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OFFSHORE RELIABILITY APPROACH FOR FLOATING RENEWABLE ENERGY DEVICES

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ABSTRACT

This paper describes the test facilities developed within the Peninsular Research institution for Marine Renewable Energy (PRIMaRE) group and discusses the approach of the group to mitigate risk for marine renewable energy installations. The main consideration is given to the reliability assessment of components within mooring configurations and towards power umbilical for typical renewable energy sites. Load and response data from sea trial will be used to highlight the importance of these research activities, and a Dynamic Marine Component Test rig (DMaC) is introduced that allows four degree of freedom fatigue or destructive tests. Furthermore it is discussed how this facilities could also aid in the reliability assessment of wider offshore applications.

Keywords: offshore reliability, floating renewable energy devices, dynamic marine component test rig, floating mooring test buoy

1 INTRODUCTION

Marine energy technology is currently emerging from a research and development phase toward commercial deployment. Some devices have already reached a pre-commercial stage and in the UK, commercial-scale projects with a capacity of 57.5MW are being developed [1].

Prototype development and testing has largely focused on the demonstration of working principles, conversion efficiency and the survivability of devices. However, the viability and success of Marine Renewable Energy installations is strongly dependent on the reliability of devices as this determines the amount of generated electricity and the cost for operation and maintenance. Reliability testing of critical components could mitigate these difficulties and provide device developers with a possibility to reveal early failures, gain information on lifetime criteria and provide project developers, investors and certification agencies with the required reliability demonstration and evidence of suitable risk control. The application of component reliability testing can reveal design weaknesses prior to deployment and establish necessary reliability and maintenance information. Components tested under service simulated conditions could be evaluated regarding performance, expected lifetime and subsequently be (cost-)optimised. Employing extensive testing in representative conditions is considered suitable [2] but so far sparsely applied in the marine energy industry.

Two test facilities are described that enable component reliability testing for marine renewable energy converters developed within the Peninsula Research Institute for Marine Renewable Energy (PRIMaRE) group at the University of Exeter. Those two facilities will allow measuring loads that are experienced in the field through prototype testing at the South Western Mooring Test Facility (SWMTF) and subsequently replicate those load conditions (or information from device developers) at the DMaC for accelerated reliability testing and design enhancement.

The (SWMTF) is a unique mooring load and response test facility, at large scale in real sea condition and has been recently installed. The Dynamic Marine Component Test facility (DMaC) is capable to perform accelerated component testing under simulated in-service field conditions in four degree of freedom. Loads that are experienced in the field through testing at the SWMTF, or through information from device developers, can be used to accurately replicate load conditions for accelerated testing at the DMaC facility. The appeal of such testing is not only to obtain necessary data for marine energy applications but to reveal all potential failure modes and gain valuable insight into the physics of failure, and improve designs.

Figure 1. Installation location of SWMTF

2 MOORING TEST FACILITY

Mooring designs for Marine Energy Converters (MECs) could be simply adopted from the offshore oil and gas industry. However, the difference in required installation locations, mooring arrangement, motion requirements and physical size will typically result in different coupled response and load characteristics for the Marine Energy Converter [3] and its mooring. These could affect the accumulated cycle loading from extreme tensions due to non-linear mooring line behaviour, reducing the fatigue life of mooring components and having an effect on the required capacity of components to withstand ultimate dynamic loadings, as discussed by Johanning et.al. [4, 5]. It is evident that this is still a key area of interest for Marine Energy Converters in general.

As moorings are a significant part of the cost of a MEC installation simple over-design will lead to non viable economics. The research challenge is to develop a thorough understanding of mooring system behaviour of MECs in real wave, wind, current and tidal conditions; and to improve computer simulation models and robust design procedures that allow the design of reliable, yet economic mooring systems. For marine energy converter who convert the energy from waves, Wave Energy Converters (WECs), the mooring should also aid in the dynamic performance of the coupled system to enhance the energy conversion efficiency.

The intention for this research facility is to identify uncertainties for moored WECs that will respond in a coupled fashion. Instead of using tank tests, prototype installations and numerical analysis to support the design of a WEC, the data gathered from the test facility will be used to calibrate numerical models, enhance the physical understanding of the coupled behavior and obtain understanding of component loading and deteriorating.

In particular, enhancing the understanding of the required input data for a fully dynamic coupled mooring system will avoid discrepancies in the simulation of moored systems. Understanding the discrepancies identified during comparisons with numerical models will lead to an advanced understanding of the behaviour of the couple system, provide better calibration values to the numerical models and ultimately reduce uncertainties in engineering design. Consequently a relatively simple assembly was initially chosen within the arrangement of the mooring test facility that allows to reduce complexities that otherwise would lead to additional unknowns in the numerical analysis. This is why a generic elementary cylindrical buoy and a three leg catenary hybrid (rope-chain) configuration was selected for this initial installation.

