype becoming stranded. Clearly catastrophic failure of an MRE device is not only damaging to the device developer, but also the entire nascent MRE sector.

A balance must therefore be struck between the specification of an over-engineered mooring system which would not be commercially viable for large scale deployments and one which circumvents current guidance[9]. Rather than being prescriptive, certification agencies may be open to adaptation of their guidelines as long as it can be demonstrated that the mooring system can satisfy particular criteria (i.e. operational and extreme scenarios throughout the lifetime of the device) through numerical and/or experimental modelling.

3.3.1 Existing Certification Guidelines

It is not the intention of these guidelines to detail current offshore position mooring guidelines. Instead a summary of currently available documentation is provided in this section (Table 4). For the reasons introduced in Section 2 this guidance is not entirely relevant to MRE devices but is likely to inform forthcoming publications such as those produced by the TC114 group of the International Electrotechnical Commission [22]. The certification of a mooring system will involve determining the boundaries of mooring line and component performance when the moored system is subjected to operational, environmental and accidental loading. The Det Norske Veritas offshore standards, for example, three limit states are specified in the DNV-OS-E301 *Position Mooring* guidelines [18]:

- *Ultimate limit state*: Used to ensure that components have adequate strength to withstand loads resulting from extreme environmental conditions
- *Accident limit state*: Used to ensure that the mooring system is capable of withstanding the failure of one mooring line, assuming that the system has built-in redundancy
- *Fatigue limit state*: Used to ensure that individual mooring lines can withstand cyclic loading.

In [18] two consequence classes are used to classify the outcome of mooring system failure; Class 1: *“Where mooring system failure is unlikely to lead to unacceptable consequences such as loss of life, collision with an adjacent platform, uncontrolled outflow of oil or gas, capsize or sinking”* and Class 2: *“Where mooring system failure may well lead to unacceptable consequences of these types.”* To-date Det Norske Veritas is the only agency which has produced a detailed design guideline for a MRE device, in the form of DNV-OS-J103: *Design of Floating Wind Turbine Structures* [8].

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[9] This would only be possible in certain locations. Elsewhere certification by a recognised agency may be a requirement of insurance underwriters, consenting agencies and funding programs.

Guideline	Publication Date
Det Norske Veritas	
Position Mooring: DNV-OS-E301	2010
Offshore Mooring Chain: DNV-OS-E302	2009
Offshore Fibre Ropes: DNV-OS-E303	2013
Offshore Mooring Steel Wire Ropes: DNV-OS-E304	2009
Design and Installation of Fluke Anchors: DNV-RP-E301	2012
Design and Installation of Plate Anchors in Clay: DNV-RP-E302	2002
Geotechnical Design and Installation of Suction Anchors in Clay: DNV-RP-E303	2005
Environmental Conditions and Environmental Loads: DNV-RP-C205	2010
Design of Floating Wind Turbine Structures: DNV-OS-J103	2013
Certification of Tidal and Wave Energy Converters: DNV-OSS-312	2012
Det Norske Veritas and Carbon Trust	
Guidelines on design and operation of wave energy converters	2005
Bureau Veritas	
Classification of Mooring Systems for Permanent Offshore Units. NR 493 DT R02 E	2012
Certification of fibre ropes for deepwater offshore services. 2nd edition. NI 432 DTO R01E	2007
Rules for the Classification of Offshore Loading and Offloading Buoys NR 494 DT R02 E	2006
International Standards Organisation	
Petroleum and natural gas industries -- Specific requirements for offshore structures -- Part 7: Stationkeeping systems for floating offshore structures and mobile offshore units: ISO19901-7:2013	2013
Shipbuilding and marine structures -- Mooring winches: ISO3730:2012	2012
Fibre ropes for offshore stationkeeping: Polyester: ISO18692:2007	2007
Fibre ropes for offshore stationkeeping: High modulus polyethylene (HMPE): ISO/TS14909:2012	2012
Ships and marine technology -- Stud-link anchor chains: ISO1704:2008	2008

Table 4a: Existing offshore guidelines which may be relevant to the mooring of MRE devices

