Component Reliability Testing for Wave Energy Converters: Rationale and Implementation

This paper is dedicated in memory of Prof. George H. Smith

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***Abstract*—The reliability of marine renewable energy (MRE) converters is a key issue that has to be addressed and included in a whole system approach, in order to make the energy extraction from these sources a viable option. At the current development stage of MRE converters, an increasing number of devices are being field tested at pre-commercial demonstration scale, yielding field experience and load data useful for refining, demonstrating and improving the reliability of devices.**

This paper gives a brief review of the most advanced technologies and common reliability aspects that provide the rationale for dedicated component testing. It describes a service simulation test approach and the development of a unique large-scale component test facility. The test rig is capable of replicating the forces and motions experienced by components for a range of floating marine applications. The replication of motion angles is demonstrated in this paper.

The service simulation test of a marine power cable is presented as a case study on how component performance can be assessed and demonstrated prior to long-term field deployments in order to ensure the reliability of crucial sub-systems and components in the harsh marine environment.

***Index Terms*—reliability, wave energy, failure mode, component testing, service simulation testing**

I. INTRODUCTION

Marine renewable energy has strong potential as a future energy source. For the UK alone it is estimated that wave and tidal energy could provide up to 17% of the present electricity demand [1]. This would help the security of energy supply and would contribute to the reduction of carbon emissions. It also promises the opportunity to create a new industry sector estimated to be worth 15 billion [2]. However, from an engineering point of view, marine renewable energy is one of the least developed renewable energy technologies and has to be regarded as unproven. One of the main engineering challenges is repeatedly being identified as the reliability of components and devices [3]–[5].

The importance of device reliability is rooted in the economic impact failures and downtimes may have. It is important to note that reliability is not a simple performance characteristic. Reliability itself is influenced by a multitude of design decisions, operational conditions and maintenance strategies, which in turn affect the overall cost of energy. Several input parameters for a generic energy conversion cost model are either influenced or driven by reliability considerations. The device design and its reliability characteristics govern how much of the annual available wave resource can be captured and what costs are incurred through operation and maintenance. Figure 1 illustrates the key cost parameters that are influenced by reliability aspects and how they relate to the unit cost of energy. For example, a key feature of the device characteristics is the failure behaviour, such as the Mean time to failure (MTTF). It depends on the device design and the operating conditions. This in turn influences the availability of the device and the expected annual electricity output. The device design is heavily dependant on the required reliability level and determines the device cost. Moreover, depending on the type and frequency of failure, operation and maintenance (O&M) activities are also driven by reliability, even though they are governed by access conditions.

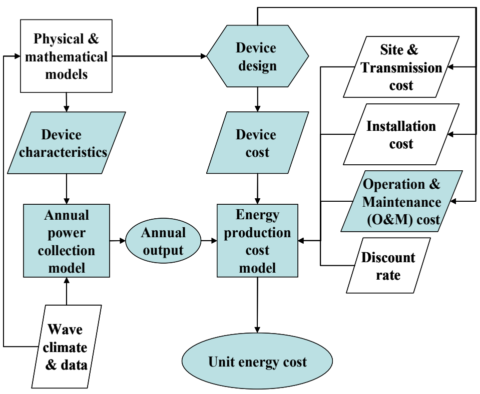

Fig. 1. Generic cost model for wave energy conversion - parameters influenced by reliability are shaded, based on [6]

The technological risk and uncertainty about the reliability of marine energy systems is identified as a potential barrier [7]. A survey among original manufacturing companies involved in the sector and large utility companies who are

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potential end-users of devices emphasised this as a main concern. In this context, one of the recommendations of the Marine Energy Action Plan for the UK [2] is to provide funding for improving the performance, reliability and survivability of MRE converters, focussing on “enabling components” such as foundations and moorings, power take-offs and wet-mateable power connectors.

This paper aims to outline component reliability testing as an approach to assess and improve the reliability of wave energy devices and components. It provides a reliability-centred review of wave energy converters (Sec. II-A) as a background to the rationale for a novel reliability test rig (Sec. III). The development and implementation of the rig is then outlined in Sec. IV and initial service simulation tests with a marine power cable are presented in Sec. V. The paper concludes with a view on how dedicated service simulation tests can be used in providing an essential part in a lifecycle approach to support commercial viability of MRE deployments.