2.1 Mooring Facility configuration

The mooring buoy will be instrumented to gather data relating to its response and the mooring limbs to the environmental loads acting upon the system. In order to be able to measure important events, most data will be collected continuously and stored in 10 minutes intervals. Data will be transmitted to a shore station via a dedicated point to point telemetry link and will be logged on board the buoy for backup. The influences like wave action, tidal currents, wind blown surface currents and wind will be measured by sensors fitted to the buoy or positioned on the sea bed. Operating autonomously, the buoy will have its own electrical power system comprising gel type batteries, a wind turbine and a photovoltaic array.

In general the hardware for the mooring test facility includes:

a) Environmental instruments

- ADCP wave/current profiler(s)

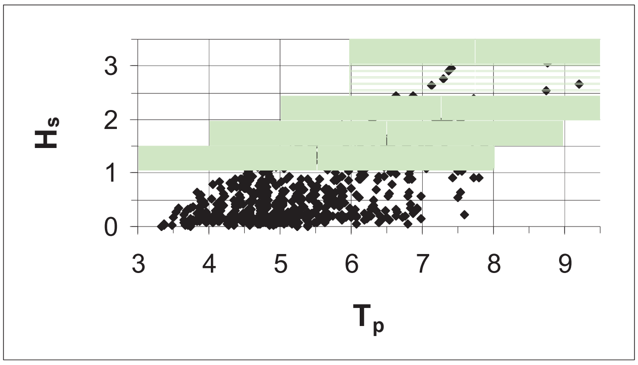

Figure 2. Annual wave statistic for SWMTF location

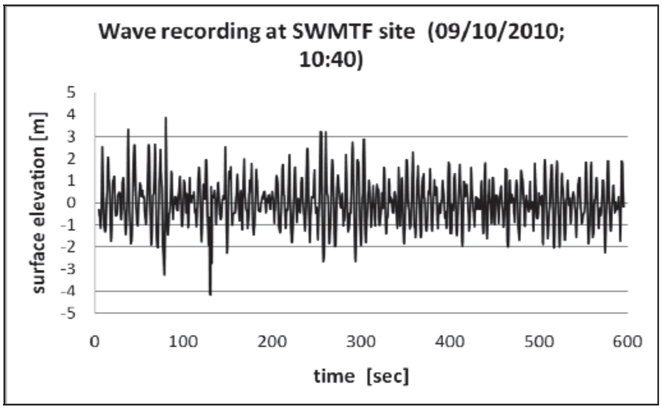

Figure 3. Time history of wave elevation at SWMTF site

- Wind/Current instrumentation

b) Response and loading instruments
- 6-degree 'Motion pack' system
- DGPS system
- In-line mooring load cells
- Tri-axis load cell
- Anchor positioning system

c) Data acquisition/radio communication
- Data acquisition system
- Large capacity computer systems
- Radio telemetry system

d) Mooring configuration
- Three leg catenary mooring configuration
- Embedment anchors

Location and Environmental climate

In order to identify a suitable location for the installation of the test facility three aspects were considered i) water depth/tidal range, ii) wave and current condition and iii) the accessibility. The most suitable installation location was found to be in Falmouth Bay, Cornwall, UK (fig. 1) having a low tide water depth of 27m. The maximum tidal variation for this location is 5.4m with a mean tidal variation of 4.6m. No measured wave characteristics were available during the design phase for this location and a first approximation of the wave climate was obtained using numerical modelling.

The wave climate at the site was analysed using the nearshore wave model SWAN (Simulating WAves Nearshore). SWAN is a phase-averaged, Eulerian wave model that accounts fully for shallow-water processes such as refraction, energy dissipation by bottom friction and wave breaking, and non-linear energy transfers (Booij et al., 1999) [6]. Boundary conditions for the model were provided by output from the UK Met Office's UK waters wave model. Twelve-hourly data for the period from November 2005 to October 2006 were used into a 200m resolution SWAN model. Corresponding height, period and directional wave data were output for the test site, that was used to derive an annual wave statistic (fig. 2). As can be seen from the scatter plot in figure 2, maximum significant wave heights of 3m are expected at a wave period between 7.5 to 9 sec. There was also no detailed information on surface current measurements available for the site, but a peak value of 0.8 m/s was obtained from the admiralty chart.

