Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability
229(5):403–416

DOI:10.1177/1748006X15580837
http://mms.sagepub.com

Component reliability test approaches for marine renewable energy [*]

Philipp R. Thies[†] and Lars Johanning
University of Exeter, College of Engineering, Mathematics and Physical Science (EMPS), Renewable energy research group, Penryn Campus, Treliever Rd, Penryn, TR10 9FE, UK

Kwaku Ampea Karikari-Boateng, Chong Ng and Paul McKeever
Offshore Renewable Energy Catapult (ORE Catapult), Offshore House, Albert Street, Blyth Northumberland, NE24 1LZ

Abstract

An increasing number of marine renewable energy (MRE) systems are reaching the stage where a working prototype must be demonstrated in operation in order to progress to the next stage of commercial projects. This stage is often referred to as ’valley of death’ where device developers face the challenge to raise capital needed to demonstrate the prototype. The dilemma is that investors understandably demand a proven track record and demonstrated reliability in order to provide capital. One way to resolve this dilemma is specific component reliability testing that not only satisfies investor expectations but holds the potential to improve and de-risk components for MRE.

This paper gives an overview to different component reliability test approaches in established industries and for marine renewable energy, covering both wave and tidal energy technologies. There has been notable activity in the research community to develop and implement dedicated component reliability test rigs that allow the investigation and demonstration of component reliability under controlled, yet representative conditions. Two case studies of physical test rigs will illustrate the possible test approaches. The Nautilus Powertrain test rig, a facility at the Offshore Renewable Energy (ORE) Catapult, focuses on the demonstration and testing of drive train components including gearboxes, generators, mechanical couplings and bearings. The Dynamic Marine Component test rig (DMaC) at the University of Exeter aims to replicate the forces and motions for floating offshore applications and their subsystems, including mooring lines and power cables.

---

[*] This version is the author’s manuscript of the published article. Please cite the published version as: Thies PR, Johanning L, Karikari-Boateng KA, Ng C, McKeever P. (2015). Component reliability test approaches for marine renewable energy. Proc IMechE Part O: Journal of Risk and Reliability, Spec. Issue, Vol. 229 (5), pp. 403-416, DOI:10.1177/1748006X15580837.

[†] Corresponding author; e-mail: P.R.Thies@exeter.ac.uk

The paper highlights the relevance of component testing and qualification prior to large-scale commercial deployments and gives an insight to some of the test capabilities available in the sector. Several case studies illustrate the component test approach for tidal energy (Nautilus) and wave energy (DMaC) applications.

Keywords
Reliability, Maritime risk, Maritime system reliability, Physics of failure, Reliability engineering, Reliability optimisation, System failure modelling, Component testing, Offshore renewable energy, Review

Contents

1 Introduction **2**
1.1 Technology development stages . . . 3
1.2 Risk perception . . . 3

2 Reliability prediction and component testing **4**
2.1 De-risking and reliability growth . . . 5
2.2 Component testing for marine renewable energy . . . 7

3 Nautilus Powertrain Test Rig **7**
3.1 Facility Overview . . . 7
3.2 Addressing drawbacks and trends . . . 9
3.3 Typical testing Activities . . . 9
3.4 Case study 1 - Atlantis AR1000 . . . 10
3.5 Case study 2 - Siemens/MCT 1MW tidal turbine . . . 11

4 Dynamic Marine component test rig (DMaC) **11**
4.1 Description and capabilities . . . 11
4.2 Case study 3 - Marine power cable . . . 13
4.3 Case study 4 - Mooring tether . . . 14

5 Discussion and Conclusion **15**

References **17**

1. Introduction

The long-term potential for wave and tidal technologies is estimated to be up to 10% of worldwide electricity consumption (1), with up to 20GW capacity planned in the UK. The driver to go offshore is the access to additional energy resources and the creation of a new industry. If successful, the marine energy industry for the UK could be worth as much as £6.1bn per year, creating up to 19,500 jobs and is forecasted to make a considerable contribution to the UK economy in the order of £800m GVA per year by 2035. The wave energy resources in the UK could supply an estimated 40-50TWh/year (2) of electricity by 2050 (approx. 10% of present UK demand). This renewable energy supply would increase the energy security of the UK, would help to alleviate issues of fluctuating supply and grid stability and would contribute to carbon emission reductions in the energy sector.

However, the sector is facing challenging operating environments leading to lower plant availability and higher operational costs than conventional means of generation. The levelised cost of electricity generated by early commercial marine energy farms are estimated (3) to be about 20 p/kWh (tidal) to 33 p/kWh (wave) more expensive than onshore wind (ranging between 9-10.5 p/kWh). The strike prices for tidal stream and wave energy under the Contract for Difference (CfD) in the UK is set at 30.5 p/kWh for the first 30MW of each project (4).

1.1. Technology development stages

Amidst considerable logistical challenges that are being addressed by the offshore wind industry (5) there is large uncertainty regarding the long-term behaviour, durability and reliability of assets with a typical expected lifetime of 20 years. The challenge is to build reliable, yet cost effective systems. Improving device reliability is one of the key target areas for cost reductions (2) as this will not only improve availability and annual yield, but reduce costly maintenance interventions.

This stage of MRE technology development where a number of full-scale prototypes have to be proven in a commercial setting to operate reliable and cost-effective is commonly dubbed as ’valley of death’. More precisely there are two dry valleys to cross during the technology innovation cycle (6):

- The *technological* valley of death lies between the initial innovation (R&D) phase and the prototype/proof of concept.
- The *commercialisation* valley of death has to be faced in a later stage of the development where a working prototype has to be demonstrated within early commercial projects.

In order to cross both valleys ’alive and well’ the technology developer requires investments of moderate amount (£500 - 5m) for the technological valley and considerable amount for commercialisation (in the order of £10-50 million) (7).

“Both valleys of death exist due to a perception of risk and a scarcity of appropriately matched risk capital in the energy technology market. Because of these barriers, many advanced and innovative energy ventures fail to reach commercialization, and as a result, potentially transformative innovations are never introduced into the marketplace.” (6, p.6).

1.2. Risk perception

The reliability of marine renewable energy is often stated as being one of the largest risks for the commercial development, see e.g. (8, 9). The term reliability is often tainted by an informal, almost binary judgement (yes/no). For this reason we start with a brief definition and description of the concept to be clear what the testing described in this paper tries to achieve. The formal reliability adopted in standards such as ISO8402 is:

> **Reliability**: “The ability of an item to perform a required function, under given environmental and operational conditions and for a stated period of time”

Reliability is intrinsically tied to common performance parameters, such as safety, availability, maintainability which are e.g. discussed in (10). It is important to note that reliability is not a given property of the device itself but is governed by the “given environmental and operational conditions”. It should be also noted that ’ability’ is understood as a probability that the required function can be achieved. As a result reliability engineering is in fact both understanding of the physical/engineering aspects as well as a statistical representation of the problem (11).

Traditionally, high reliability was achieved through high (yet sometimes unknown) safety factors. However, safety factors that are not justified, by e.g. catastrophic consequences such as the loss of life, are essentially a cost bearing overdesign. The challenge for the reliability of marine renewable energy is to provide reliable generation systems in harsh environments, that must be highly cost-effective in order to be financially viable.

The dilemma is that without proven reliability and availability the uncertainties and risk quantification for pilot and early commercial projects is not possible to an accurate enough level to satisfy and convince investors during their project appraisal. This leads to the situation that due to the upper bound of uncertainty, the risk is perceived as too high for investment. Yet, without investment both uncertainty and risk are difficult to reduce. This situation can be resolved by relatively risk-neutral funding (such as public investment) or dedicated reliability testing of the most critical components and subsystems.

This paper provides a review of component reliability test approaches (section 2) employed by other industries to reduce both the perceived risk of investors and the actual risk of field failures. It is argued that a similar approach will be beneficial for the marine renewable sector. Case studies for both tidal (section 3) and wave applications (section 4) are presented, offering an insight into ongoing component reliability testing prior or in conjunction with commercial deployments. The key findings and conclusions are discussed in section 5.

2. Reliability prediction and component testing

Reliability predictions offer the decision maker a wealth of information during the design and qualification of a product or technology (12). This includes the identification of design weaknesses, comparison of design alternatives, data provision for reliability and availability assessments as well as informing operation and maintenance strategies.