Guideline	Publication Date
American Petroleum Institute	
Recommended Practice for Design, Manufacture, Installation, and Maintenance of Synthetic Fiber Ropes for Offshore Mooring: API RP 2SM *(amended version)*	2007
Mooring Chain. API Spec 2F	1997
American Bureau of Standards	
Guidance Notes on the Application of Fiber Rope for Offshore Mooring	2011
Guidelines for the purchasing and testing of SPM hawsers	2000
Standards Norway	
Marine fish farms - Requirements for site survey, risk analyses, design, dimensioning, production, installation and operation: NS 9415:2009	2009

Table 4b: Existing offshore guidelines which may be relevant to the mooring of MRE devices

Det Norske Veritas has also recently produced the *DNV-OSS-312 Certification of Tidal and Wave Energy Converters* guideline [9], which provides less detail about mooring systems and mainly refers back to existing documents, including *DNV-OS-E301 Position Mooring* guideline, some of the recommended practices listed in Table 4 and certification standards including: *Certification of offshore mooring steel wire ropes*, *Certification of offshore mooring chains* and *Standard for certification of offshore mooring fibre rope*. The DNV-OSS-312 *Certification of Tidal and Wave Energy Converters* guideline includes a list of areas which would typically be analysed and documented for the verification of a mooring system design (Table 5).

- Line and anchor pattern
- Type and weight and dimension of all line segments
- Characteristic line strength
- Anchor type, size, weight and material specification
- Arrangement of fairleads and anchor points/pretensions
- Position and weight of buoyancy elements and weight elements
- Position and weight of buoyancy elements and weight elements
- Windlass, winch and stopper design
- Mooring line tensions in ULS and ALS limit states
- Fatigue calculations of mooring line segments and accessories
- Strength calculations of anchors, windlass components and fairleads
- Corrosion allowance.

Table 5: Design areas which would be typically documented for design certification according to the DNV-OSS-312 *Certification of Tidal and Wave Energy Converters* guidelines [9]

3.3.2 Redundancy

The two examples of MRE device failure introduced in this section illustrate the need to consider i) a range of environmental conditions and ii) redundancy in mooring system design. An increase in the survival requirements of offshore equipment mooring systems was initiated after the occurrence of breakaway events resulting from total loss of offshore platform mooring systems[10]. From the diverse range of MRE devices which have been proposed or trialled, provision for the loss of critical components is not always present, particularly for WECs which are tethered using a single mooring line. Including redundancy into a mooring system (in the form of additional mooring lines) is standard practice for large platforms to give a sufficient allowance for component failure [23]. Redundancy can also be provided by the use of safety lines around critical components such as load cells (e.g. Figure 5). The alternative to incorporating redundancy into a mooring system design is to increase the safety factor of the system, which is permissible according to certification guidelines such as DNV-OS-E301 *Position Mooring* for particular single point mooring applications [18] and the more relevant DNV-JS-J103 *Design of Floating Wind Turbine Structures* guideline [8].

Figure 5: Example safety rope used on one mooring connection point of the SWMTF

3.3.3 Device Separation Distance

For the operation of MRE devices to be commercially viable, MRE devices are unlikely to be deployed as isolated units. Instead, arrays or ‘farms’ comprising multiple devices will be installed which share power transmission, measurement, control and even mooring infrastructure [14]. Similarly to wind turbine arrays, the spatial planning of MRE devices is critical to the performance of all devices, particularly for the wake effects of multiple tidal stream turbines in close proximity. For WECs, hydrodynamic interactions occurring between devices has a significant influence on the level of power extracted [24] and therefore requires the use of planning tools to accurately predict array performance [25]. The

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[10] Examples of catastrophic platform mooring system failure include; the *Argyll Transworld 58* floating production platform (1981), Fulmar floating storage unit (1988), Ocean Lexington (2002) and Deepwater Nautilus semi-submersible (2004). Multiple line failures continue to occur with severe incidents prevented by the inclusion of redundancy measures. A typical failure rate is one per three years of operation [23].

proposed close separation distances of these devices[11] will have implications for the level of mooring system compliance permitted to reduce the risk of device collision and mooring line entanglement.