Detailed information of the wave and current conditions, however, are obtained since August 2010 measuring continuously the surface elevation at four points within the footprint area of the SWMTF and the current profile in a 10sec interval. For this an 600kHz Teledyne RDI 'Workhorse – Waves Array' [7] Acoustic Doppler systems (ADCPs) was positioned at the seabed, which will be recovered every two to three month to upload data and exchange batteries. Figure 3 represents a time history during a storm in October 2010, when maximum wave heights off up to 5.8m were measured with a

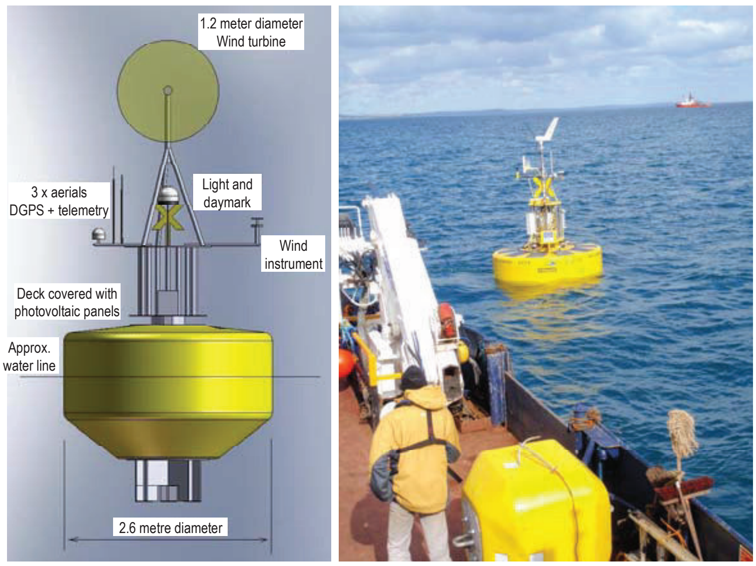

Figure 4. Schematic drawing and installed buoy

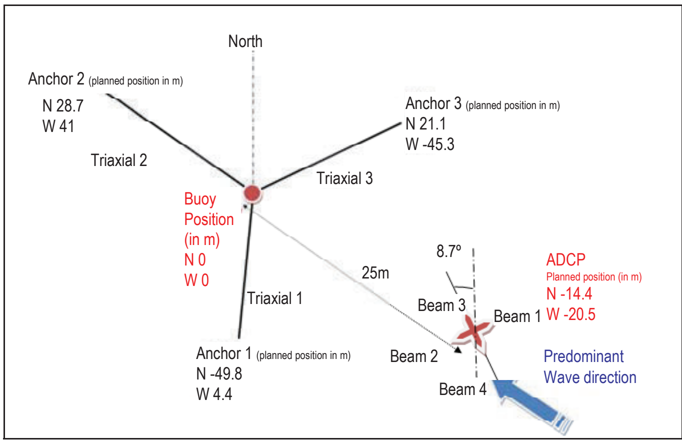

Figure 5. Schematic drawing of mooring arrangement

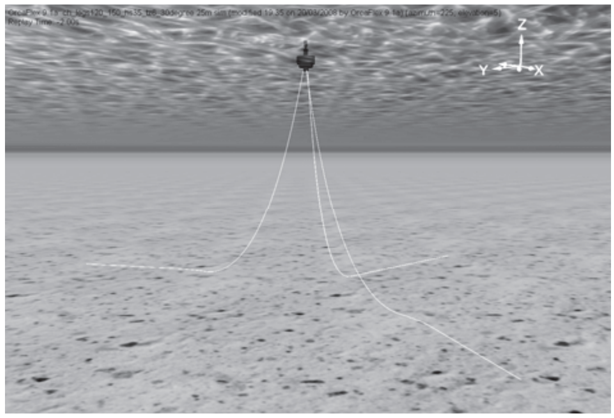

Figure 6. Plan view of mooring configuration

mean return period of 6.5sec at a mean water depth of 29m.

In order to obtain information about the wind conditions at the site a WindSonic wind sensor is attached to the upper frame of the wave buoy. The configuration of the instrument provides a mean wind statistics and time series at a sample frequency of 4Hz.

Buoy design

The main components of the buoy will be a cylindrical steel support structure, a floating body manufactured using foam elastomer technology and the lantern. Figure 4 presents a schematic drawing of the buoy with its lantern and attached instrumentations. The structural integrity will be provided by the central support structure that will provide the fixing points for the floating body, the lantern and three tri-axis load cells, which will provide the attachment points to the mooring lines.

