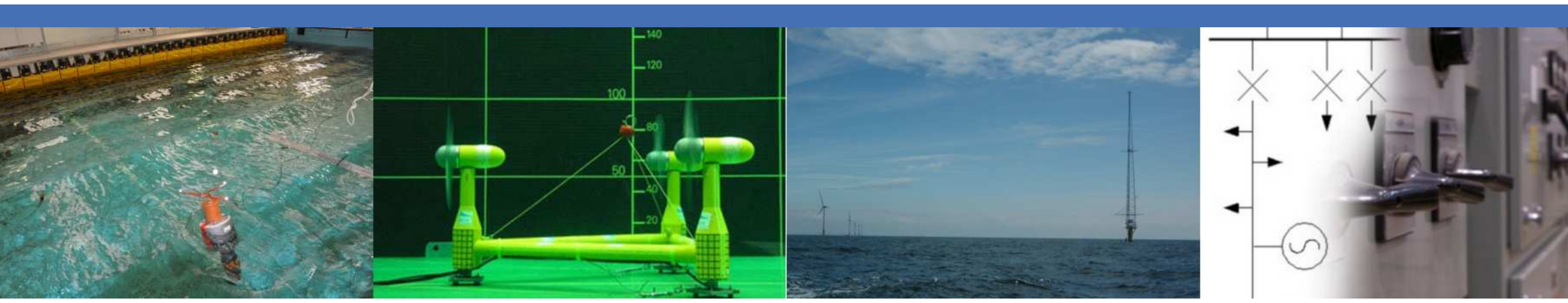
Marine Renewables Infrastructure Network



WP2: Marine Energy System Testing - Standardisation and Best Practice

Deliverable 2.21

Technical note: Mooring Testing

Status: Draft
Version: 03
Date: 01-July-2014

EC FP7 Capacities: Research Infrastructures
Grant Agreement Nº. 262552, MARINET

ABOUT MARINET

MARINET (Marine Renewables Infrastructure Network for emerging Energy Technologies) is an EC-funded network of research centres and organisations that are working together to accelerate the development of marine renewable energy - wave, tidal & offshore-wind. The initiative is funded through the EC's Seventh Framework Programme (FP7) and runs for four years until 2015. The network of 29 partners with 42 specialist marine research facilities is spread across 11 EU countries and 1 International Cooperation Partner Country (Brazil).

MARINET offers periods of free-of-charge access to test facilities at a range of world-class research centres. Companies and research groups can avail of this Transnational Access (TA) to test devices at any scale in areas such as wave energy, tidal energy, offshore-wind energy and environmental data or to conduct tests on cross-cutting areas such as power take-off systems, grid integration, materials or moorings. In total, over 700 weeks of access is available to an estimated 300 projects and 800 external users, with at least four calls for access applications over the 4-year initiative.

MARINET partners are also working to implement common standards for testing in order to streamline the development process, conducting research to improve testing capabilities across the network, providing training at various facilities in the network in order to enhance personnel expertise and organising industry networking events in order to facilitate partnerships and knowledge exchange.

The initiative consists of five main Work Package focus areas: Management & Administration, Standardisation & Best Practice, Transnational Access & Networking, Research, Training & Dissemination. The aim is to streamline the capabilities of test infrastructures in order to enhance their impact and accelerate the commercialisation of marine renewable energy. See www.fp7-marinet.eu for more details.

Partners

Ireland
University College Cork, HMRC (UCC_HMRC)
Coordinator
Sustainable Energy Authority of Ireland (SEAI_OEDU)

Denmark
Aalborg Universitet (AAU)
Danmarks Tekniske Universitet (RISOE)

France
Ecole Centrale de Nantes (ECN)
Institut Français de Recherche Pour l'Exploitation de la Mer (IFREMER)

United Kingdom
National Renewable Energy Centre Ltd. (NAREC)
The University of Exeter (UNEXE)
European Marine Energy Centre Ltd. (EMEC)
University of Strathclyde (UNI_STRATH)
The University of Edinburgh (UEDIN)
Queen’s University Belfast (QUB)
Plymouth University(PU)

Spain
Ente Vasco de la Energía (EVE)
Tecnalia Research & Innovation Foundation (TECNALIA)

Belgium
1-Tech (1_TECH)

Netherlands
Stichting Tidal Testing Centre (TTC)
Stichting Energieonderzoek Centrum Nederland (ECNeth)

Germany
Fraunhofer-Gesellschaft Zur Foerderung Der Angewandten Forschung E.V (Fh_IWES)
Gottfried Wilhelm Leibniz Universität Hannover (LUH)
Universitaet Stuttgart (USTUTT)

Portugal
Wave Energy Centre – Centro de Energia das Ondas (WavEC)

Italy
Università degli Studi di Firenze (UNIFI-CRIACIV)
Università degli Studi di Firenze (UNIFI-PIN)
Università degli Studi della Tuscia (UNI_TUS)
Consiglio Nazionale delle Ricerche (CNR-INSEAN)