Even though reliability predictions are necessary, they may be the subject of considerable criticism due to two main limitations (13). Firstly, the failure rate models are point estimates, based on available data. Therefore, in a strict sense they are only valid for the assessed system and the environmental and operating conditions that prevailed during the data collection. For example, the deviation of field failure rates from reliability predictions is found to be small for ground electronics whereas significant errors occur for aviation applications due to differing environmental stresses (14). Similarly to this, failure rates are also influenced by factors like operational characteristics, maintenance regimes, measurement techniques and failure definitions. As a conclusion "a reliability prediction should never be assumed to represent the expected field reliability as measured by the user" (15, 3-2).

The second limitation is the continuous industrial development of new materials, components and processes that impede accurate reliability predictions. Assessments that are based on past data ignore any reliability improvement that might have taken place. Thus, past data for future reliability predictions tend to result in more pessimistic failure rates, i.e. would lead to a more conservative system design.

However, if these shortcomings are recognised reliability predictions are a valuable tool to support decision making, to improve the design and to increase the overall reliability of a system. Available reliability prediction techniques can be classified into three distinct types (16):

Statistical ’bottom-up’ methods are based on component failure data that has been collected during operation in service or component testing and is subsequently statistically fitted to establish a component failure rate distribution. This approach is widely used and a range of statistical methods is available (17).

Physics of failure (PoF) methods for reliability predictions combine the knowledge about component loading and potential failure mechanisms to estimate component reliability (18) in a ’bottom-up’ approach. The governing failure mechanisms are modelled based on the fundamental physical principals. The failure mechanisms comprise the full spectrum of structural, mechanical, electrical, chemical and thermal processes (19). A prominent example where the Pof approach has been implemented is The Mechanical Reliability Handbook (20). It covers different failure modes for seals, valves, bearings, pumps and electric motors. Based on quantitative estimates of stresses and associated material behaviour, the expected failure mechanisms are quantitatively modelled through engineering equations for every part/component/subsystem.

Top-down similarity analysis is appropriate when extensive, often proprietary, reliability databases are available. The concept involves the comparison of existing (sub-) systems with the new development. Thus the the reliability track-record of existing components is used to estimate the reliability of a similar system or product (21, 22).

Table 1. Comparison of reliability prediction methods, based on (16)

Method	Data input	Accuracy	Required resources
Bottom-up statistical	Component type, count and quality level; operating environment; system environment	Relative	Small
Top-down similarity	Failure rates of similar components, main differences	Absolute	Medium
Bottom-up physics of failure	Material- and design properties, assembly process, loading and operating environment	Absolute	Large

Component reliability testing has to be carried out in order to gain specific reliability information required in all three approaches. Table 1 compares some of the main criteria. The bottom-up statistical methods require the least detailed information and can be performed with relative ease, but do not offer an absolute reliability estimate. The top-down reliability approach necessitates detailed information of similar components and systems to be conducted while the Pof approach is based on the understanding of the fundamental failure mechanisms and load characteristic for each individual part. These more complex approaches offer an absolute reliability estimate but require comprehensive information.

2.1. *De-risking and reliability growth*

The endeavour to improve reliability levels is one of the core engineering activities. Duane (23) devised a method to monitor and predict reliability growth (which is since called the Duane plot). He realised that different mechanical and electromechanical systems in aircraft applications (such as generators, hydraulic systems and jet engines) follow a similar learning pattern, evoked by efforts to reduce component and system failures. On a log-log scale the relationship between cumulative failure rate and the cumulated operating hours showed to be linear. The reliability growth concept mainly applies for items that are in the development stage. As such it is noted that “(e)arly test data will never be entirely representative of operational conditions, but the closer it simulates such conditions, the better will be the accuracy of extrapolation from test curves to operational data (23, p.565).” This gave the justification to extensive reliability test programmes that would simulate the operating environment in order to reduce the failure rate (i.e. improve reliability). This section will give a brief overview to relevant examples from the automotive, aviation, electronics and wind energy industry:

Automotive industry One of the first engineering products for which reliability data was systematically collected and analysed was the automobile (24, 25). Modern cars must come to market quickly, whilst they are more reliable and less costly than previous models. A statistical approach, i.e. the collection of sufficient reliability data, is time intensive. As a result, reliability tests are often accelerated. Porter (26) devises an accelerated reliability qualification using a failure mode verification test, which qualitatively ensures that the design is suitable for the environment and will reach an acceptable product lifetime. A method to test and quantify the achieved reliability growth test is described in (27), classifying siuations in which reliability verification tests may satisfy the requirements as opposed to a full reliability growth test.

Aviation industry Realistic flight simulation tests for fatigue testing have been used in the aviation industry for several decades (28, 29). Reported tests include specimen, component and full-scale testing. These tests are typically accelerated aiming to reproduce the expected accumulated fatigue damages in service within practicable test duration. An example of subsystem validation testing is reported by (30, 31) who developed an Optical System and Component Assessment Rig to evaluate the through life operation of fibre optic communication systems in aircraft.

Electronics Accelerated testing is also a standard practice in the electronics industry (32, 16) that lead to the development of acceleration models describing failure mechanisms due to use rate, temperature, humidity, UV light and voltage levels. An example where a smart electricity meter is exposed to these stressors in accelerated tests in order to predict the system reliability is reported in (33).

Wind industry The most critical wind turbine components have also been extensively tested to improve their reliability. Composite turbine blades are complex components that are now routinely tested structurally to validate their integrity regarding static and dynamic fatigue loads, to calibrate associated finite element simulations and to determine governing failure mechanisms (34, 35, 36). Similarly, gearboxes have attracted much attention through combined numerical and full-scale experimental investigations as described in (37, 38). A dynamometer test rig typically allows brake and control system tests, power converter functionality tests, as well as gearbox and bearing test regarding structural integrity and long-term endurance behaviour.

The common aspect across the different industries is the attempt to de-risk systems through test-led reliability improvements. Depending on the technology readiness level (TRL) the tests are informed by numerical models and theoretical calculations (TRL 0-2); early, small scale measurements (TRL 3/4), large-scale prototype information (TRL 5/6) or field test/operating conditions (TRL 7-9). Along those different scales and technology levels, the physical reliability tests provide a range of information and serve distinct purposes.

Prototype / Functional testing - Testing of an early prototype, where the focus is on demonstrating the working principle, rather than reliability.

Calibration testing - Physical testing to inform, improve and verify existing numerical models.

Validation / performance testing - These tests aim to confirm an expected system or component characteristic, typically performed in real-time.

Comparative testing - Direct comparison of different component / design solutions under similar load conditions.

Reliability testing - Tests focus on the understanding and quantification of failure mechanisms, wear- and degradation behaviour.

Each of these test types typically comprises at least four steps for a realistic reliability test (39), including i) Modelling/Measurement of realistic load data, ii) Identification of representative load regimes, iii) Physical testing of representative specimens/load regime on a laboratory test rig, iv) Result (failure) analysis, root cause identification and statistical evaluation.

The laboratory tests are typically performed on a purpose build test rig that subjects the component under investigation to the representative load regime. In order to complete the testing within justifiable time and cost budgets, the load signal length 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 (40). Reliability tests may be accelerated by increasing any of the following characteristics (32):

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

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

It is argued in the following that dedicated reliability testing for marine renwable energy is needed in order to de-risk these technologies prior to commercial applications. Some important efforts specifically targeted at the marine renewable applications have been made which will be described in the following section.

2.2. *Component testing for marine renewable energy*

As reliability is increasingly the key concern for marine renewables (41, 42) a number of applications have been reported that aim to tackle this formidable challenge for wave and tidal devices. Referring back to TRL levels, the most developed technologies have reached the pre-commercial level of TRL7 (Demonstration system), striving to proceed to commercial levels TRL8/9. Whilst most of the potential failure modes and operating conditions have been identified (42), the actual (long-term) load conditions in the field are not well understood, due to a lack in field experience and the associated component/system reliability is thus difficult to predict.