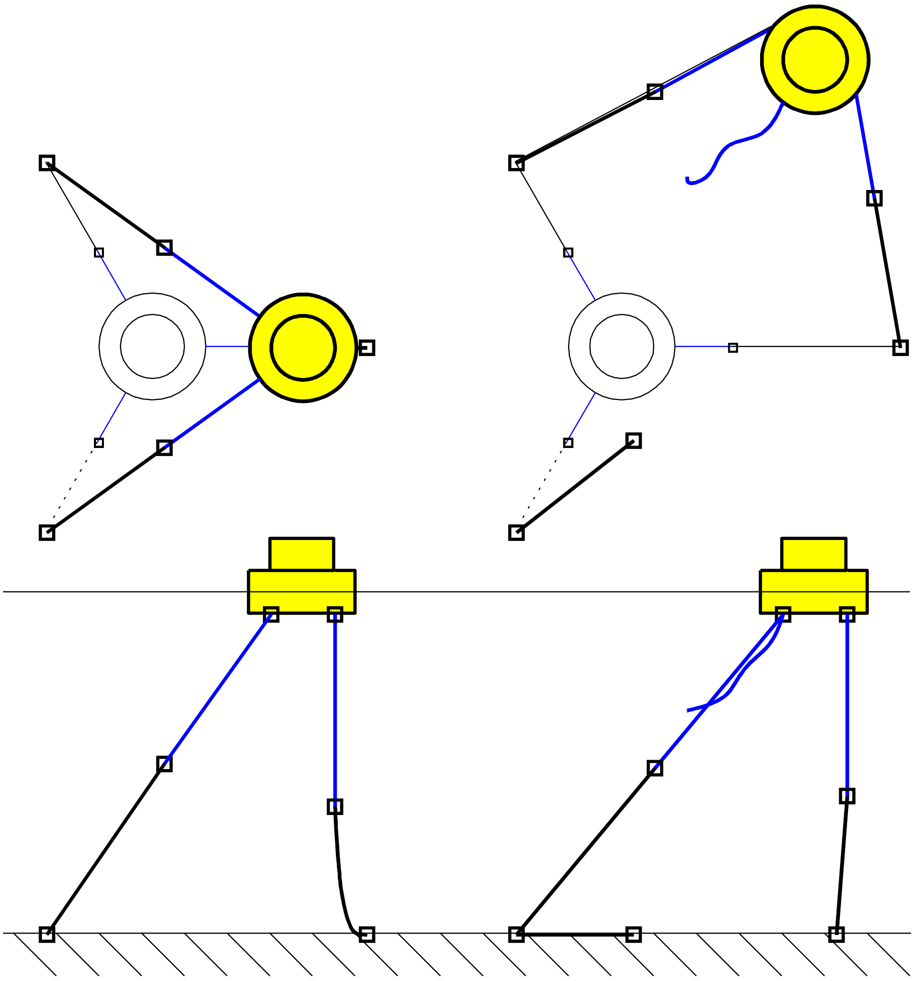

Figure 6: Indicative horizontal displacement limits of a buoy-like MRE device; (*left*) with an intact mooring system and (*right*) after failure of one mooring line. The actual position of the device in both scenarios will depend on the design of the moored device and environmental conditions

The DNV-OS-E301 *Position Mooring* guidelines [18] state that there should be at least 300m between offshore accommodation units and fixed equipment[12]. For ships the distance should be at least twice the vessel length. These requirements are wholly unsuitable for MRE devices which requirement close separation distances in order to share infrastructure or take advantage of hydrodynamic interactions, particularly because the minimum

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[11] Interaction effects have been investigated for a number of a devices including axisymmetric geometries with centre-to-centre separation distances greater than one diameter (i.e. the lower limit of separation distance).

[12] This can be reduced to 150m for units designed to Consequence Class 1 provided that sufficient redudancy is in place to prevent unit collision in the event of mooring line failure. A distance of 50m is permitted for lines designed to Consequence Class 2. Larger separation distances are required for water depths greater than 300m.

distances are based on water depths which are much greater than those which are relevant to MRE devices. Although the response of a device will depend on its design, it would not be difficult to specify a more relevant minimum safe separation distance for MRE devices which are mainly unmanned (see Section 2.4) . Limits for MRE devices could be based on the maximum possible surge or sway displacements of the device during a) with the mooring system intact and b) after failure of a mooring line (illustrated in Figure 6). This approach is suggested in the DNV-OS-J103 *Design of Floating Wind Turbine Structures* guidelines [8], although distances are not explicitly stated.