Brazil
Instituto de Pesquisas Tecnológicas do Estado de São Paulo S.A. (IPT)

Norway
Sintef Energi AS (SINTEF)
Norges Teknisk-Naturvitenskapelige Universitet (NTNU)

DOCUMENT INFORMATION

Title	Technical note: Mooring Testing
Distribution	Work Package Partners
Document Reference	MARINET-D2.21
Deliverable Leader	Lars Johanning UNEXE
Contributing Authors	Dr Lars Johanning UNEXE Dr Philipp Thies UNEXE Dr Sam Weller UNEXE

REVISION HISTORY

Rev.	Date	Description	Prepared by (Name & Org.)	Approved By (Task/Work-Package Leader)	Status (Draft/Final)
01	07/12/2013	Technical note: Mooring Testing	Lars Johanning, UNEXE		DRAFT 01
02	18/01/2014	Technical note: Mooring Testing	Lars Johanning, UNEXE		DRAFT 02
03	01/06/2014	Technical note: Mooring Testing	Lars Johanning, UNEXE		DRAFT 03
04	23/12/2014	Technical note: Mooring Testing	Lars Johanning, UNEXE		Final

ACKNOWLEDGEMENT

The work described in this publication has received support from the European Community - Research Infrastructure Action under the FP7 “Capacities” Specific Programme through grant agreement number 262552, MaRINET.

EXECUTIVE SUMMARY

This report constitutes deliverable WP2 D2.21 as part of MARINET project. The aim of this report is to provide a technical note for mooring line testing. The report summaries the needs for mooring line testing, small and large scale testing, rope testing and testing requirements for mooring line fatigue testing.

Over the past years the marine renewable energy sector has progressed towards TRL 6 -7 that required a great experience in the application of mooring concepts and installations. The following provides a short exposition of mooring aspects that have been found elementary to inform the development of suitable mooring concepts. In particular the emphasis, where mooring methodologies have been applied based on commonly used approaches within the oil and gas industry, needed to be modified to meet the different operational conditions for marine renewable energy applications. There are two reasons for this. Firstly, the device response characteristics often result in a more dynamic behaviour resulting in an increased fatigue load and the requirement to consider issues of reliability and mean time to failure. Secondly, the mooring has a significant impact on the overall viability requiring deployment and O&M strategies that allow cost effective solutions.

The focus of this report note is towards testing methodologies and associated analysis techniques. The report is presenting a general overview to this topic, starting with an introduction (section 1) that is followed by section 2, describing test methods to identify dynamic line behaviour; section 3, describing general test methods and suitable instruments; section 4, describing specific methods related to fibre rope testing; and section 5, describing a methodology for fatigue load analysis and prediction methods related to mooring assessments.

An overview is given detailing dynamic line behaviour testing, as well as the effect of second-order wave forces, tidal change and mean wind forces towards slow heave, surge and sway motions. . All these slow varying forces contribute to the overall mean excursion of a device, and this in turn will result in different stiffness properties of the mooring system, altering line tension and damping behaviour of the mooring line(s). Furthermore, the importance of frequency response is discussed and two different test methodologies identified. As this report is specific to test method requirements no consideration has been given to numerical analysis methods.

Further reference is made towards synthetic rope testing. In particular breaking test strength is discussed as well as test methods to study viscoelastic and viscoplastic behaviour during the extension of the rope material leading to recoverable or permanent deformation. Finally methodologies for fatigue load analysis and prediction are discussed and related to conclusions from field measurements.

CONTENTS

RELEVANT MARINET PUBLICATIONS

HARNOIS, V., WELLER, S.D., JOHANNING, L., THIES, P.R., LE BOULLUEC, M., LE ROUX, D., SOULÉ, V., AND OHANA J.; (2014) Numerical model validation for mooring systems: Method and application for wave energy converters; Renewable Energy 75 (2015) 869-887, http://dx.doi.org/10.1016/j.renene.2014.10.063

P.R. THIES, L. JOHANNING; V. HARNOIS; H.C. SMITH; D.N. PARISH. (2013) Mooring line fatigue damage evaluation for floating marine energy converters: Field measurements and prediction, Renewable Energy, volume 63, pages 133-144, DOI:10.1016/j.renene.2013.08.050

P.R. THIES, L. JOHANNING, P MCEVOY, (2014) A novel mooring tether for peak load mitigation: Initial performance and service simulation testing, International Journal of Marine Energy (IJOME) 7 43–56, http://dx.doi.org/10.1016/j.ijome.2014.06.001

WELLER S.D., DAVIES, P., VICKERS, A.W. AND JOHANNING, L. (accepted, 2015) Synthetic Rope Responses in the Context of Load History: The Influence of Aging, Ocean Engineering, OE-D-14-00128

V. HARNOIS; L. JOHANNING; P.R. THIES; I. BJERKE; On peak mooring loads and the influence of environmental conditions for marine energy converters; Applied Ocean Research, under review

V. HARNOIS, A. BOUFERROUK, B. STRONG AND L. JOHANNING; (2014) Practical considerations for the analysis of wave and current data from ADCP measurements during long term sea trials; 1st International Conference on Renewable Energies Offshore (RENEW 2014), 24 - 26 November 2014, Lisbon, Portugal

V. HARNOIS, L. JOHANNING, P.R. THIES; Wave Conditions Inducing Extreme Mooring Loads on a Dynamically Responding Moored Structure; 10th European Wave and Tidal Energy Conference (EWTEC 2013), 2-6 September 2013, Aalborg, Denmark.