One of the first proponents for dedicated component test rigs for MRE was Salter (41, 43) who wanted to “provide a facility to expose (…) any new components and subassemblies at sea before they are chosen for use”. His design of a floating platform was ambitious as it aimed not only to replicate the load conditions but also the marine environment of several components at once, including steel girth, seals, cables, belts, hydrofoils, anti-fouling coatings and electric enclosures, but was not realised.

The subsystem and component tests that have been reported in the literature are classified and summarised in table 2. Whilst there is a considerable number of specific tests reported, the majority of applications focusses on performance/validation testing of power take-offs and electrical control systems. Whilst this is by all means necessary, only few reliability tests are reported that aim to degrade and/or fail the component in question. The following sections will illustrate the test capabilities and conducted tests at the ORE Catapult’s Nautilus Powertrain Test Rig (section 3) and the Dynamic Marine component test facility (DMaC) at the University of Exeter (section 4).

3. Nautilus Powertrain Test Rig

3.1. *Facility Overview*

The Nautilus powertrain test facility was constructed with funding from the European Union’s European Regional Development Fund (ERDF) and the UK Government’s Department of Energy and Climate Change (DECC) to de-risk the marine renewables industry by promoting confidence through the process of testing, validation and certification. The rig is capable of testing subsystems of tidal turbines such as the powertrain and its components such as gearboxes, bearings, generators and the power converter.

The Nautilus powertrain test facility is a dedicated test rig for testing and validating components, subsystems, systems and the entire nacelle of tidal turbines. The test rig is capable of loading a turbine’s nacelle using a full envelope of load cases. Contrary to most test setups in other industries, the test rig’s capabilities stretch across several fields including mechanical, electrical and electronic, and control. The prime mover, which weighs almost 60 tonnes, is designed to develop a high torque with excellent speed accuracy to meet the demands of the test programme. The 40m long, 14.5m wide and 13m high test facility can accommodate the test piece nacelle inside the test facility as well as the option to test a nacelle outdoors.

Table 2. Overview on reported component and subsystem testing for marine renewable energy

Subsystem	Test rig	Application	Test type	Reference
Control	*HMRC* 22kW Rotating test rig	Dry test electrical/control system	Validation/Performance	(44)
Control	*Tecnallia* Hardware-In-the-Loop (HIL) test bench	Emulation of wave energy converter	Validation/Optimisation	(45)
Power take-off	Pelamis full-scale hydraulic test rig	Hydraulic power take-off system test	Perfomance and Validation	(46, 47)
Power take-off	Aegir Dynamo 55kW linear test bed	Simulated wave force conditions	Performance test	(48)
Power take-off	*HMRC* 22kW Rotating test rig	Efficiency and power quality of Wells turbine	Optimisation	(49)
Bearings	Linear bearing test rig	Accelerated wear of polymer bearing materials	Comparative/Reliability	(50, 51)
Materials	*IFREMER* Materials in Marine Environment Laboratory	Durability of natural rubber in sea water	Reliability	(52)
Materials	*IFREMER* Materials in Marine Environment Laboratory	Accelerated aging tests composites tidal turbine blades	Reliability	(53, 54)
Moorings	*TTI* tensile test rig	Nylon fibre rope tests for wave energy converters	Compliance/Fatigue	(55)
Moorings	Dynamic Marine Component test rig (DMaC)	Simulated operating load conditions	Performance/service simulation	(56)
Nacelle & Drivetrain electrical system	Nautilus Powertrain Test Rig	Performance validation and accelerated life testing for tidal turbines	Validation/Endurance	(57, 58)

3.2. *Addressing drawbacks and trends*

One of the key drawbacks for utilising component reliability databases such as OREDA (59, 60) or formulations given by (61) is that failure rates may not be fully representative. Often, a crude adjustment factor is applied to account for the possible disparities in failure rate (62, 63). Fully representative failure rates may be obtained when the representative infield loads are applied on components. Heege et al. (64) have shown that component loads are dependent on the dynamic behaviour of an assembled wind turbine. A major advantage offered by the Nautilus full-scale test setup is the ability to test an assembled nacelle as a whole. Often, the dynamic behaviour of components when coupled together means testing components in isolation may achieve misleading results. Furthermore, some competing component failure modes may be overlooked by testing components in isolation.

A common trend observed for testing components such as gearboxes is the use of a back to back (65) gearbox configuration for torque only verification of reliability. Converse to these practices, (38, 66) have pointed out that non-torsional loads are key contributors to failures. One of the distinctive features of the Nautilus test rig is the ability to apply non-torque loads. Mechanically, the test rig aims to replicate the 6 degrees of freedom (6 DOF) dynamic loads on a turbines' main shaft. This is achieved through the use of a Dynamometer and a Force Application System (FAS). The functionality of the FAS is key to the test facility and differentiates it from conventional rotary test facilities. The FAS applies typical and extreme forces and moments that the marine environment will exert on a tidal turbine device in service. The Dynamometer is coupled to a step-down gearbox and is driven by a variable speed drive to supply a maximum input power of 3MW. Non-torque loads are applied through the FAS. The FAS can be operated in 'position mode' or 'force mode', thus force or displacement at a given point may be used as input loading. The gearbox is connected to the FAS through a flexible coupling to avoid non- torque loads being transmitted back to the gearbox. The general control schematic of the test facility can be seen in figure 1 a fish-eye view of the installation setup is shown in figure 2. The functional capabilities are listed in table 3.

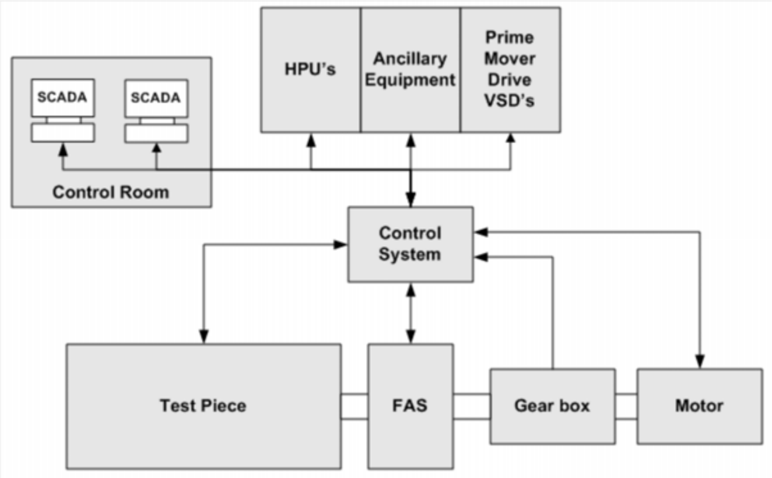


Fig. 1. Control Schematic - Nautilus Test facility

3.3. *Typical testing Activities*

The wide range of capabilities of Nautilus enables customers to target specific components or systems to be tested. Some typical tests which may be carried out in the test facility include:

- Functional test

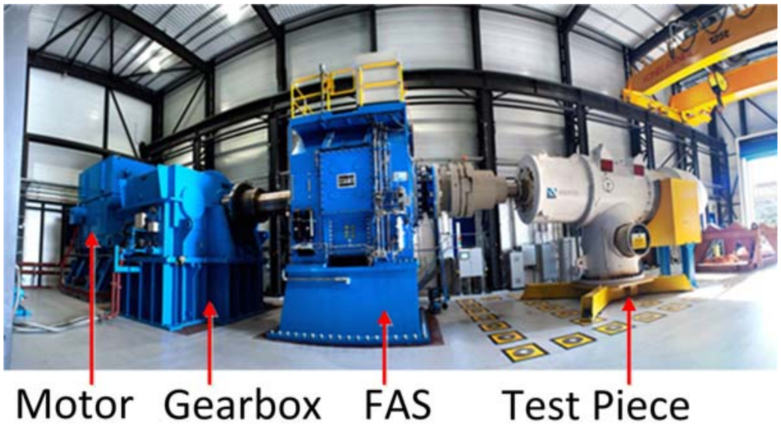


Fig. 2. Typical test setup for Nautilus test rig

Table 3. Functional Capabilities of Nautilus Test Rig

Parameter	Value
Maximum input power to test piece	3 MW
Maximum torque	5 MNm
Operating shaft speed	± 30 rpm
Maximum instantaneous torque	10 MNm
Maximum bending moment	15 MNm
Maximum axial thrust	4 MN
Facility crane capacity	125 tonnes
Recirculation voltage	11kV
Customer data acquisition system	400 channels

- Thermal characterisation
- Performance testing
- Efficiency evaluation
- Extreme load validation (including transient events such as: brake deployment; grid loss; overspeed; torque reversal)
- Control system testing, verification and tuning
- Power quality assessment
- Simulated grid faults, low voltage ride-through (LVRT)
- Reliability tests
  - Screening tests
  - Highly accelerated life test (HALT)
  - Accelerated life test (ALT) / Endurance test

The Nautilus test facility at ORE Catapult's National Renewable Energy Centre can compress many months of tidal exchanges down to a testing programme lasting a matter of days and this gives developers in the UK an advantage on their development to commercialisation. Below, two of the tests conducted in the Nautilus facility are discussed. Due to the client confidentiality, all the details of the case studies shown below were gathered from information already in the public domain (67, 57, 58).