3.4 In-service Considerations

The analysis of multiple line mooring systems is often carried out with the assumption that the tension in all of the lines is equal when the device is at equilibrium. This potentially may not be the case due to:

- Anchor placement inaccuracies[13]
- Unequal pre-tensioning of mooring lines[14]
- Features on the sea bed (i.e. bathymetric variations across the site)
- Events occurring during operation (such as anchor dislodgement[15]).

The unequal loading of lines may result in particular line tensions which are significantly higher than those estimated during mooring system studies. This could have implications not only for maximum line tensions but also a reduction in the fatigue life of components. Premature component failure and total line loss may cause a sudden increase of loading on remaining lines and large device displacements (illustrated in Section 2.3.3), or in the case of systems without redundancy, total loss of station-keeping ability. It is therefore important that sensitivity studies on anchor and line placement are conducted as part of mooring systems analysis. An unequal mooring layout can be detected from mooring tension measurements (i.e. at the fairlead) in calm conditions. Clearly this relies on the installation of calibrated sensors and the accuracy of measurements[16]. Other methods to determine the equality of line tensions include line payout/pull in tests and the assessment of mooring line angles using dive teams and remotely operated vehicle (ROV) equipment [23].

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[13] During the first deployment of the SWMTF an anchor placement accuracy of +/- 2m was specified but an accuracy of +/- 5m was achieved. Further information regarding in-service practices can be found in the MERiFIC deliverables: *D3.6.2: Best practice report - installation procedures* and *D3.6.3: Best practice report - operation and maintenance requirements*.

[14] For synthetic ropes further comment is given on this topic in the MERiFIC deliverable *D3.5.2: Guidance on the use of synthetic ropes for marine energy devices.*

[15] One of the SWMTF anchors became dislodged during a storm in January 2011 and then re-embeded 7m away from the initial anchor position. The result of this was to alter the buoy position by 3.5m west and 1.5m south and a change in pre-tension of the three mooring lines [26].

[16] Load cells measurements are prone to drift, hence the use of more than one load cell at each fairlead connection point may be prudent.

4 Moored System Modelling

Device motions and mooring system tensions for a given range of environmental conditions can be estimated using quasi-static and dynamic numerical modelling techniques. It is good practice to determine the accuracy of estimated dynamic responses by comparing the results with physical testing, either conducted at reduced scales in the laboratory or from sea trials [27]. An example of the comparison between quasi-static numerical analysis and model tests of a 1:5 scale version of the SWMTF is shown in Figure 7 (further details can be found in [28]). It can be seen that the catenary geometry of the mooring system provides a non-linear relationship between surge displacement and mooring tension. Comparative analysis of experimental measurements and numerical simulations will be reported in a forthcoming publication [29].

Further guidance on resource and physical modelling can be found in the literature, as well as MERiFIC deliverables *D3.1.6 Best practice guidelines for wave and current resource assessments for island communities* and *D3.4.2 Best practice report - Cross border laboratory and field test procedures.* A discussion of possible in-service simulation techniques used to test MRE components can be found in [30,31] and is illustrated in Figure 8. In addition, the physical testing of synthetic ropes is discussed in deliverable *D3.5.1: Testing of synthetic fibre ropes*. For a comprehensive overview of recommended modelling practices the reader is also directed to the EquiMar protocols [27].