S. WELLER, P. DAVIES, L. JOHANNING; The Influence of Load History on Synthetic Rope Response; 10th European Wave and Tidal Energy Conference (EWTEC 2013), 2-6 September 2013, Aalborg, Denmark

V. HARNOIS, D. PARISH AND L. JOHANNING, 2012, Physical measurement of a slow drift of a drag embedment anchor during sea trials, 4th Int. conference on Ocean Energy (ICOE 2012), 17 - 19 October 2012, Dublin, Ireland

J. BARD, J-B. RICHARD, J-M. ROUSSET , B. ELSÄSSER, E.R. SESTAFE, M. FINN, L. JOHANNING, 2012, Research activities in the MaRINET project: Keeping the European marine energy development facilities at world top level, 4th Int. conference on Ocean Energy (ICOE 2012), 17 - 19 October 2012, Dublin, Ireland

1 INTRODUCTION

According to the Accelerating Marine Energy report published by the Carbon Trust and Black & Veatch in July 2011 the mooring systems of array based wave and tidal energy devices represent approximately 7% and 6% of the overall cost of each device [1], with studies based on individual designs estimating higher costs (i.e. up to 30% for the Seabreath device [2]). 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 1, [3]). The report also estimates reductions in levelised costs for wave and tidal mooring systems of up to 50% and 40% respectively by 2020 and 85% and 60% by 2050 are possible. Whilst often the assertion is that floating wave energy devices use conventional mooring systems with arguably little direct cost reduction potential, consideration should be given to innovative solutions in this area. One such example is a study conducted by Tension Technology International and Promoor (summarised in [1]) which demonstrated significant cost of energy reductions (5 to 10%) through using lightweight nylon mooring ropes instead of steel cables.

	Cost of Energy [3] (Wave, Tidal)
Foundations and moorings	10%, 10%
Installation	10%, 35%
O&M	25%, 15%

Table 1: Cost of energy for foundations and moorings, installation and O&M [3]

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 is 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).

In technical terms 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 marine renewable energy (MRE) devices which have large support structures (e.g. floating wind turbines and proposed multi-purpose platforms). 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.

The ability to design MRE devices away from excitation frequencies is often a challenge. Whilst the design of a floating MRE device will depend on the mode of operation, in general devices which are small compared to the incident wave length will dynamically respond to first-order and second-order (low frequency) wave loading as well as the combined effects of wind and currents. The loads experienced by an MRE mooring system will therefore be heavily influenced by the motions of the device to the extent that the response of the mooring system and device are closely coupled [4-6]. Conversely the mooring system of a large floating platform will have the primary function of station keeping whilst allowing low frequency motions to occur (within permissible, small amplitude limits). Hence although a degree of commonality exists between the two areas of application (i.e. mooring system types), the mooring loads will clearly differ, necessitating a new approach to mooring system design and influencing the analysis and testing of MRE devices.

2 DYNAMIC LINE BEHAVIOUR TESTING

Second-order wave forces, tidal changes and mean wind forces lead to slow heave and surge and sway motions. All these slow varying forces will contribute to the overall mean excursion of a device, and this in turn will result in different stiffness properties of the mooring system, altering line tension and damping behaviour of the mooring line(s). Furthermore, first-order wave frequency loadings can significantly influence the variation in stiffness and damping for different mean pre-tensions. A full understanding of the stiffness, damping and pre-tension is required to design a reliable mooring system for any floating device and hence should be part of a testing program.

The mooring line damping can be assessed through (a) physical model test investigations, (b) fully dynamic finite element methods and (c) simple analytical models as discussed in [7]. This report is focused towards physical model tests to element uncertainties from field tests. The results of the damping investigations can be generally presented in the form of non-dimensional damping ($E/\delta_A wh$) presented over a range of non-dimensional pre-tension (T_0/wh), where E denotes the dissipated energy, $\delta_A wh$ a reference potential energy based on an amplitude of surge oscillation δ_A, T_0 is the pre-tension in the mooring line, *h* water depth and *w* submerged weight per meter of a mooring line. An example is presented in Figure 1 as shown in [7].