3.4. Case study 1 - Atlantis AR1000

In 2012, Atlantis Resources Corporation (ARC) became the first tidal current power device developer to undergo full scale nacelle testing in the laboratory environment offered by the Nautilus test rig. This followed the deployment of the prototype device in the field. Testing in a laboratory environment as opposed to field conditions enabled key reliability aspects to be tested in a controlled manner. The aim of testing was highlighted as follows:

- Complete commissioning on all third party supplied equipment
- Provision of thermal characteristics of the power train components
- Study the performance of the brake and optimise its use within the automated control system
- Subject the turbine to mechanical loading up to design load conditions to ensure that the system is fully functional
- Carry out control system testing to observe the automated control system behaviour and tune the algorithm
- Conduct accelerated lifecycle testing on the turbine to provide valuable running hours of data from the turbine (as requested by the industry)

In two weeks' of full testing on its AR1000 turbine ARC has secured performance data equivalent to four months of tidal exchanges (68).

3.5. Case study 2 - Siemens/MCT 1MW tidal turbine

Siemens-owned Marine Current Turbines (MCT) underwent an 11-month long testing programme of its first 1MW power-train using the Nautilus test facility. The testing focused on key subsystems required for reliability such as the powertrain, power electronics and grid connection. During the testing, the test piece demonstrated its performance at full load for an extended period of time. Among the several tests that were carried out, a major part of the testing focused on an accelerated endurance test which compressed the 20-year life of the turbine into a 6-month testing programme. The endurance testing yielded performance data equivalent to over 18 years of operation. The utilisation of the FAS during the endurance testing ensured that loads applied were realistic and comparable to loading experienced in the subsea conditions.

4. Dynamic Marine component test rig (DMaC)

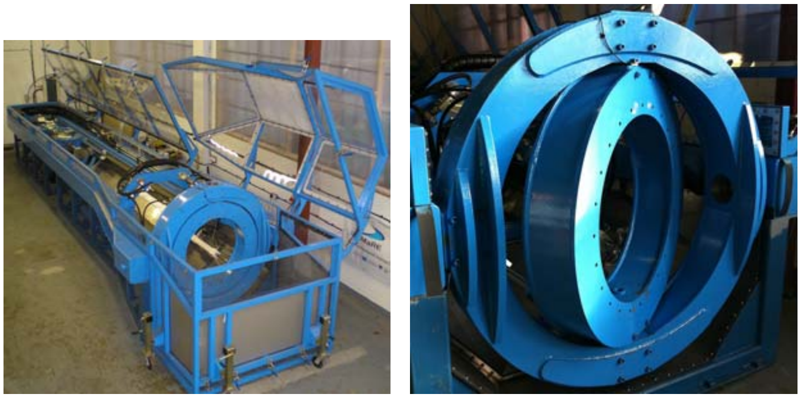
A simple tensile test is not sufficient to investigate the particularities of wave energy converters. Evidence gathered in field tests, such as the South West Mooring test Facility (SWMTF) (69, 70), suggests that at least three degrees of freedom are required to replicate the dynamic mechanical load regime that the components connected to a floating body are subjected to. The component test rig described in the following has been developed to replicate the dynamic movements of mooring assemblies and other components/subsystems in order to assess the reliability implications of operational field loads.

At the heart of the design requirement for any component test rig lies the test cycle that can be performed. “A cycle with a high degree of simulation is more complex and is closer to the actual conditions of use (...). A high degree of simulation is recommended when the outcome of the test is crucial, for example, when failure consequences are critical in terms safety and economic loss (...)” (71). The distinct features of the Dynamic Marine Component test rig (DMaC) that allow a high degree of simulation are:

1. Three degree of freedom (3DOF) moving headstock, replicating realistic dynamic load cases
2. Linear hydraulic actuator providing fast-acting axial loading.
3. Test specimen can be immersed in water.

4.1. Description and capabilities

An overview of test rig and a close-up of the headstock is shown in fig. 3. The forces generated and applied are fully reacted by the frame. The frame itself is approximately 10m in length with an adjustable test bed length between 1-6m. The frame is surrounded by a sealed outer housing and Polycarbonate safety cover.



(a) Assembled machine (b) Gimble system, tilted inner ring

Fig. 3. Dynamic Marine component test rig

The moving headstock is realised through a two-plane-gimble system. The inner gimble is pivot-mounted to the outer gimble ring, which itself is pivot-mounted to the main frame of the rig. Figure 3(b) shows the assembly arrangement for the gimble system. The outer ring is pivoted on the horizontal axis and thus performs the y-bending, while the inner ring is pivoted on the vertical axis and conducts the x-bending movement. Each axis has an angle encoder fitted to monitor and control the angular position of both rings.

The rings are driven by four hydraulic actuators which are pivot-mounted on the inner ring and are reacted by the brace of the headstock. The superposition of linear displacements by the hydraulic actuators achieves the desired angular motion of the inner and outer ring. The maximum angular displacement of the two gimbles is $\pm 30\,^{\circ}$, with a frequency of $f = 0.25$Hz, exerting a maximum off-axis bending moment in relation to the center point of $M_{max} = 10kNm$. The dimension of the test specimen is constrained by the brace at the headstock, allowing a maximum diameter $D_{max} = 800mm$.

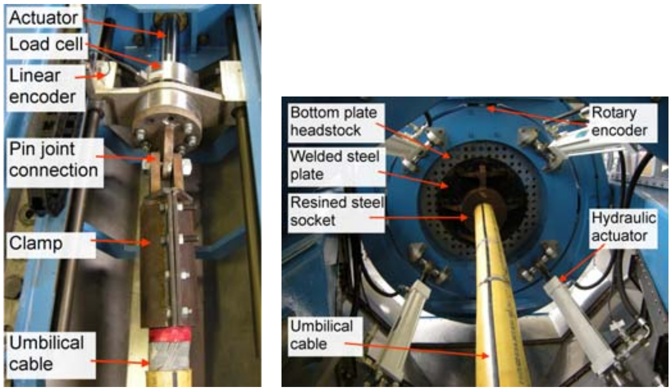
At the other end of the rig, the linear z-force is applied by a single hydraulic actuator, which is mounted on a moveable trolley that is bolted down to the main frame at the desired position. In this way the available test bed can be varied in length to accommodate different specimen lengths and/or to allow potential pre-loads. The key functional parameters are listed in Table 4. The main limiting factors are the maximum displacement stroke of 1m and a maximum applicable force of 45 tonnes in static conditions and 25 tonnes under dynamic conditions. The rig can be operated in two distinct modes in which either the force exerted on the specimen or the displacement is chosen as the control parameter.