The properties of the assembled buoy are:

Mass of buoy (excluding mooring chains)	3300 kg
Draft excluding load cells (including 1500kg mooring chains)	1658 mm
COG (of buoy only)	111 mm
PCD of mooring attachment points	700 mm
Diameter of float body	2900 mm
Diameter of central column	355 mm
Radius of gyration:	
In x, y directions	0.5765 m
In z direction	0.7446 m

Buoy Instrumentations

The SWMTF is based around the heavily instrumented buoy. Specially developed 'tri-axial' load cells bolted to the underside structure, provide data corresponding to both the instantaneous magnitude and direction of the mooring line loads at the attachment points. Further axial load measurement is made on each mooring limb to provide redundancy to these data sets. On-board measurement of the buoy's dynamic behavior is recorded to a high accuracy by a six-degree inertial sensing unit and the buoy position is additionally recorded by a survey quality DGPS rover set operating with a dedicated base station located close by. The data acquisition system operates at 20 Hz using the GPS time stamp to mark the individual data sets for post processing and analysis. The orientation of the buoy is further monitored with a tilt-compensated flux-gate compass. Wind and surface water currents are also measured on-board the buoy as well as the water temperature and conductivity is monitored. High priority has been placed on ensuring the structural integrity of the buoy and of the load cells and components that transfer loads from the mooring limbs to the buoy, and Vishay CEA-06-250UR-350 strain rosettes have been mounted to the buoys cylindrical steel support structure to understand the strains on the system. A summary of the instruments is presented in table 1.

Processing of the data will allow a detailed analysis of the

Table 1: Summary of main SWMTF sensors

Sensor	Sample frequency [Hz]	Signals
Multi axis inertial sensing system, 'MotionPack'	20	6
Tri-axis Load Cell	20	9
In-line Load Cell	20	6
Vishay CEA-06-250UR-350 strain rosettes	4	6
Tilt-compensated flux-gate compass	1	1
Temperature sensor	0.07	1
Trimble 57001-51-46 DGPS RTK rover	20	digital
WindSonic wind sensor	4	digital
Aanderaa DCS 4100R velocity sensor	10 second averages	digital
Aanderaa 3919 conductivity sensor	15 minutes averages	digital

effectiveness of each mooring system at holding the buoy on station in a variety of conditions and will provide a thorough understanding of the loads and the responses imposed on the system.

Mooring design

A three-leg hybrid chain-nylon rope catenary arrangement was chosen to support the initial mooring study and meet the objectives of the research facility. The top end of the mooring lines will be attached to an in-line load cell, which will provide the final link to the tri-axis load cells that are solidly fixed to the bottom of the buoy. The mooring lines will be spread equally at 120 degrees (fig. 5) and anchored on the seabed with three embedment anchors at a diameter of 80m. A plan view of the mooring arrangement is shown in figure 6.

The specification of the mooring configuration:

1.1 tonne drag embedment anchor
5m ground chain Φ32mm stud link + swivel
36m riser chain Φ24mm open link + swivel
20m rope tail Φ44mm jacketed parallel lay nylon + swivel

3. DYNAMIC COMPONENT TEST FACILITY

Uncertainties about the availability of marine renewable energy devices is described by Mackay et. al. [8] as one of the hindering factors within the commercial development of this upcoming industry. The main reasons are that i) the predictability of mechanical failures for a new technology and ii) the lack of operational experience. In particular, the marriage of applying proven components from well established applications in a harsh environment, where load and response conditions are not well established, may lead to unforeseen failures. These uncertainties in the load conditions may lead either costly design safety factors or early field failures both of which would impede project viability that hinder commercial development and necessary investment.

The Dynamic Marine Component Test facility (DMaC) provides the ability to perform accelerated component testing in four degree of freedom, whilst the SWMTF provides the ability to perform component testing in a realistic environment. With the lack of information for component reliability of MRE

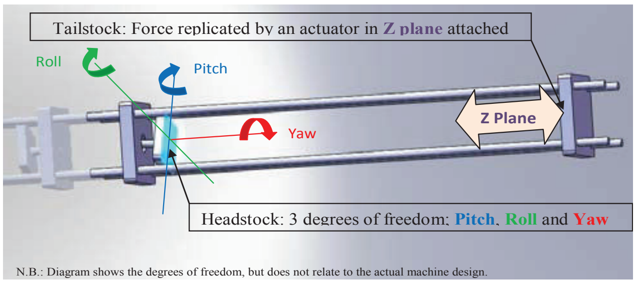

Figure 7. Functional illustration of the DMaC

devices in realistic installation situations, information can be cost effective obtained from the nearshore test site. These informations can be replicated at an accelerated manner in the DMaC to improve performance and develop suitable components for the marine offshore industry and consequently aid in their design.