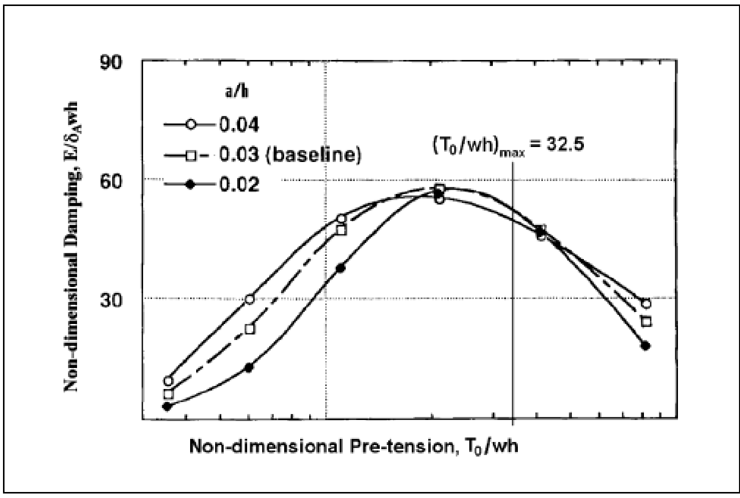


Fig. 1: Mooring line damping variation due to changes in pre-tension for different amplitude to water depth ratio. [7]

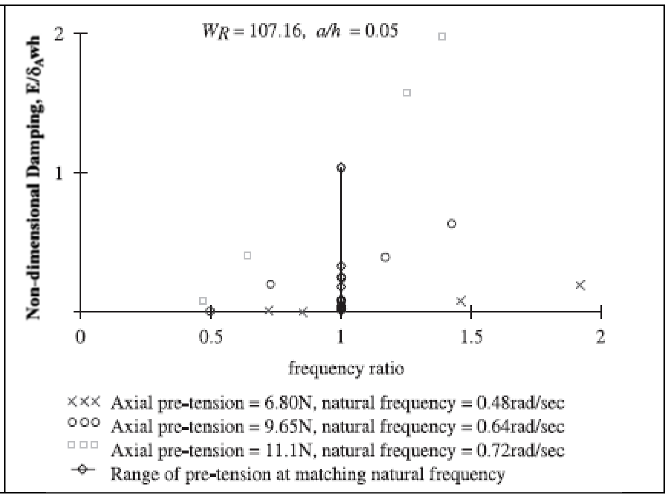


Fig. 2: Mooring line damping variation due to changes in frequency ratio for different pre-tensions. [8]

In addition to the pre-tension damping investigation a conclusive dynamic line behaviour study should also investigate the relation between the top-end frequency of a floating structure and the natural frequency of the mooring line. Damping properties are affected if these frequencies vary (i.e. shown in Figure 2 and in [8]). In order to implement these tests top-end frequencies need to be investigated which are below and above the natural frequency of the mooring line frequency.

Two experimental techniques can be applied to obtain damping from physical investigations, namely i) the decaying method and ii) the forced oscillation method. Both methods are described in the literature as suitable techniques, however the decay method will not allow a sophisticated damping investigation for specific amplitudes.
The technique for the decay method is based on displacing a structure and measuring the decaying motion once released. In order to obtain the mooring line damping, initially the 'system' damping without mooring needs to be

investigated. Once this is known the mooring line damping can then be evaluated by measuring the total damping from the decaying motion and subtracting the evaluated 'system' damping. The total damping can be calculated from the logarithmic decrement experienced by the moored structure during its decaying motion, by using the decreasing peak amplitude during a cycle $\hat{x}$.

$$\Lambda + \Lambda_S = log\left(\frac{\hat{x}_i}{\hat{x}_{i+T}}\right)$$

Here Λ is the mooring damping and Λ_S the system damping. The damping coefficient can then be found from the average of *N* measured logarithm decrements from adjacent cycles in the decaying motion's time history

$$b = \frac{2M_{\mathrm{T}}\left(\sum_{j=1}^{N} \Lambda_j/N\right)}{T},$$

where M_T is the total mass consisting of the mass of the structure M_S and line *M* and their respective added masses m_{aB} and m_{aC}, *T* the period of surge motion and *N* the number of cycles. Figure 3 presents decaying motion for the same mooring configuration at different pre-tensions [8].

The second method, used to quantify the mooring line damping is based on the forced oscillation of the moored system. In this case, the structure is oscillated in specific directional modes, e.g. surge, at sinusoidal displacements at specific amplitudes, but with varying tensions or frequency ratios. By measuring the displacement (Figure 4a) and the mooring line tension (Figure 4b), indicator diagrams (Figure 4c) can be derived by plotting the measured top-end motion against tension. The area within the resulting closed loop of the indicator diagram can then be related to the energy dissipation *E* [8], through the integration of the closed loop, where *F* is the mooring force