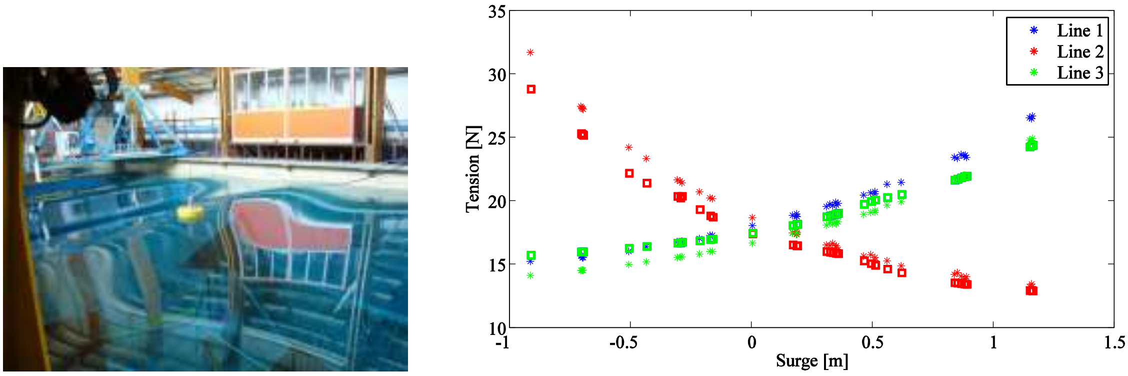

Figure 7: (*left*) 1:5 scale model of the SWMTF tested in the salt water basin at IFREMER (*right*) quasi-static analysis of the scale model mooring system conducted as part of the MERiFIC WP3.5 [28,29]. Measured and simulated values are shown as asterisk and square markers respectively

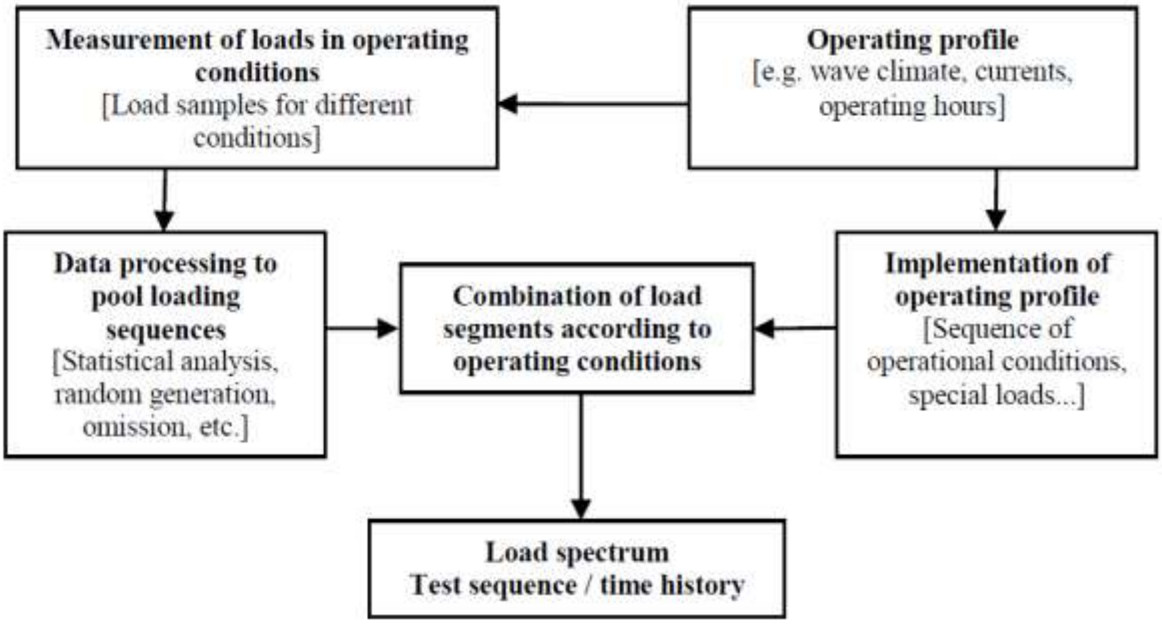

Figure 8: Simplified in-service simulation testing approach involving the generation of standardised load-time histories (taken from [30])

Several commercial programs exist which can be used to conduct static, quasi-static and dynamic analysis of complete mooring systems, including (but not limited to) *Orcaflex* by Orcina[17], *Optimoor* by TTI[18] and *Deeplines* by Principia[19]. Although sophisticated, it is not possible to model all of the distinct features of MRE devices using existing mooring system software, such as power take-off systems. *WaveDyn* by GL-Garrad Hassan[20] is one of the first commercially available simulation tools which has been specifically designed for the dynamic response of WECs. Assuming that the device design has been formalised, the procedure for numerical modelling can be split into several stages (Figure 9). It will be noted that the focus of this chart is on numerical modelling of the moored system with contributions from resource assessment modelling and physical testing. However, this approach is not rigid and an indicative study could be conducted with no prior knowledge of the site characteristics, starting from Step 1 (Figure 9).