3.1 Properties of DMaC

To be able to replicate the motion characteristics and loadings experienced by MEC components, or sub component, the test rig will provide a one degree linear motion that can be

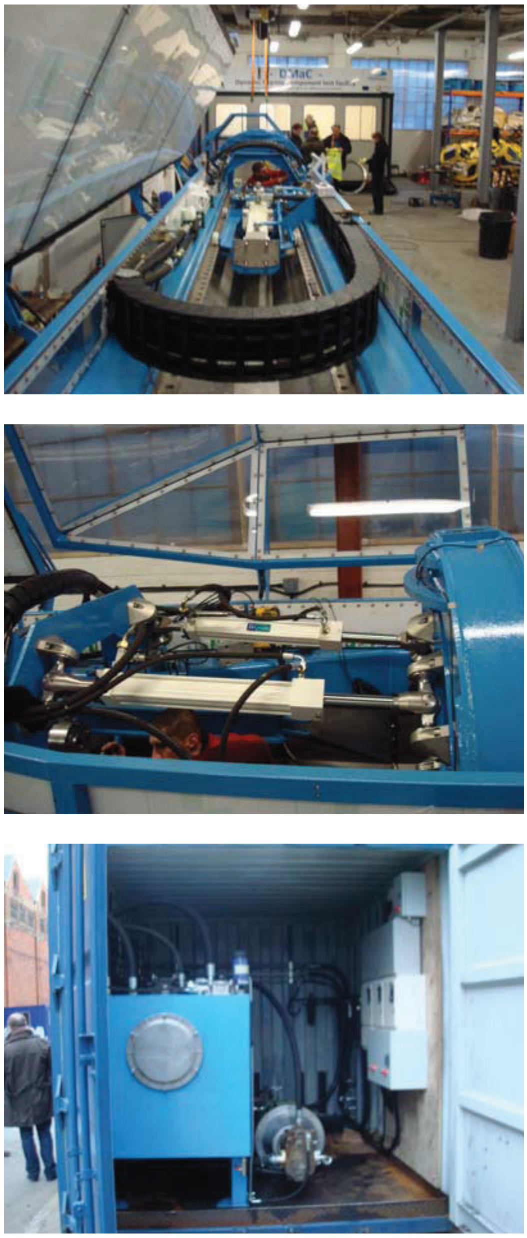

Figure 8. DMaC images (Test bed & Z-actuator, Headstock(-ramps), Power unit)

Table 2: DMaC functional specification

Amplitude 1 [m]	Frequency 1 [Hz]	Amplitude 2 [m]	Frequency 2 [Hz]
0.5	0.1		
0.25	0.1	0.05	1
0.05	1		
0.025	1	0.005	10Hz

used to replicate a pulling and pushing force representative of dynamic loadings, pre-loadings, etc. (termed the Z actuator in the tailstock position), and a headstock with three degrees of freedom (namely pitch, roll and yaw) representative of x- and y-bending or torsion; shown in principle in figure 7.

Furthermore, the DMaC comprises of the typical sub-systems of a conventional test rig:

i. Force transmission - The subsystem that directly acts on the specimen/component.
ii. Drive/Actuation - in order to transmit the forces necessary for component deformation the point of force transmission needs to be actuated; this is achieved with a servo-hydraulic system.
iii. Control - the drive has to be controlled for a systematic deformation of the specimen.
iv. Response structure - The actuated forces need to be balanced with a structural frame.

Beyond that, the proposed test rig will have a unique feature that are relevant to the testing of components for marine renewable energy devices, allowing to immerse components in fresh water and the dynamic testing in a wet environment. These features will allow a dynamic testing of components in large scale under controlled environment applying realistic motion characteristics.

The DMaC was constructed during 2010 and is now installed (figure 8) and commissioning tests are performed. The intention was to design a test rig that allows testing of components for floating MRE devices. However, early indications are that this rig will provide the capabilities of testing components not restricted to the MRE industry, but provides also applications to the wider offshore industry. As such studies are intended to perform umbilical test to obtain performance indicator in severe bending regimes for wider offshore applications.

The technical capabilities of the rig are as follows:

1. Hydraulic Power system

i. Electrical Power Supply:
Power 130 kW
Voltage 415 V
ii. Hydraulic Power Unit:
2off 55kW induction motors
2off variable displacement pumps
Drive Circuit Pressure 140 Bar
Flow Rate 362 l/min
Pilot Circuit Pressure 210Bar

2. Z-actuator

i. Max. Stroke 1 m
ii. Capable to replicate different superimposed frequencies as defined in table 2
iii. Z-actuator properties:
Rod diameter 70 mm
Bore 160 mm
Maximum Dynamic Force 30 Tonnes
Maximum Static Force 45 Tonnes
Servo-hydraulic control valve 462 l/min
Preload force 14 Tonnes

3. Headstock

i. x- and y-bending:
Displacement 30°
Frequency 0.25 Hz
Off-axis load 10 kNm
ii. Torsion:
Angle Infinite 360°
Torque 1500 Nm
Speed 10 rpm
iii. Maximum specimen properties:
Diameter 800 mm
Base to pivot point 300 mm
Weight 500 kg