$$E = \int_t^{t+T} F\frac{\mathrm{d}\delta}{\mathrm{d}t}\,\mathrm{d}t.$$

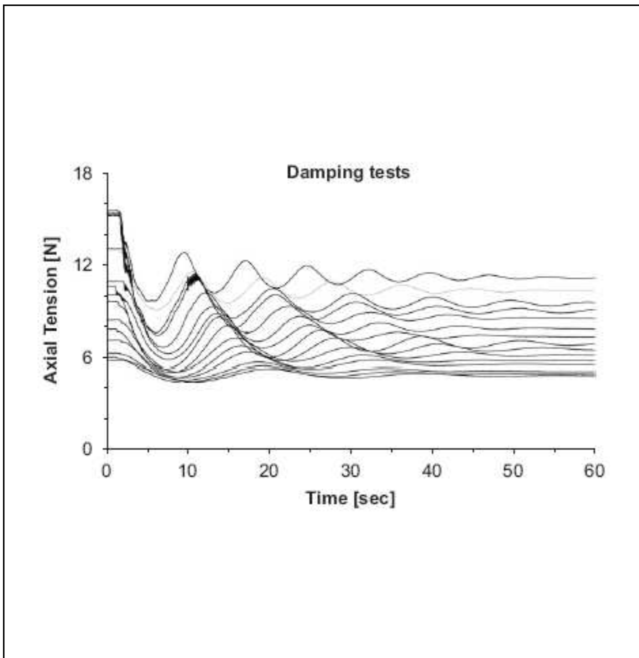


Fig. 3: Decaying motion for the same mooring configuration at different pre-tensions [8]

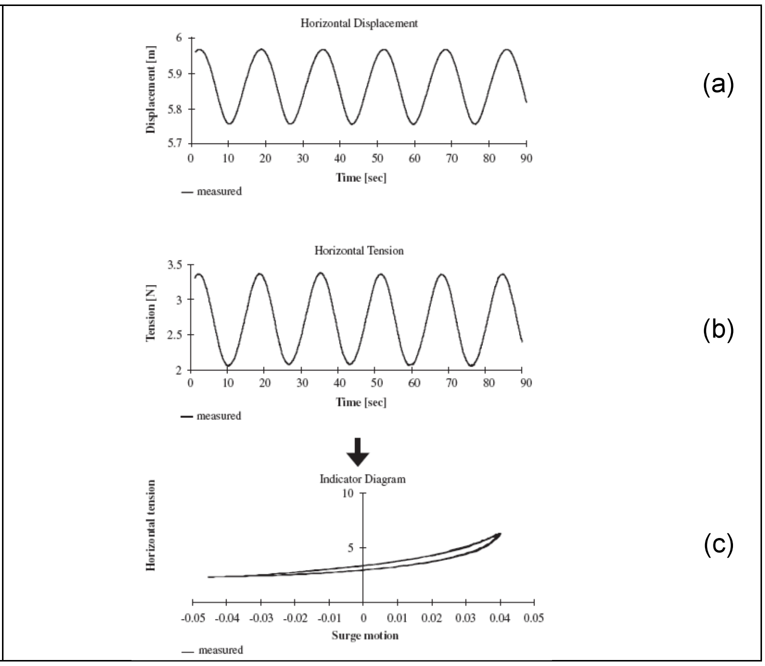


Fig. 4a-c: Development of indicator diagram [8]

3 MOORING TESTING

Mooring tests can be performed under controlled conditions in tanks or during offshore testing in realistic sea conditions. This section is a general description of methods related to tank test (3.1) or field tests (3.2). Aspects of scaling are often an uncertainty and hence tank tests at small scales provide basic design information that need to be supported with measurements through large scale field testing. Often scaled mooring line testing has the complication of incoherent scaling parameters namely the Froude scaling parameters and the viscous scaling parameters (Reynolds). See Chakrabarti [9] for further details.

3.1 TESTING AT SMALL SCALE IN CONTROLLED ENVIRONMENT

To support mooring analysis and the behaviour study of a mooring system under controlled conditions in a tank environment, the following tests are suggested:

i. Free decay methods (tests):

Free decay methods should be conducted to obtain individual motion characteristics for simulation purposes with and without the mooring system.

ii. Stiffness tests:

Stiffness tests should be performed by displacing the system in the heave, surge and sway directions to obtain the mooring stiffness characteristics.

iii. Umbilical tests:

Performance behaviour with and without umbilical attached.

iv. ULS tests

Ultimate Limit State (ULS) tests should be performed with all mooring lines intact.

v. ALS tests:

Accidental Limit State (ALS) tests should be performed with one or more mooring line removed.

vi. Extreme tests:

Extreme tests should be performed at worst case scenario for environmental loadings.

3.1.1 Scaling factors

The scaling factors should be based on the 'Froude similitude Law' (FSL) or 'viscous scaling laws'. FSL has the following scaling factors for the physical modelling:

Length/translational motion	ε
Velocity	$\varepsilon^{1/2}$
Time	$\varepsilon^{1/2}$
Acceleration	1
Angle/angular motion	1
Frequency	$\varepsilon^{-1/2}$
Force	ε^{3}
Mass	ε^{3}
Buoyancy	ε^{3}
Mass/weight per unit length	ε^{2}
Elasticity/axial stiffness	ε^{3}
Bending stiffness	ε^{5}
Energy/work	ε^{4}
Power	$\varepsilon^{3.5}$

3.2 Large Scale Field Testing

For field testing it is essential to acquire extensive data regarding the structures equilibrium position, motion response and the associated mooring line loads, as well as the environmental wind, wave and current velocity conditions. Furthermore, salinity and water temperature could be recorded to investigate mooring dynamics in more detail.