Table 4. Functional capabilities of Dynamic Marine Component test rig

Parameter	Value
Maximum stroke	1m
Maximum headstock angles	$\pm 30^{\circ}$
Maximum Dynamic Force	25 tonnes
Maximum Static Force	45 tonnes
Maximum Bending moment	10 kNm
Pre-load force	14 tonnes
Maximum specimen length	6 m
Maximum specimen diameter	800 mm
Maximum specimen weight	1000 kg

4.2. Case study 3 - Marine power cable

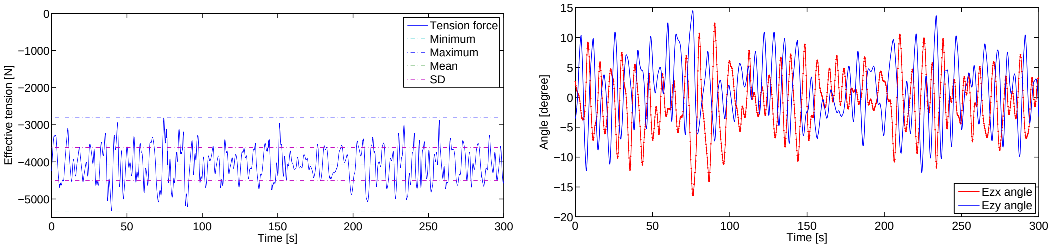
A critical component for all floating offshore installations is the umbilical that passes through the water column and provides an electrical and/or hydraulic connection. The mechanical load conditions for marine renewable energy are likely to be highly dynamic and well outside the load envelope that umbilical cables have been previously designed to (**?**). The DMaC has been used to apply realistic two degree of freedom load regimes to a marine power cable. The test setup is shown in fig. 4



(a) Linear actuator (b) Moving headstock

Fig. 4. Experimental set-up with marine power cable fitted to test rig

The input load data was provided by a numerical model for a floating wave energy converter to which a marine power cable in lazy wave configuration is attached, a similar model is described in (**?**). The modelled time series of mechanical loading imposed on the cable near the attachment point are used as input parameters for the service simulation test of the cable, an excerpt of the timeseries is shown in fig. 5. The negative values in fig. 5(a) denote the tensile force experienced by the cable section which varies between -2.8kN and -5.3kN (the rig convention denotes tensile forces as negative). The tension force and bending motion are both highly cyclic. An excerpt of the force signal and the bending angles, which are combined to drive the rig, are depicted in fig. 5(b).



(a) Force (b) Headstock angles

Fig. 5. Umbilical service simulation test signals, showing the effective tension force 5(a) and the associated headstock angles 5(b) for cable section below bend stiffener

In order to assess the simulation accuracy, four identical tests have been carried out. The correlation plots of the head-stock angles for the Ezx-angle (y-axis) are given in Figure 6. Points above the ideal correlation line $Y = X$ show that the measured parameter is below the value that was requested by the input signal. In analogy, points below the perfect fit line show that the measured value is above the one requested. For both angles (y and x-axis) the input signals were well replicated with correlation coefficients between 0.996 and 0.998. Similar tests will have to be carried out over substantially longer durations in order to verify the long-term integrity of power cables deployed in such conditions.

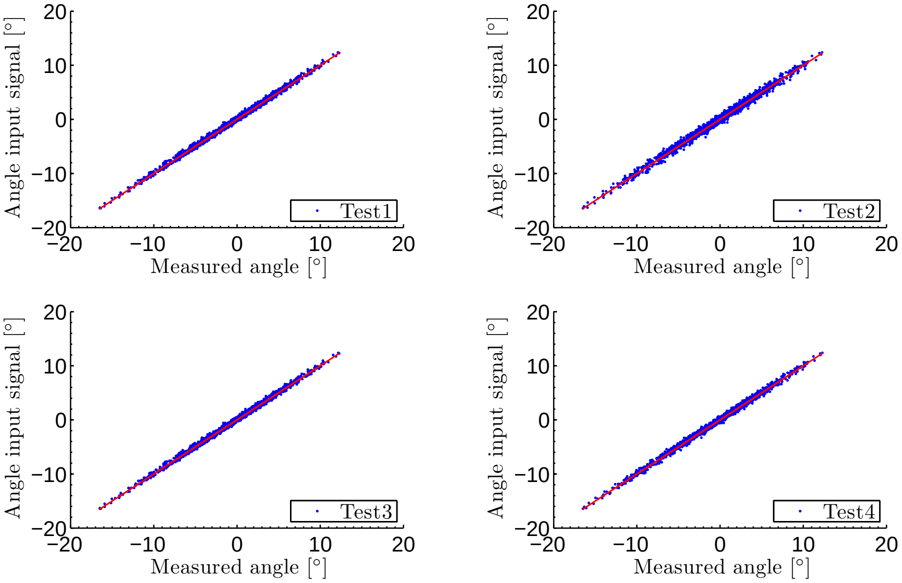


Fig. 6. Correlation plots of input signal and measurement for Ezx-angle (y-axis)

4.3. Case study 4 - Mooring tether

Mooring systems for MRE have to be highly reliable to warrant safe station keeping of devices whilst being as cost-effective as possible. For offshore oil and gas applications extensive component tests are commonly performed to validate the long-term reliability for offshore moorings. Specific operational conditions like the tension-torsion fatigue behaviour of wire ropes have been quantified by (72), while (73) engages in detailed examination and tensile testing for internal wear. The damage-tolerance behaviour of mooring ropes is physically tested and assessed in (74). These tests apply traditional tension testing to determine component reliability under specified load conditions.

Novel mooring solutions for MRE typically offer lower lifecycle cost, but are in need of thorough testing to ensure performance and reliability levels are adequately met. One such test was performed for a novel mooring tether, a technology developed by Technology for Innovation. The tests are fully reported in (56) and will be summarised here in the context of component testing. The tether offers an elastic, ’soft’ load response using an elastomeric rubber material together with a region of much stiffer response, utilising the properties of thermoplastic compression elements (see Fig 7) and is in more detail described in (75). The main objective of the test was to validate the working principle and the performance characteristic of the tether in a wave energy application. Five different test regimes were carried out:

Performance tests To establish a reference case before, during and after the tests, load-extension curves were measured, cycling the tether to its maximum extension. This performance test was repeated throughout the entire test programme to assess potential performance variations.

Hysteresis amplitude testing The stress-strain response at non-zero pre-tension levels was measured for a range of different amplitudes. From a zero displacement position the tether was pre-tensioned to specific target displacements to assess the influence of the amplitude on tether hysteresis.

Hysteresis frequency testing These tests measured the hysteresis behaviour of the tether for varying wave frequencies/periods at different pre-tension levels.

Extreme ansd storm condition testing To validate the tether performance in extreme sea states, these tests included a combination of extreme load cycles in the elastomeric/thermoplastic transition region as well as storm sea conditions using the load signal from a 3-hour numerical simulation.

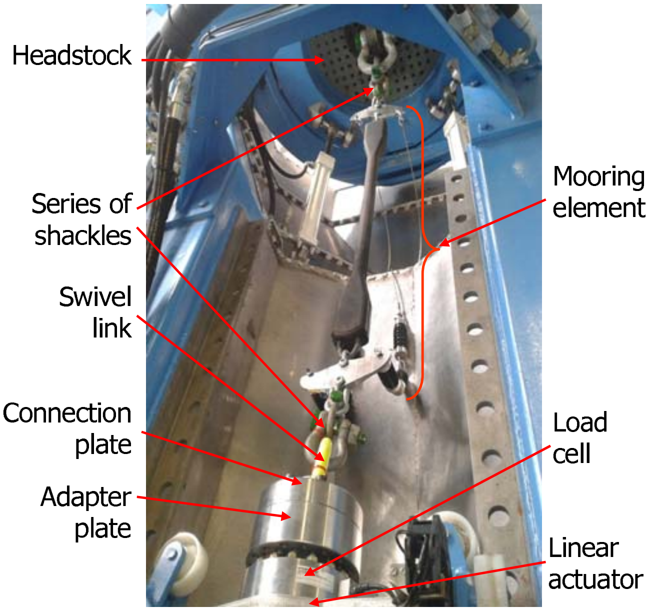


Fig. 7. Technology for Innovation (TfI) mooring tether during performance and service simulation test at Dynamic Marine component test rig (DMaC) at University of Exeter

Endurance tests These tests applied accelerated load levels to give an indication of the long-term behaviour of the mooring element.

The tests demonstrated the working principle of the tether under realistic, nonlinear load conditions and were also able to reveal a design issue of the connectors used for the prototype which could then easily be mitigated.

5. Discussion and Conclusion

This paper has reviewed different reliability prediction approaches and how component reliability tests may be used to inform and improve reliability estimates for the marine renewable energy sector. The perceived investor risk that epitomises the commercialisation ’valley of death’ is largely due to the fact that (long-term) field experience for marine renewables is scarce and that the ratio of risk/return is larger than in say offshore oil and gas. Nevertheless, resource estimates and projections do hold a valuable return on investment in the mid-long term. To achieve a satisfactory ratio, the risk and uncertainty must be reduced.