II. Rationale for component reliability testing

A. Reliability-centred Review of Wave Energy Converters

One of the peculiarities of wave energy is the vast number of technologies and concepts that have been proposed and are being utilised to produce useful energy from waves, typically electricity. Reference [8] reports over 1,000 patents for wave energy converter techniques and the *Marine and Hydrokinetic Database* [9] lists a total of 134 different wave energy devices. Thus, neither an exhaustive list of devices nor a complete review is attempted here. The technology review which is presented in the following focuses on a selection of the most advanced technologies to be found in the literature [10]–[13], which have achieved at least prototype status.

The aim of this review is to explicate pertinent reliability aspects of the four distinct technology approaches. For each technology a brief technical description of the working principle is coupled with reported and/or potential reliability concerns. The technologies considered are Oscillating Water Columns with air turbines, direct drive linear generator point absorbers, hydraulic systems and overtopping devices employing low-head water turbines as power-take off.

1) Oscillating Water Column: The Oscilliating Water Columns (OWC) design was the first full-scale devices to be built, as it could be erected at shore. They consist of a chamber that is open to the sea. Through the heave motion of incoming waves the air in the chamber is pressurised and depressurised. This results in an air flow that reciprocates at wave frequency and is forced through an air turbine.

Three prominent devices at full-scale are the LIMPET [14], Pico [15] and Oceanlinx device [16]. A detailed comparison and evaluation of the different OWC systems can be found in a study compiled for the Carbon Trust [17].

The maintenance regime of the LIMPET (Land Installed Marine Power Energy Transmitter) foresees weekly visual checks and regular maintenance activities (e.g. grease of bearings). Beyond that, during the first two years of operation some unplanned maintenance occurrences were reported in [18], [19]:

- Blockage of collector
- Vibration loosening of bolts and screws
- Vane valve flutter
- Seizure of the butterfly valve shaft bearings
- Storm damage, water ingress

For the Pico plant, the following reliability related encounters were made [20], [21]:

- Excessive vibrations in the turbo-generator set at higher turbine speeds $N > 1,200\,rpm$.
- Power electronic equipment and transformers had to be renovated and relocated outside the plant due to the aggressive marine environment inside the plant.
- The guide vane stator on the atmospheric side of the turbine failed due to material fatigue.

Some of these issues are due to the long marine exposure of the mechanical and electrical equipment, but the vibrations and failure of guide vanes are design-related issues. The turbine design appears to follow the requirements for conventional unidirectional turbines and fell short to accommodate the conditions in a bidirectional, OWC turbine. The failure of the guide vane stator was attributed to pressure oscillations caused by vortex shedding under turbine stall conditions on the atmospheric side of the turbine [21]. The problem was resolved with a new reinforced set of guide vanes.

The OceanLinx device was continuously developed from a nearshore device to an offshore floating platform. Not much operational information is available, but the so called MK-3 device, a pre-commercial scale floating platform with 2 turbines, broke free of its catenary moorings and sunk in May 2010 [22].

2) Direct drive linear generator: Linear generators can be directly connected to a prime mover of a wave energy device to generate electricity. The advantage over conventional high speed rotating generators is that the movement is directly converted into electricity and no secondary energy conversion is necessary. The appeal is a more reliable power conversion, as there are fewer parts to fail and less maintenance requirements as the number of moving parts is reduced [23]. However, the disadvantage of this technology is that the output voltage varies in frequency and amplitude which necessitates a further electrical conversion before the electricity can be fed into the grid [24].

A number of point absorbers operate with linear generators. The more prominent devices are the Archimedes Wave Swing (AWS) [25], [26], Trident energy [27] and the Seabased floating buoy developed at Uppsala University [28], [29].

Two of the devices suffered from delays and difficulties during the offshore deployment. The 2MW AWS prototype was deployed off the northern Portuguese coast in 2004, but this was preceded by two failed attempts in 2002 and 2003. During the deployment the control cubicle was flooded which led to the failure of crucial control and communication components. As a results the device was only operational, i.e. feeding electricity into the grid, for 15mins, before the testing was halted by Enersis, the funder of the project [30]. The device is currently being redesigned by the AWS ocean energy consortium. The Trident energy device capsized and sunk five miles offshore while it was being towed to its installation site on the 20th September 2009 [31]. Both examples underline the challenge of offshore deployments and the careful planning it requires, but are not informative regarding the reliability of linear generators in wave applications.