A point to emphasise is the relatively high sampling frequency that would be needed to assess mooring dynamics. Mooring line loads should be measured at kHz sampling frequency and the load threshold should be set to capture snatch loads. In general it is recommended to store all data at a minimum sampling frequency of 20Hz. This sampling frequency is essential to accurately capture the peak mooring loads. An assessment of required sampling frequencies that improve the accuracy of mooring line peak load measurements is presented in Ref. [10]. It was shown that a sampling frequency of 20 Hz improves the capture of the peak mooring line load by about 8% for the recorded peak loads, compared to a 2 Hz sampling frequency. This improved capture of peak loads is important for fatigue estimates, as any load uncertainties translate exponentially into the required fatigue life safety factor.

Example instruments suggested for field tests can be found in MARINET deliverable D4.13 and are summarized in table 2:

data	tool	Picture	Resolution	range
in-line loads	3 axial loadcells:		1kg	0-7te
Tri-axial loads	3 tri-axial loadcells:		1kg	0-7te except in the z direction: 0-14te
6DOF: 3 accelerations, 3 angular speed	Motionpak inertial sensing system		acceleration: 0.001g, angular speed: 0.01deg/s	+/-2g in the x and y direction, +/-3g in the z direction, +/-50deg/s for the roll and pitch, +/-30deg/s for the yaw
GPS position	GPS Trimble 5700 (RTK correction)		Latitude, longitude: +/- 1cm, height: +/- 2cm	/
Compass orientation	flux gate compass Autonnic A4025 OEM		0.1 magnetic deg	0-360 deg
Wind speed and direction	Sonic anemometer: Gill Windsonic		Speed: 0.1m/s, direction: 1deg	Speed: 0-60m/s, direction: 0-360deg
Water current (X and Y direction) and temperature	Aanderaa 4100 DCS		Current: 0.001 m/s, temperature: 0.1 deg C	Current:+/- 3 m/s, temperature:+/-90deg C
Water properties	Aanderaa 4120 IW		water conductivity: 0.01 mS/cm, water temperature: 0.1 deg C, water salinity: 0.01 ppt, water density: 0.01 kg/m3	water conductivity: 40-60 mS/cm, water temperature: 0-20degC, water salinity: 20 to 50 ppt, water density: 990-1030 kg/m3
Beam elevation and current	ADCP Teledyne RDI Workhorse Sentinel (600 kHz) ADCP with Waves Array firmware.		Velocity: 0.1cm/s	Velocity: +/-5m/s(default) Min observable wave period: • Non-directional wave:2.88sec • Directional wave:4.85sec

Table 2: Example instruments suggested for field testing

.

4 SYNTHETIC ROPE TESTING

If a synthetic mooring rope is subjected to many hundreds or thousands of identical harmonic load cycles then the performance of the rope will eventually reach a steady-state. The standardised approach to determine the average stiffness of the rope is to use the final 5-10 cycles of steady-state response. Prior to reaching a steady-state, the response of the rope will be transient, and the evolution of strain (e.g. Figure 5) is related to the changing properties of the rope. The instantaneous properties of the rope will depend not only on the applied load history, but also the level of strain achieved [11]. In order to determine accurate predictions of performance and longevity, it is therefore essential that synthetic ropes are specified in the context of loading regimes relevant to the application through testing. In order to obtain specific rope characteristics ‘breaking strength’ and ‘viscoelastic and viscoplastic behaviour’ tests need to be performed.

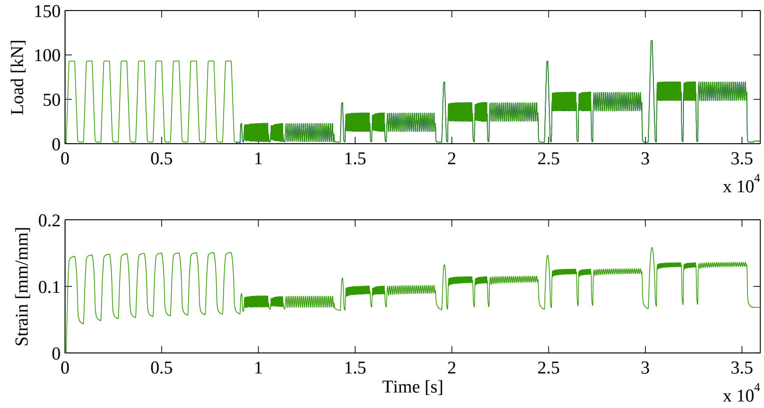


Fig. 5: Example applied load and measured strain of a nylon mooring rope sample

4.1 BREAKING STRENGTH

Breaking strength is defined as the ability to withstand increased loading until a sufficient number of fibres have been damaged that total failure of the rope will occur with continued loading. The load at which this occurs is often quoted by rope manufacturers as the minimum break load (MBL) and will depend not only on the applied load rate but also the condition of the rope. In terms of strength, the selected rope will need to be tested under the expected extreme loads that the rope will withstand.