4. Test Bed

i. Wet or dry operation
Fresh water submersion operation
ii. Watchdog system with safety interlocks
iii. 6mm Polycarbonate safety shield
iv. Spare data acquisition inputs for specimen specific data recording applications
v. Adjustable Z-actuator positioning system
vi. Maximum specimen dimensions:
Length 6 m
Diameter 800 mm
Weight 1000 kg

5. Control Centre

i. Fully autonomous control and data logging
ii. Programmable test design
Force driven
Displacement driven
iii. Data acquisition and control channels
NI Compact RIO / Labview
32 analogue inputs
8 differential strain gauge inputs

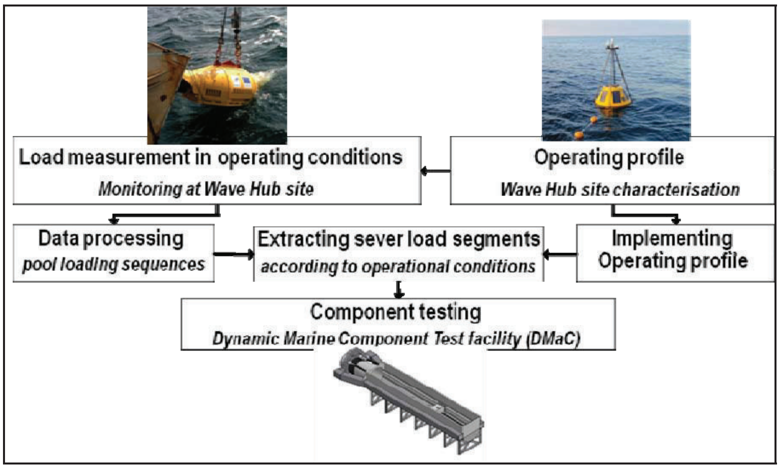

Figure 9. Generic reliability approach for device improvement (based on [14])

64 digital inputs
32 Digital Outputs
16 Analogue Outputs

iv. Sampling frequency (combined) 250 kHz
v. Position control frequency 120 kHz
vi. Internet enabled for real time viewing and control

4. RELIABILITY TESTING

Reliability testing is widely used in numerous industries to provide assurance of components and products. The general requirements and procedures are defined e.g. in the British Standard BS 5760:2003 [9]. Industries that made extensive use of reliability testing are e.g. the automotive-, aviation-, offshore oil and gas-, mining- and the astronautic industry. In all such cases the reliability of systems had to be assured before operational deployment/product launch, or long term specifications (e.g. operational safety, fatigue life) had to be established with limited operational experiences. A detailed list of the range of reliability test applications can be found in [10]. Cardenas et al. [11] demonstrated the accelerated degradation process of umbilical cables caused by the combined environmental effects of cyclic loading, marine environment and ultraviolet radiation.

The number of failure modes that must be considered is diverse, ranging from marine fouling to fatigue and the loading regimes (type and frequency) can be quite different from those normally experienced by the naval and offshore industries. However, for decision making on project investment vital information are required related to the performance assessment of a system regarding reliability, availability and maintainability (RAM). This information is a necessity in the design alternatives, operations & maintenance strategies and the identification of components and subsystems for further improvement. Efficient RAM analysis is a tool to reach low failure rates and long mean time between failures (MTBF) that could be performed using a i) measurement-based or ii) model-based method [12].

For any reliability assessment the quantity and quality of device information and knowledge of failure rate is crucial. Unfortunately the measured performance information available for marine energy devices is rather thin, and the model based method cannot directly be applied since components have often different response and load characteristics. Consequently it is crucial that specific performance indicators are established for the MRE industry

The process of providing evidence of system/component reliability under operational conditions can be divided into four subsequent steps [13]:

i. Measuring realistic load data
ii. Identify representative loading regimes
iii. Testing a (representative) sample on a laboratory test rig
iv. Root cause analysis and statistical evaluation of test results

Ideally, realistic load data is of course measured in situ, e.g. the loads experienced by the components of a device or sub-system at installation location. For the approach described here a more cost effective method was chosen where a component behavior is measured on a real sea test facility, SWMTF, to obtain component responses and loadings. The laboratory test are consequently performed at the DMaC test rig, able to force or load driven accelerated testing. The long term aspiration, however, will be to i) characterise the environmental climate of a specific installation locations to high accuracy (such as the Wave Hub site, Cornwall, UK), ii) obtain realistic load and