The view to other industries, such as the automotive and wind industry, points towards the fact that reliability behaviour can be improved and validated by means of component testing, stepwise de-risking the most critical subsystems and components. There have been promising developments in a similar direction within the wave and tidal sector and a number of case studies have been presented.

Whilst component reliability testing is in principle well suited for offshore renewable energy applications, a number of aspects warrant a critical analysis.

Technology convergence Based on the technology development experience in other industries, a technology convergence facilitates reliability growth and demonstration, as test and development resources have a common focus. Offshore renewable energy has not reached a phase of technology convergence, yet. Offshore wind technology maintains a focus on horizontal axis turbines with variable speed direct drive or gearbox power transmissions. These designs are challenged by large-scale hydraulic transmission concepts, as well as vertical axis concepts, promising benefits for floating installations.

Wave and tidal energy technologies have even less converged to a reference technology. Although tidal energy has a tendency towards horizontal axis turbines, no single technology has claimed the initial stakes for commercial deployments. For wave energy there is a plethora of concepts and working principles, with difficulties to single out a clear forerunner.

As such, it is important to identify common sub-systems and applications that can benefit from a cross-sector reliability testing and improvement effort. Reliability demonstration and testing is particularly difficult, as many of the companies are typically small and medium enterprises involved with relatively limited resources. In this context, rotary drivetrains and dynamic power cables are certainly amongst the generically applicable sub-systems, but technologies and demonstration of moorings, linear generators or hydraulic transmission are also likely to benefit the industry in the long-medium term.

Confidentiality The confidentiality of reliability and failure data is restraining reliability assessments and reliability improvements. It is the norm in a competitive sector, where reliability progress is offering a competitive advantage, and indeed the tests reported in this paper are also subject to these confidentiality agreements. Yet, there are prominent examples where the specific confidentiality has been obeyed whilst improving reliability measures and data quality.

The Offshore Reliability Data (OREDA) (76, 77, 60, 59) project has been collecting equipment failure data in the offshore oil and gas industry since 1981. It was initiated following political pressure from the Norwegion government. It provides information about failure modes, failure rates and repair times. OREDA handbooks are considered to contain high quality reliability data, because the data has been collected over a long period of operational time using a standardised, consistent procedure.

Another successful initiative in generating and utilising a failure statistic and reliability data base is the Scientific Measurement and Evaluation Programme (WMEP) (78), where 1,500 onshore turbines have been closely monitored and reported over a period of 17 years. A similar, yet less extensive database for the operation and failure statistics is being established for offshore wind conditions (79), monitoring the 60MW installation alpha ventus (80).

A comparative initiative for offshore renewables in the UK is the SPARTA project (System performance, Availability and Reliability Trend Analysis), facilitated by the ORE Catapult. It aima to collect all available reliability data for offshore wind applications, in order to improve the data basis. This should assist to indentify and mitigate the most critical risks. It should be noted though, that offshore wind does already posess a considerable installed capacity in excess of 4GW, whilst marine renewable operates tens of MW. Nevertheless, a similar early-stage initiative for wave and tidal energy would be advantageous.

Accelerated testing On a technical level, accelerated reliability tests are often sommoned as a tool of choice to establish reliability information / demonstration within reasonable time and cost boundaries. However, careful judgement and investigation is required in every single application whether accelerated tests are suitable. As a general rule, all accelerated tests are, from a statistical point of view, a form of extrapolation and thus require justification (81) either thruogh pysical models or empirical evidence.

The range of pitfalls that have to be avoided during the design and implementation are described in (82, 83, 84, 85). These include the masked or unrecognised failure modes, the assigned number of test samples, accelerated paramter, correct statistical data interpretation. This experience is not directly available for offshore marine renewable applications and thus has to be established as part of the technology development. In general it should be noted that it is difficult to directly infer field reliability from accelerated tests.

Component testing is capable to validate and assess the reliability of critical subsystems. The close simulation of operating conditions plays an important role in the simulation of field conditions in order to yield an accebtable reliability level. In any case a structured test programme should reduce the failure rate uncertainty. Continued collaboration along the supply chain and with technology developers is needed in order to generate meaningful and applicable results. The Marine Renewables Infrastructure Network (MARINET) initiative, funded as part of the EU 7th Framework programme is a good example of targeted support with direct benefit to both facility providers and end-users (86).

The reported case studies share the feature that they are individual reliability validation/demonstration tests, rather than statistical significant samples, as they are e.g. required to establish appropriate fatigue estimates. The reason is that such tests are time- and resource intensive and will necessitate several years in order to meet the reliability levels of comparable industries. The successful implementation of dedicated test rigs is a considerable step in the right direction. A concerted effort of funding bodies, technology developers, research institutions, certification agencies, insurance companies and investors is needed to successfully de-risk marine renewable energy by means of component testing. Dedicated component reliability tests will not only help component manufacturers to redesign their products according to the expected load envelopes, but will also increase the confidence levels among stakeholders for long-term installations.

Acknowledgement The Nautilus powertrain test facility was constructed with funding from the European Union's European Regional Development Fund (ERDF) and the UK Government's Department of Energy and Climate Change (DECC). The Dynamic Marine component test rig was made possible through funding by the Peninsula Research Institute for Marine Renewable Energy (PRIMaRE) funded by European Union's European Regional Development Fund (ERDF). This work was also partly supported by the Engineering and Physical Sciences Research Council (EPSRC) [grant number EP/I027912/1]. Further for this work was received by the Energy Technoliogy Istitute (ETI) and the Research Councils UK (RCUK) Energy programme for the Industrial Doctorate Centre in Offshore Renewable Energy (IDCORE), [grant number EP/J500847/1].

References

[1] A Lewis et al . Ocean Energy. In: IPCC Spec. Report on Renewable Energy Sources and Climate change Mitigation. CUP; 2011. .

[2] Low Carbon Innovation Coordination Group. Technology Innovation Needs Assessment (TINA) Marine Energy Summary Report; 2012.

[3] Energy and Climate Change Committee. The Future of Marine Renewables in the UK. London: House of Commons; 2012. HC 1624. The Stationery Office Limited.

[4] DECC. Investing in renewable technologies – CfD contract terms and strike prices. Department of Energy and Climate Change; 2013. Available from: `https://www.gov.uk/government/publications/investing-in-renewable-technologies-cfd-contract-terms-and-strike-prices`.

[5] Kaldellis JK, Kapsali M. Shifting towards offshore wind energy. Recent activity and future development. Energy Policy. 2013;53(0):136 – 148.

[6] Jenkins J, Mansur S. Bridging the clean energy valleys of death. Breakthrough Institute; 2011. Available from: `http://thebreakthrough.org/archive/bridging_the_clean_energy_vall`.

[7] Thies PR. Bridging the gap – Market interventions for commercial marine energy deployments. In: BIEE Conference. British Institute of Energy Economics; 2010. Available from: `www.biee.org/wpcms/wp-content/uploads/Bridging_the_gap_market_interventions_for_2010_post.pdf`.

[8] of Commons H. The Future of Marine Renewables in the UK. Energy and Climate Change Committee; 2012. HC 1624.

[9] Magagna D, MacGillivray A, Jeffrey H, Hanmer C, Raventos A, Badcock-Broe A, et al. Wave and Tidal Energy Strategic Technology Agenda. Strategic Initiative for Ocean Energy Ocean (SI Ocean); 2014.

[10] Rausand M, Høyland A. System reliability theory. Models statistical methods and applications. 2nd ed. Series in probability and statistics. Wiley; 2004.

[11] Kanert W. Robustness Validation - A physics of failure based approach to qualification. Microelectronics Reliability. in press;(0):–. Available from: `http://www.sciencedirect.com/science/article/pii/S0026271414002066`.

[12] EPSMA. Reliability - Guidelines to understanding reliability prediction. European Power Supply Manufacturers Association; 2005. Available from: `www.epsma.org`.

[13] O'Connor PDT. Practical reliability engineering. 4th ed. Wiley; 2008.