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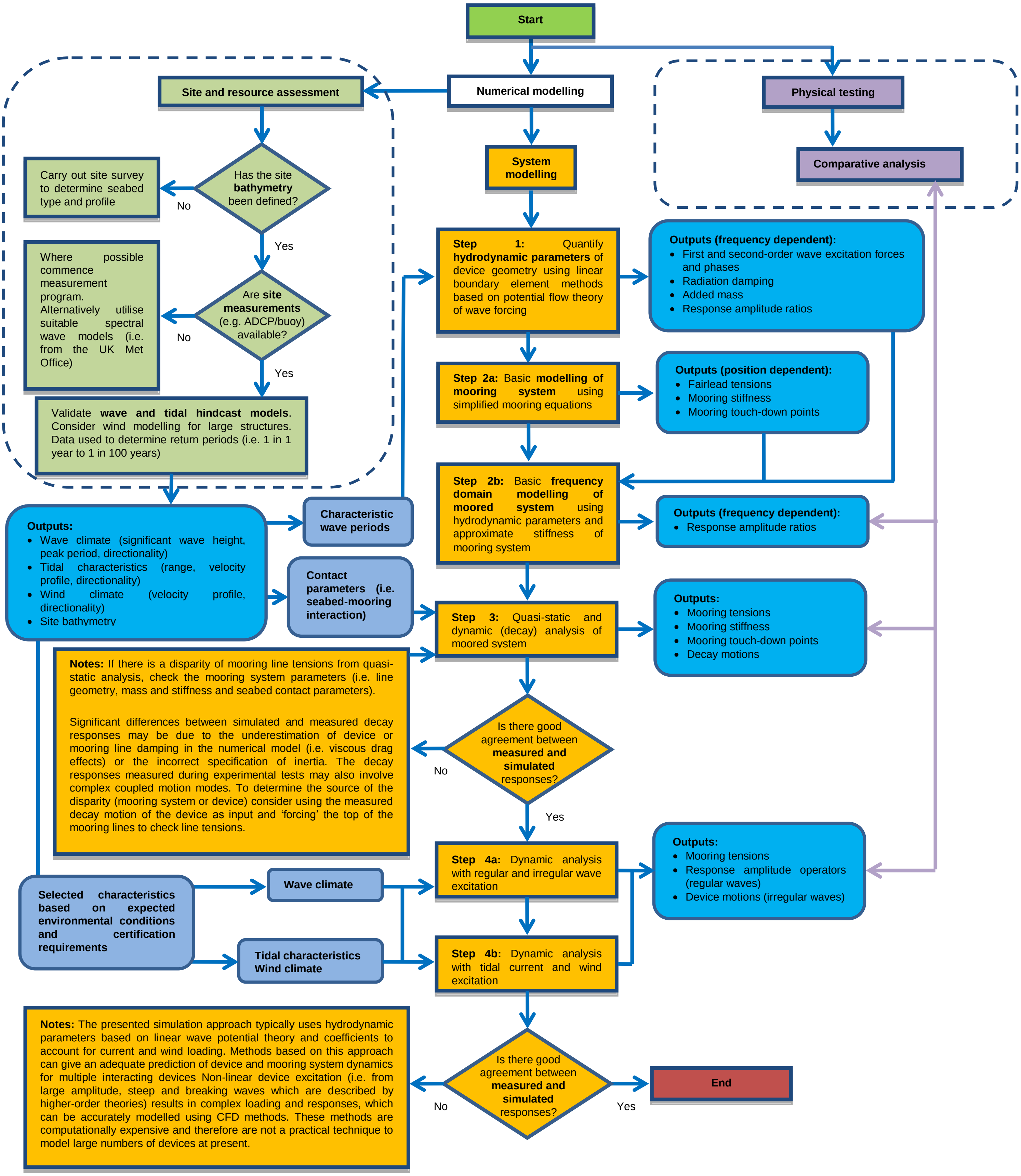
[17] http://www.orcina.com/SoftwareProducts/OrcaFlex/ (accessed online: 05/10/2013).