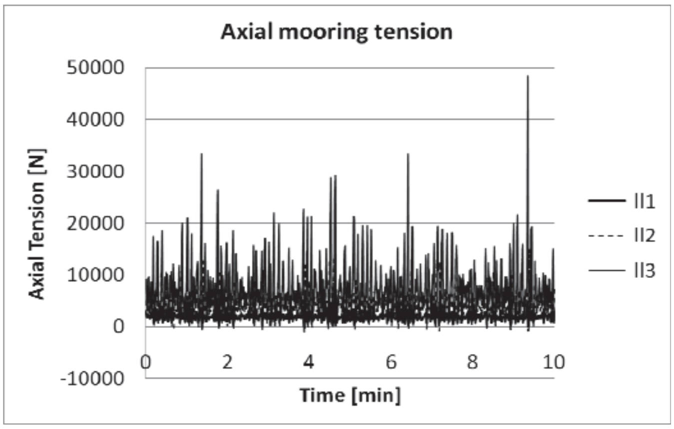

Figure 10. Axial tension of load link 1,2 & 3 measured at SWMTF

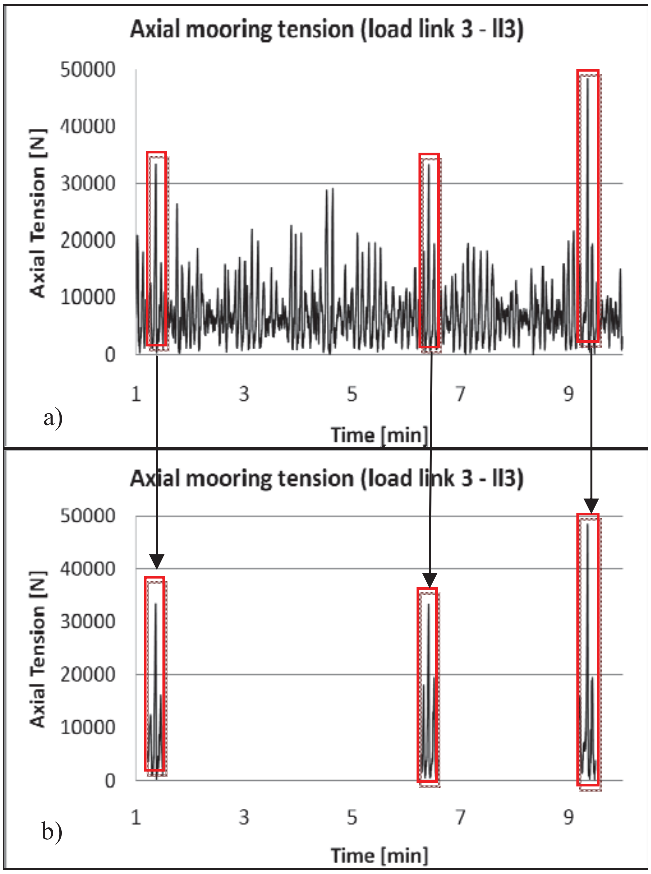

Figure 11a,b. tension signal of ll3 and extracted peak

response characteristics from a commercial device for statistical environmental conditions, iii) analyse and extract severe load or response cycles and iv) undertake accelerated laboratory component testing (see diagram in figure 9).

4.1 Test results and procedure

To provide an example here, measured load data from the SWMTF are presented over a 10min interval (figure 10). The load data represent the axial loading (load link 1, 2, 3 (ll1, ll2, ll3)) of the three mooring legs shown in figure 5 and 6. Whilst only moderate maximum tensions were measured on ll1 and ll2 (3.4kN and 14kN respectively), significant peak loads were measured for ll3 with various peaks around 30kN and one maximum tension load of 48.3kN. The cyclic load is in the order of a 6sec period, whilst the average return cycle of peak loading is in the order of 2min.

Once representative load data are established, the most severe load cycles can be used to derive a loading regime for the accelerated testing. This has been done only for the ll3 in figure 11a,b, extracting peak tensions.

Heuler and Klätscke [14] describe how standardised load spectra and load-time histories have been generated and used in various industries to assess the fatigue behavior of structures and components when simple constant amplitude assumptions/data do not provide a sufficient level of confidence. This is particular the case if the load spectra significantly differs in amplitude and mean-stress variations compared to constant amplitude loading and in the case of multiaxial loading. As a result, a number of standardised load-time histories (SLH) are in use, which cover the representative fraction of the expected in-service spectrum to facilitate fatigue analysis. Standardised load sequences and load time histories have been proposed for aircrafts (TWIST, FALSTAFF), helicopters (HELIX), cars (CARLOS), wind turbine blades (WISPER/WISPERX) and offshore structures (WASH). It is intended within this research to use the WASH method [15, 16].