[14] White M, Bernstein JB. Microelectronics Reliability: Physics-of-Failure Based Modeling and Lifetime Evaluation. National Aeronautics and Space Administration (NASA); 2008. NASA WBS: 939904.01.11.10. Available from: `http://trs-new.jpl.nasa.gov/dspace/bitstream/2014/40791/1/08-05.pdf`.

[15] Mil-Hdbk-217F. Reliability Prediction of Electronic Equipment, Military Handbook 217 F; 1995.

[16] Foucher B, Boullié J, Meslet B, Das D. A review of reliability prediction methods for electronic devices. Microelectronics Reliability. 2002;42(8):1155 – 1162. Available from: `http://www.sciencedirect.com/science/article/B6V47-4625HPD-1/2/b2d05c9261ec54721c6cf3a690172be6`.

[17] Meeker WQ, Escobar LA. Statistical methods for reliability data. vol. 314. John Wiley & Sons; 1998.

[18] Pecht M, Jie G. Physics-of-failure-based prognostics for electronic products. Transactions of the Institute of Measurement and Control. 2009;31(3-4):309–322. Available from: `http://tim.sagepub.com/content/31/3-4/309.abstract`.

[19] Quintero PO, Pecht M. In: Physics-of-Failure based Reliability Engineering. John Wiley & Sons, Ltd; 2013. p. 389–402. Available from: `http://dx.doi.org/10.1002/9781118701881.ch26`.

[20] MechRel. Handbook of reliability prediction procedures for mechanical equipment; 2004. Available from: `www.mechrel.com`.

[21] Hitziger T. Übertragbarkeit von Vorkenntnissen bei der Zuverlässigkeitstestplanung. Institut für Maschinenelemente IMA, University Stuttgart; 2007. Available from: `http://deposit.ddb.de/cgi-bin/dokserv?idn=996852220&dok_var=d1&dok_ext=pdf&filename=996852220.pdf`.

[22] Gullo L. In-service Reliability Assessment and Top-Down Approach Provides Altemative Reliability Prediction Method. In: Reliability and Maintainability, Annual Symposium - RAMS. Los Angeles; 1999. p. 365–377.

[23] Duane J. Learning curve approach to reliability monitoring. Aerospace, IEEE Transactions on. 1964;2(2):563–566.

[24] Fragola JR. Reliability and risk analysis data base development: an historical perspective. Reliability Engineering & System Safety. 1996;51(2):125 – 136. Design of Reliability Data Bases. Available from: `http://www.sciencedirect.com/science/article/pii/0951832095001107`.

[25] Dhillon BS, Choueiry E. Bibliography of literature on reliability in automotive industries. Microelectronics Reliability. 1987;27(2):361 – 373. Available from: `http://www.sciencedirect.com/science/article/pii/0026271487901909`.

[26] Porter A. Accelerated Reliability Qualification in Automotive Testing. Quality and Reliability Engineering International. 2004;20(2):115–120. Available from: `http://dx.doi.org/10.1002/qre.619`.

[27] Parigi P, Vianello M. Experimental 'Reliability Growth' or 'Reliability Verification' Related with the Amount of Innovation in a New Car Model. Quality and Reliability Engineering International. 2004;20(2):167–184. Available from: `http://dx.doi.org/10.1002/qre.626`.

[28] Schijve J. The significance of flight-simulation fatigue tests. Delft University of technology; 1985. Report No. LR-466. Available from: `http://repository.tudelft.nl/file/918177/378573`.

[29] Schijve J. Fatigue of structures and materials in the 20th century and the state of the art. International Journal of Fatigue. 2003;25:679–702.

[30] White H, Proudley G, Aldridge N, Proudfoot A. Development and testing for through-life operation of fibre-optic components and systems in mil-air applications. In: Avionics, Fiber-Optics and Phototonics Technology Conference, 2009. AVFOP '09. IEEE; 2009. p. 36–37.

[31] White H, Proudley G, Charlton DW, Kazemi AA. Proc. SPIE 8368, Photonic Applications for Aerospace, Transportation, and Harsh Environment III. In: Photonic Applications for Aerospace, Transportation, and Harsh Environment III. vol. 8368; 2012. p. 836809–836809–12. Available from: `http://dx.doi.org/10.1117/12.951050`.

[32] Escobar LA, Meeker WQ. A Review of Accelerated Test Models. Statistical Science. 2006;21, 4:552–577.

[33] Yang Z, Chen YX, Li YF, Zio E, Kang R. Smart electricity meter reliability prediction based on accelerated degradation testing and modeling. International Journal of Electrical Power & Energy Systems. 2014;56(0):209 – 219. Available from: `http://www.`

sciencedirect.com/science/article/pii/S014206151300481X.

[34] Kong C, Bang J, Sugiyama Y. Structural investigation of composite wind turbine blade considering various load cases and fatigue life. Energy. 2005 Aug;30(11âŁ“12):2101–2114. Available from: http://www.sciencedirect.com/science/article/pii/S036054420400369X.

[35] Jensen FM, Falzon BG, Ankersen J, Stang H. Structural testing and numerical simulation of a 34m composite wind turbine blade. Composite Structures. 2006;76(12):52 – 61. Fifteenth International Conference on Composite Materials ICCM-15 Fifteenth International Conference on Composite Materials. Available from: http://www.sciencedirect.com/science/article/pii/S0263822306002480.

[36] Malhotra P, Hyers RW, Manwell JF, McGowan JG. A review and design study of blade testing systems for utility-scale wind turbines. Renewable and Sustainable Energy Reviews. 2012;16(1):284 – 292. Available from: http://www.sciencedirect.com/science/article/pii/S1364032111004011.

[37] Musial WD, McNiff BP, Industry ML. Wind turbine testing in the NREL dynamometer test bed. In: Proc. AWEA WindPower 2000 Conference. Palm Springs, California: National Renewable Energy Laboratory; 2000. .

[38] Musial W, Butterfield S, McNiff B. Improving wind turbine gearbox reliability. In: European Wind Energy Conference, Milan, Italy; 2007. p. 7–10.

[39] Weltin U. Reliability in Engineering Dynamics; 2009. Lecture notes Reliability Engineering TUHH. Available from: http://www.tu-harburg.de/education/master/mechatronics/course.html.

[40] Lydersen S, Rausand M. A systematic approach to Accelerated Life Testing. Reliability Engineering. 1987;18, 4:285–293.

[41] Salter SH. Research requirements for fourth generation wave energy devices. In: Results from the work of the European Thematic Network on Wave Energy (WaveNet). European Community; 2003. p. 194–224.

[42] Wolfram J. On Assessing the Reliability and Availability of Marine Energy Converters: The Problems of a New Technology. Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability. 2006;220(1):55–68.

[43] Salter SH. Proposals for a component and sub-assembly test platform to collect statistical reliability data for wave energy. In: Proc. of the 4th European Wave Energy Conference EWTEC, Cork; 2003. .

[44] Duquette J, O'Sullivan D, Ceballos S, Alcorn R. Design and construction of an experimental wave energy device emulator test rig. In: Proceedings of European Wave and Tidal Energy Conference; 2009. .

[45] Delmonte PMLGFCP Nicola; Ruol. Multi-chamber oscillating water column device for harvesting Ocean Renewable Energy. Marine Renewables Infrastructure Network for emerging Energy Technologies MARINET; 2014. MARINET-TA1-MORE.

[46] Henderson R. Design, simulation, and testing of a novel hydraulic power take-off system for the Pelamis wave energy converter. Renewable Energy. 2006;31:271–283.

[47] Yemm R. Pelamis WEC - Full scale joint system test. DTI; 2003. V/06/00191/00/00/REP.

[48] Al-Habaibeh A, Su D, McCague J, Knight A. An innovative approach for energy generation from waves. Energy Conversion and Management. 2010;51(8):1664 – 1668. Available from: http://www.sciencedirect.com/science/article/pii/S0196890409004919.

[49] Ceballos S, Rea J, Lopez I, Pou J, Robles E, O'Sullivan DL. Efficiency Optimization in Low Inertia Wells Turbine-Oscillating Water Column Devices. Energy Conversion, IEEE Transactions on. 2013 Sept;28(3):553–564.