[18] http://www.tensiontech.com/software/optimoor.html (accessed online: 05/10/2013).

[19] http://www.principia.fr/expertise-fields-software-products-deeplines-126.html (accessed online: 05/10/2013).

[20] http://www.gl-garradhassan.com/en/software/25900.php (accessed online: 05/10/2013).



Notes: If there is a disparity of mooring line tensions from quasi-static analysis, check the mooring system parameters (i.e. line geometry, mass and stiffness and seabed contact parameters).

Significant differences between simulated and measured decay responses may be due to the underestimation of device or mooring line damping in the numerical model (i.e. viscous drag effects) or the incorrect specification of inertia. The decay responses measured during experimental tests may also involve complex coupled motion modes. To determine the source of the disparity (mooring system or device) consider using the measured decay motion of the device as input and 'forcing' the top of the mooring lines to check line tensions.

Notes: The presented simulation approach typically uses hydrodynamic parameters based on linear wave potential theory and coefficients to account for current and wind loading. Methods based on this approach can give an adequate prediction of device and mooring system dynamics for multiple interacting devices Non-linear device excitation (i.e. from large amplitude, steep and breaking waves which are described by higher-order theories) results in complex loading and responses, which can be accurately modelled using CFD methods. These methods are computationally expensive and therefore are not a practical technique to model large numbers of devices at present.

Figure 9: A suggested procedure for numerical modelling of moored MRE systems

Suggested modelling procedure

Step 1**:** Boundary element methods are used to solve the velocity potential around the device geometry using potential flow theory for a range of regular wave frequencies[21]**.** Commercially available codes such as *WAMIT* by WAMIT Inc[22]. and *AQUAPLUS* by Ecole Centrale de Nantes[23] are widely used for this purpose. A fundamental assumption of these linear methods is that device displacements are small; therefore the variation of calculated hydrodynamic parameters with varying device position (i.e. draft) is not accounted for.

Step 2a**:** Simplified mooring equations (e.g. catenary formulae) or finite element methods can be utilised to produce an initial mooring system design based on the water depth of the site and device features (e.g. mass, geometry and draft). The variation of touchdown points and mooring tensions with device position can be investigated, with the latter used to infer the stiffness of the mooring system. Checks on device stability can be carried out using well-established equations in the literature (e.g. [6,32]).

Step 2b**:** An approximation to the response of the moored system, quantified as non-dimensional response amplitude ratios, can be made by using the outputs of Step 1 (frequency dependent wave excitation forces and phases, radiation damping, added mass) using a linearised approach [33]. The mooring stiffness (from Step 2a) for a unit displacement can also be included into the approximation[24]. The power take-off system can be included as a single damping term (and if applicable, include a stiffness term). This approach, although highly simplified, is useful for checking that the expected regular wave frequency response of a device. Efforts have been made to estimate the time-varying response of a device in an irregular wave-field by assuming linear superposition of response to each regular wave component [34]; however this approach may only be valid for optimal device responses.

Step 3**:** A more detailed approach to numerical modelling is possible through time domain simulations which can be conducted using commercially available mooring system software. As previously mentioned, the particularities of MRE devices may necessitate the use of specific MRE modelling software, or alternatively approaches which can be found in the literature. Of these, two commonly used approaches are favoured. The first, which utilises hydrodynamic parameters from BEM analysis (Step 1) in impulse response functions [35], is the basis for several commercially available tools[25]. The second is based on Froude Krylov approximations to wave forcing, including use of the Morison equation to account for drag

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[21] The selected wave frequencies are based on the most likely first and second-order wave frequencies at the proposed device location

[22] http://www.wamit.com/ (accessed online: 05/10/2013).

[23] http://www.ec-nantes.fr/version-francaise/recherche/laboratoires/lmf/lmf-ehgo-codes-de-calcul-3862.kjsp?RH=Rech5 (accessed online: 05/10/2013).

[24] The use of a single stiffness value will not account for the non-linear stiffness-displacement relationship of a catenary system.