In order to complete the testing within justifiable time and cost budgets, the load signal is usually reduced and if possible accelerated. Accelerated testing cycles the items under more severe stresses compared to the expected normal operation which leads to earlier failures and hence reduced testing periods. It is important, that the failure mode of normal operation and accelerated conditions stays the same [17]. Escobar and Meeker [18] distinguish four general possibilities that can be applied to accelerate reliability tests, by increasing the following characteristics:

i. Use rate of the component , e.g. increased load cycle frequency
ii. Radiation exposure intensity, e.g. increased UV radiation
iii. Aging rate of the component, e.g. increasing the chemical degradation process through higher levels of humidity

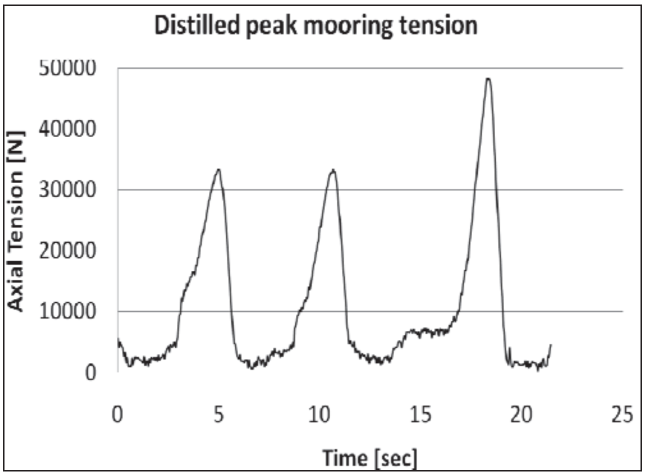

Figure 12. distilled tension signal of three peak loads for accelerated testing

iv. Test stress levels, e.g. increased load force ranges compared to normal operating conditions

It must be noted that failure mechanisms are not always independent of cycle frequency. An important example is corrosion fatigue, as the crack growth is heavily dependent on cycle frequency and corrosion is a function of time. Accelerated frequency tests of this failure mechanism would overestimate the fatigue life (regarding the number of load cycles) of the component since the effect of corrosion is decreased over the shorter test times, by the higher cycle frequencies [19].

The results of accelerated tests may be used in a qualitative or quantitative way [18]. A quantitative accelerated test (QuanAT) has the objective to determine failure distributions (e.g. time to failure or degradation rate). The failure modes are usually already known as well as the accelerating effect on the failure mechanism, based on physical/chemical theory. The test is then carried out for one particular load/stress that is accelerated. The gained information may then be fitted to an acceleration model in order to extrapolate towards 'normal use' loads of the tested item.

In contrast to this, qualitative accelerated tests (QualAT) aim to identify the weaknesses of the tested item in order to subsequently improve the design. The test is carried out for a combination of accelerated stressors. A QualAT can be considered as non-statistical, as the results are used to change the design rather than predicting failure distributions."

To provide an example for a potential QualAT here, the use rate of the mooring assembly can be accelerated when the original load signal is distilled to the most severe load cycles (tensile load force in excess of 30kN). This distilled line tension signal, the corresponding turning points and a possible test rig signal (interpolation between turning points) are shown in figure12. The use of such a test signal could replicate the most severe loads of a 10min field test in 20sec of laboratory test time and could hence simulate one year operational loads under the assumed conditions in approx. 12 days of continuous testing.

The integrity of the mooring assembly can be assessed with magnetic particle inspection to identify surface and near-surface cracks and eddy current testing to monitor the crack growth.

Such a qualitative test could help to improve the mooring design by testing different mooring arrangements and/or materials. It would also strengthen the confidence that the tested assembly will withstand the expected load conditions.

5. CONCLUSION

Dedicated reliability testing of components under operational conditions, using e.g. accelerated reliability testing, does not seem widely adopted in the marine renewable industry. As a result, the reliability assessment of MECs is burdened with high uncertainties which have cost implications due to higher safety factors requirements to avoid early field failures.

For the marine renewable energy sector to emerge successfully from the research and development phase toward commercial-scale deployment, confidence in the economic operation of large arrays is fundamental. Properly specifying the reliability of the device with a reasonable level of confidence is a key element and the testing of components must be an essential goal.

To overcome uncertainties in the reliability assessment of MRE devices a testing approach and the capability of two facilities developed by the research group has been described. Loads that are experienced in the field through prototype testing, or through information from MEC developers, could be used to replicate load conditions for accelerated testing and ultimately evaluate the operational failure rates of component.

Adopting such a testing approach might be time- and capital expensive, but provides a possibility to assess and demonstrate the component reliability of MECs before they are deployed. As a consequence components can be improved prior field installation, where failures would result most likely in prohibitively high costs, in particular in the case of array configuration with numerous devices.

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