[50] Caraher SL, Chick JP, Mueller MA, Steynor J, Stratford TJ. Test Rig Design and Development for Linear Bearings in Direct Drive Generators. In: Proc. of 3rd Int. Conference on Ocean Energy ICOE; 2010. 6th-8th October, Bilbao, Spain.

[51] Caraher S. Bearing options, including design and testing, for direct drive linear generators in wave energy converters. The University of Edinburgh, School of Engineering; 2011. Available from: http://hdl.handle.net/1842/5740.

[52] IFREMER. FANROE - FAtigue behaviour of Natural Rubber for Ocean Energy devices;. Accessed: 20/09/2014. Access report. Available from: http://www.fp7-marinet.eu/access_completed-projects_FANROE.html.

[53] Davies P, Germain G, Gaurier B, Boisseau A, Perreux D. Evaluation of the durability of composite tidal turbine blades. Philosophical Transactions of the Royal Society A: Mathematical,Physical and Engineering Sciences. 2013;371(1985). Available from: http:

//rsta.royalsocietypublishing.org/content/371/1985/20120187.abstract.

[54] Davies P. Accelerated Aging Tests for Marine Energy Applications. In: Davies P, Rajapakse YDS, editors. Durability of Composites in a Marine Environment. vol. 208 of Solid Mechanics and Its Applications. Springer; 2014. p. 165–177.

[55] Ridge I, Banfield S, Mackay J. Nylon fibre rope moorings for wave energy converters. In: OCEANS 2010. IEEE; 2010. p. 1–10.

[56] Thies PR, Johanning L, McEvoy P. A novel mooring tether for peak load mitigation: Initial performance and service simulation testing. International Journal of Marine Energy. 2014;(0):–. Available from: `http://www.sciencedirect.com/science/article/pii/S2214166914000174`.

[57] Resources A. Atlantis Resources Corporation completes testing of the AR-1000 tidal turbine at Narec.; 2013. Accessed on 28/09/2014. online. Available from: `http://atlantisresourcesltd.com/medianews/media-coverage/187-atlantis-resources-corporation-completes-testing-of-the-ar-1000-tidal-turbine-at-narec.html`.

[58] Turbines MC. Marine Current Turbines completes endurance testing at the National Renewable Energy Centre; 2014. Accessed 28/09/2014. Press release. Available from: `http://www.marineturbines.com/sites/default/files/Marine_Current%20Turbines_completes_endurance_testing_at_Natrec_110614_v2.pdf`.

[59] SINTEF. OREDA - Offshore Reliability Data Handbook. vol. Volume 1 – Topside Equipment, Volume 2 – Subsea Equipment. 5th ed. Det Norske Veritas DNV; 2009.

[60] SINTEF. OREDA - Offshore Reliability Data Handbook. 4th ed. Det Norske Veritas DNV; 2002.

[61] Naval Surface Warfare Center. Handbook of reliability prediction procedures for mechanical equipment. NSWC; 2010.

[62] Delorm TM, Zappalà D, Tavner PJ. Tidal stream device reliability comparison models. Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability. 2011;Available from: `http://pio.sagepub.com/content/early/2011/10/29/1748006X11422620.abstract`.

[63] Val DV, Chernin L. Probabilistic Evaluation of Failure Rates of Mechanical Components in Tidal Stream Turbines. In: 9th European Wave and Tidal Energy ConferenceEWTEC. Southampton, UK; 2011. .

[64] Heege A, Betran J, Bastard L, Lens E. Computation of dynamic loads of wind turbine power trains. Mecánica Computacional. 2007;26:2985–3004.

[65] Helsen J, Vanhollebeke F, De Coninck F, Vandepitte D, Desmet W. Insights in wind turbine drive train dynamics gathered by validating advanced models on a newly developed 13.2 MW dynamically controlled test-rig. Mechatronics. 2011;21(4):737–752.

[66] Karikari-Boateng KA, Ng C, Johanning L, Mueller M, Barltrop N. Influence of Environmental Loads on Tidal Turbine Main Bearing Life. . Tokyo. In: Proc. Asian Wave and tidal energy Conference (AWTEC); 2014. .

[67] Catapult O. 3MW Drive Train Test Facility-Atlantis AR-1000; 2012. Accessed 28/09/2014. Press release. Available from: `http://www.narec.co.uk/narec.co.uk/documents/case-tudies/marine/12.05.14_nare01__atlantis_case_study.pdf`.

[68] Welch A. Crest of a wave; 2012. Available from: `http://www.energyengineering.co.uk/features/EE43Crestofawave.htm`.

[69] Johanning L, Spargo A, Parish D. Large scale mooring test facility – A technical note. In: Proc. of 2nd Int. Conference on Ocean Energy ICOE. Brest, France; 2008. .

[70] Johanning L, Thies PR, Parish D, Smith GH. Offshore Reliability approach for floating renewable energy devices. In: Proc. of 30th Int. Conference on Ocean, Offshore and Arctic Engineering OMAE. vol. Volume 2: Structures, Safety and Reliability. Rotterdam, Netherlands: ASME; 2011. p. 579–588.

[71] BS 5760-10 2:1995. Reliability of systems, equipment and components. Guide to reliability testing. Design of test cycles. British Standards Institution [BSI]; 1995.

[72] Ridge IML. Tension-torsion fatigue behaviour of wire ropes in offshore moorings. Ocean Engineering. 2009;36(9âŁ“10):650 – 660. Available from: `http://www.sciencedirect.com/science/article/pii/S0029801809000687`.

[73] TTI. Durability of polyester ropes. Report by Tension Technology International for the Mineral Management Service MMS; 2006.

TTI-SJB-2005-321.

[74] Williams JG, Miyase A, Li D, Wang SS. Small-Scale Testing of Damaged Synthetic Fiber Mooring Ropes. In: Offshore Technology Conference. 14308-MS. Houston, Texas; 2002. p. 13.

[75] McEvoy P. Combined Elastomeric and Thermoplastic Mooring Tethers. In: Proc. of 4th Int. Conf. on Ocean Energy. Dublin, Ireland; 2012. .

[76] SINTEF. OREDA - Offshore Reliability Data Handbook. vol. Volume 1 – Topside Equipment, Volume 2 – Subsea Equipment. 5th ed. Det Norske Veritas DNV; 1984.

[77] SINTEF. OREDA - Offshore Reliability Data Handbook. vol. Volume 1 – Topside Equipment, Volume 2 – Subsea Equipment. 5th ed. Det Norske Veritas DNV; 1997.

[78] Faulstich S, Lyding P, Hahn B, Brune D. A Collaborative Reliability Database for Maintenance Optimisation. In: Proc. of the European Wind Energy Conf; 2010. .

[79] Faulstich S, Durstewitz M, Bernhard Lange aO. Research at alpha ventus Joint research at Germany's first offshore wind farm; 2013. Fraunhofer Institute for Wind Energy and Energy System Technology IWES, Kassel, Germany. Presentation DeepWind Conference Trondheim, Norway.

[80] Otto E, Durstewitz M, Lange B. The RAVE research initiative: A successful collaborative research, development and demonstration programme. In: Ecological Research at the Offshore Windfarm alpha ventus. Springer; 2014. p. 25–29.

[81] Evans RA. Accelerated Testing: The Only Game In Town. IEEE Transactions on Reliability,. 1977 Oct;R-26(4):241–241.

[82] Hu J, Barker D, Dasgupta A, Arora A. Role of Failure-Mechanism Identification in Accelerated Testing. Journal of the IES. 1993 Jul;36(4):39–45. Available from: `http://iest.metapress.com/content/B01608702H803NKM`.

[83] Meeker WQ, Escobar LA. A Review of Recent Research and Current Issues in Accelerated Testing. International Statistical Review. 1993;61:147–168.

[84] Meeker WQ, Escobar LA. Pitfalls of accelerated testing. Reliability, IEEE Transactions on. 1998 Jun;47(2):114–118.

[85] Meeker WQ, Sarakakis G, Gerokostopoulos A. More Pitfalls of Accelerated Tests. Journal of quality technology : a quarterly journal of methods, applications and related topics. 2013;45(3):213—222.

[86] The Marine Renewables Infrastructure Network (MARINET);. Funded by EU FP7 programme. Available from: `www.fp7-marinet.eu`.