[25] The addition of Morison drag and inertia coefficients and/or the addition of stiffness or damping through matrices) is possible with commercial mooring software.

and inertia [6]. Hybrid methods combining the previous two approaches have also been proposed which cater for the time-variation of forces on the device [36]. For a MRE device inclusion of the power take-off system is important as the additional time-varying damping and stiffness forces will undoubtedly influence the response of the system. At this stage wave forcing is not included in the simulations because it is essential that the simulated quasi-static and dynamic (decay) behaviour of the moored system corresponds well with what has been measured in the laboratory[26].

Step 4a**:** Once the dynamic decay response of the moored system has been validated, simulations can be conducted with regular wave excitation using wave periods and amplitudes which are representative of the proposed deployment site. If the simulated response amplitude operators and mooring tensions are comparable with experimental values then the model can be subjected to irregular waves (either as representative spectra or time-series measured at the location). The focus of the investigation will depend on the application, but it is likely that for buoy-like MRE devices, the response of the device to first-order wave forcing in the principal modes of motion will be of interest, as well as the influence of second-order wave forcing on the mean drift and slow drift motions of the device.

In general a lack of correspondence between simulated and measured behaviour of the moored device (particularly for resonant responses) may be due to the limitations of the numerical modelling approach. More detailed predictions of complex behaviour and hydrodynamic mechanisms (i.e. wave effects such as breaking and mooring dynamics) may be possible using CFD tools [37,38]. At present these methods require significant computation times and processing power.

Step 4b**:** Further detail can then be incorporated into the model through the application of tidal current and wind excitation. The selection of environmental conditions will depend on the device design stage. A developer may simply be interested in the response of a device concept to environmental loading in order to refine the design of a power take-off unit or control system. A more advanced design at the proof of concept or prototype stage may require certification and this will involve numerical modelling based on limit state analysis (Section 2.3.1).

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[26] There is a risk that direct simulation of a MRE device subjected to environmental loading will result in spurious results if the model has not been previously validated. It is therefore highly recommended that simplified conditions (i.e. quasi-static and decay responses) are simulated initially, ideally validated using experimental data.

5 Summary

Significant cost reductions are required for marine renewable energy to become a competitive electricity generation method that is attractive to investors and utility companies. Aside from the deployment of arrays comprising multiple devices, one key area that has been identified as having potential for cost reductions is the mooring system. A clear challenge therefore exists to design MRE mooring systems which can satisfy their primary role of station-keeping whilst being affordable, durable and readily deployable.

The current approach for mooring system design is to use existing offshore standards geared towards large equipment operating in deep water environments. The motion of this equipment is characteristically small relative to its size. This clearly contrasts the highly dynamic motions that smaller more responsive MRE equipment will experience, particularly for devices designed to operate at or close to resonance in one or more modes of motion. The mooring systems of these devices will experience highly dynamic tensions and potentially be subjected to short duration peak loadings, cyclic fatigue loading or other degradation mechanisms (summarised in the MERiFIC deliverable *D3.5.2: Guidance on the use of synthetic ropes for marine energy devices*). Whilst it is unsurprising that device developers have so far opted for mooring components which have a proven track record in the offshore industry, the performance and reliability of components in this new application is not fully understood. Protocols and certification guidelines which are specifically tailored for MRE mooring components and systems are required which are not just based on existing certification approaches. It will be interesting to see how these guidelines evolve as more devices are deployed and hours of sea experience are accrued, particularly in areas such as redundancy provision and device separation distance.

Whilst both numerical analysis and physical testing are widely used in the offshore industry, the differences in application with MRE devices necessitate that they must be carried out in the context of relevant mooring load regimes. For example, fully coupled dynamic analysis has to be carried out which incorporates all of the particularities of MRE devices (e.g. mooring system, floating geometry and power take-off system) in order for accurate predictions to be made. Similarly physical testing programs are required which are suitable for MRE mooring system components. The combination of physical testing and detailed numerical analysis will enable performance and reliability uncertainties to be reduced for critical components. This will subsequently enable more accurate lifecycle analyses to be conducted allowing efficient maintenance and replacement schedules to be created.

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