4.2 VISCOELASTIC AND VISCOPLASTIC BEHAVIOUR

Under constant load, synthetic materials tend to extend or creep. The extension of the material may be recoverable (i.e. viscoelastic behaviour) or permanent (viscoplastic) and this will depend on the applied load conditions and condition of the rope. Both creep and recovery can either occur immediately or be delayed. If a newly manufactured rope is loaded for the first time, constructional rearrangement of the rope will also result in permanent extension, which can be thought of as a ratchet. It is for this reason that tension-tension testing programmes used to determine the operational and fatigue properties of ropes typically commence with a number of creep and relaxation cycles (often referred to as 'bedding-in') to allow constructional rearrangement to occur so that the rope can be tested at a known state.

In addition to dynamic loading, an important consideration for mooring system design and testing is the level of expected creep in-service. It is possible that non-recoverable extension of the rope will result in a significantly different mooring geometry and lower pre-tension. Unless the mooring lines are subsequently re-tensioned the station-keeping abilities of the mooring system will be reduced, resulting in a potentially damaging change to the dynamics of the moored system. As a consequence the viscoelastic behaviour of a rope needs to be identified through testing. Viscoelastic materials demonstrate hysteresis, where there is a lag (or phase difference) between changes to the applied load and resulting elongations or relaxations. This is perhaps best illustrated through considering one load-extension loop of a Nylon sample subjected to harmonic loading (Figure 6). The energy expended during loading and unloading can be estimated from the area contained within the loop. The energy absorbed and dissipated is related to the damped response of the rope, which will contribute to the overall damped response of the moored system. Further details regarding synthetic ropes can be found in the MERiFIC deliverables: *D3.5.1 Testing of synthetic fibre ropes*[1] and *D.3.5.2 Guidance on the use of synthetic ropes for marine energy devices*[2].

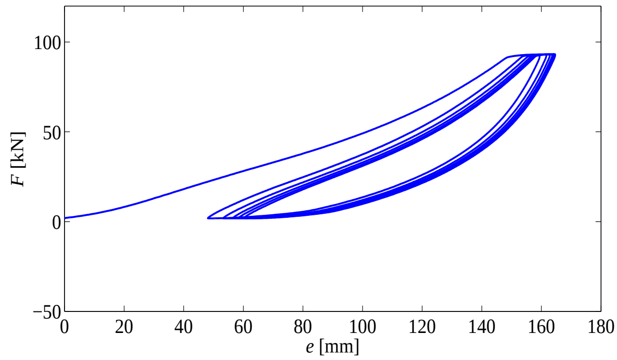


Fig. 6: Load-extension loop from rope testing

5 METHODOLOGY FOR FATIGUE LOAD ANALYSIS AND PREDICTION

The process of providing evidence of system and/or component reliability requires generating a representative and meaningful test regime. For MEC devices an iterative five stage process was suggested by [12].

1. Define an operating period and conditions (e.g. operating time, environmental conditions, wave climate) resulting in an expected operating profile

2. Undertake field load measurements under operational conditions (or alternatively calculations/assumptions)

3. Process the measured load samples to establish a ‘‘load library’’ for different operating conditions

4. Implement the operational profile for the planned test regime

5. Generate the test load sequence through the combination of operating profile and load library segments.

Steps 1. and 2. would represent data input related to a specific MEC device and site conditions. Ideally, the operating conditions and load data would be defined and measured directly in the field, e.g. the wave climate and loads experienced by the components of a prototype device or sub-system under full-scale sea conditions. Steps 3.–5. are based on established theoretical methods. To close the loop for comprehensive component reliability testing a root cause analysis of occurring failures would need to be implemented additionally.

---

[1] http://www.merific.eu/files/2012/06/D3.4.2_Best-practice-report-Cross-border-laboratory-and-field-test-proceduresv2.pdf

[2] http://www.researchgate.net/publication/258236833_Guidance_on_the_use_of_synthetic_fibre_ropes_for_marine_energy_devices_Deliverable_3.5.2_from_the_MERiFIC_Project/file/3deec5277d76e37165.pdf?origin=publication_detail

5.1 Site specific conditions

For moored MECs it has to be identified if the weighting of the ''N-year'' return extreme waves, responsible for survivability, or specific average sea state conditions, such as groupiness, governing reliability, are driving the main design consideration. To predict survivability extreme waves need to be applied, where the assessment could be based on offshore oil and gas station keeping standards, such as DNV-OS-E301 [12]. However, to prevent fatigue failure of components due to accumulated loading, which could have important implications for reliability, in-service loads need to be considered. The operational conditions for MECs are site-specific, so an assessment of these is essential for prospective component reliability. The fatigue load conditions need to be assessed for the individual sea states. Information and subsequent calculations are needed to generate an annual load spectrum from individual sea states.

5.2 Field load measurements

The two primary factors to affect fatigue reliability are the material's fatigue strength and the applied cyclic loading. While the fatigue strength is an intrinsic material and mechanical characteristic, the applied loading describes an extrinsic process. Typically S-N curves are used for fatigue assessment generated from controlled material fatigue strength tests under lab conditions, and applied cyclic loading characteristics should be obtained from realistic field tests. The probability of each sea state can be assigned to the estimated fatigue damage for individual mooring components of each sea state. The objective is to derive multiplicative factors for each individual sea state, in order to estimate the annual accumulated fatigue damage.

From a field test the critical load cycles for a possible fatigue failure can be obtained through a rainflow analysis procedure. In the first instance cyclic loading need to be quantified in their load range assessing the variation between minimum (starting load condition) and the maximum load (end load condition) over one cycle. A measured time series will have multiple load cycles, which need to be classified into specific ranges. This will allow quantification of the occurrence of load cycles in a specific range. When combined with a suitable wave scatter plot, the individual fatigue damage values can be aggregated to an annual or long-term fatigue damage estimate. An example contour plot of annual accumulated fatigue damage generated from field measurements is developed by [14] and shown in Figure 7.

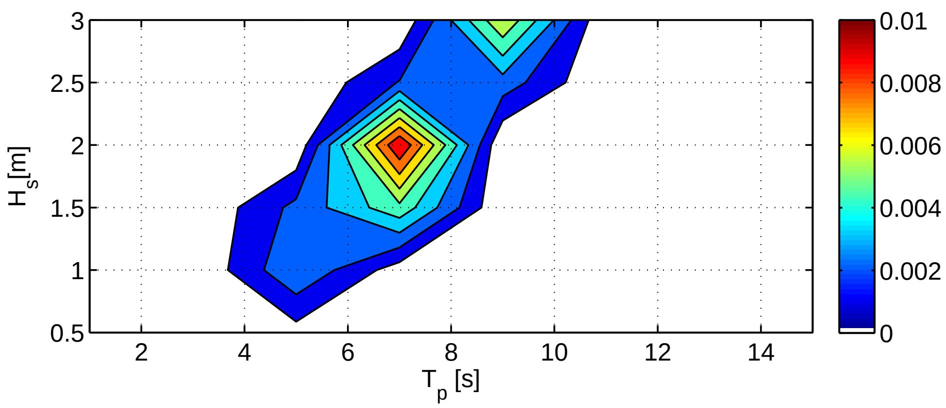


Fig. 7: Example contour plot of annual accumulated fatigue damage for mooring. Colour scale denotes accumulated fatigue D damage for one year, taken from [14].

6 REFERENCES

[1] Carbon Trust and Black & Veatch (2011) Accelerating marine energy. The potential for cost reduction – insights from the Carbon Trust Marine Energy Accelerator

[2] Martinelli, L., Ruol, P and Cortellazzo, G. (2012) On mooring design of wave energy converters: the Seabreath application. Proceedings of the International Conference on Coastal Engineering

[3] Low Carbon Innovation Coordination Group (2012) Technology Innovation Needs Assessment (TINA): Marine Energy Summary Report

[4] Johanning, L. and Smith, G.H. and Wolfram, J. (2007) Measurements of static and dynamic mooring line damping and their importance for floating WEC devices. Ocean Engineering (2007), 1918-1934.

[5] Fitzgerald, J. and Bergdahl, L. (2008) Including moorings in the assessment of a generic offshore wave energy converter: A frequency domain approach. Marine Structures, 23-46.

[6] Cerveira, F., Fonseca, N. and Pascoal, R. (2013) Mooring System Influence on the Efficiency of Wave Energy Converters. Proceedings of the 10th European Wave and Tidal Energy Conference, Aalborg, Denmark

[7] Webster, W.C., 1995. Mooring-induced damping. Ocean Engineering 22 (6), 571–591.

[8] L. Johanning, G.H. Smith and J. Wolfram; Measurements of static and dynamic mooring line damping and their importance for floating WEC devices, Ocean Engineering 34 (2007) p.1918–1934

[9] Chakrabarti, S., 1998, Physical model testing of floating offshore structures, Dynamic Positioning Conference, Oct. 13-14, 1998, Houston, USA.

[10] Harnois V, Johanning L, Thies PR, Bjerke I. The influence of environmental conditions on the extreme mooring loads for highly dynamic responding moored structures. Ocean Eng under review, Manuscript number OE-D-13-00319.

[11] 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

[12] P.R. Thies, L. Johanning and G.H. Smith, 2011, Towards component reliability testing for Marine Energy Converters, Ocean Engineering, Vol. 38, Issue 2-3, pp. 360–370. doi:10.1016/j.oceaneng.2010.11.011

[13] DNV-OS-E301, 2008; Position mooring; Det Norske Veritas [DNV]

[14] Thies PR, Johanning L, Harnois V, Smith HCM, Parish DN. (2014) Mooring line fatigue damage evaluation for floating marine energy converters: Field measurements and prediction, *Renewable Energy*, volume 63, pages 133-144, DOI:10.1016/j.renene.2013.08.050.