A known reliability challenge for linear generators are the bearings that guide the translator and maintain the air gap between the translator and the stator. This is due to large attractive force between the translator and stator, the large amount of translator cycles for a typical year of operation and the fact that conventional mechanical bearings require regular maintenance [32]. Plain contact polymer bearings are being investigated by [33], [34] who performed application specific testing of different bearing materials and point out the need to base the bearing system design on empirical test data.

3) Hydraulic system: Hydraulic power take-offs are being considered in wave energy applications, because they are well suited to the high force, low frequency conditions present in the primary energy conversion step. The most prominent device that employs this working principle is Pelamis, which consists of a number of partly submerged cylinders connected with hinged joints. The waves cause the cylinders to move relative to each other in two degrees of freedom, heave and sway [35].

The system comprises two independent hydraulic cycles, each of which is driven by one cylinder in the heave axis and another cylinder in the sway axis. A simple heaving buoy would be driven by a single hydraulic ram. The hydraulic cylinders are driven by the relative movements of the floating structure and pump the working fluid through control manifolds into high-pressure accumulators. The high-pressure fluid drives hydraulic motors that are coupled to electric generators which feed into a step-up transformer.

Regarding the reliability of the power take-off (PTO) machinery, a number of redundancies are apparent in the Pelamis configuration [36]:

- Three power conversion modules are operating independently, i.e. are in parallel.
- Two generators rated at 125 kW each are installed within each of the three power modules.
- Two independent hydraulic systems, with one heave/sway axis each.

In particular the hydraulic cylinders are subject to reliability issues as they absorb the incident wave forces as a primary energy conversion step. They effectively act as compressing pistons which is contrary to their conventional deployment as actuators and results in much higher cycle frequency and reversed, less controlled loadings.

Some of the detrimental effects that should be considered for hydraulic cylinders are [37, p. 55]

- Fatigue and buckling of piston rod
- Wear mechanisms of seals, pins and bearings
- Hydraulic fluid contamination, e.g. by seawater and bacterial growth

The abrasive wear of piston ring seals for a heaving buoy configuration has been modelled by [38], [39]. They conclude that high frequency oscillations due to the compressibility of the oil significantly increase the travelled distance of the piston ring and thereby accelerate the wear of the ring seal. Moreover average wear rates for different sea states are calculated. It is shown that the wear rate is affected by both significant wave height H_s and wave period T_p.

During the deployment of three Pelamis machines in 2008 in Aguacadora, Portugal an increased wear rate was discovered for the main cylindrical bearings of the hydraulic cylinders. As a root cause undesired lateral movement of the bearing face has been identified [40] that was not expected from preceding development testing.

The design has been subsequently changed from the two-axis hinged joints to a single universal joint, thus all bearings are on the same axis and are covered by a low-friction liner [41].

The hydraulic power take-off is a good example of how existing and well-known components may be applied for wave energy converters, but the altered loading must be understood and considered in order to evaluate and ensure component reliability.

4) Water turbine: Low head water turbines are a well established technology for hydropower plants. They may also be used in overtopping WECs where the waves run over the structure and the water is collected in an elevated reservoir from which the turbine is fed and drives an electric generator.

One of the most advanced overtopping devices is the Wave Dragon (WD). The potential rated power output ranges between 4-10 MW depending on the site specific wave climate. Compared to other devices the structural dimensions with 300m width and 170m length are large. The device can be classified as a terminator, as the structural dimensions are large compared to the wavelength. The device consists of three main components [42]:

- The main structure comprising ramp and water storage reservoir
- Two wave reflectors, fixed to the main structure, focus incoming waves onto the ramp
- Several low head Kaplan turbines (16-18), modified for variable speed operation.

As the WD is a terminator-type device, the wave forces on the structure and moorings are expected to be large. After over 15,000 hours of sea trials with a 1:4.5 prototype, in January 2005 a force transducer in the main mooring line failed during a large storm [42] and the device broke free.

Nevertheless, the device has been at sea for en extended period of time and several reliability and maintenance issues have been identified by [42], [43]:

- Turbine bearings were intruded by salt water and began to corrode.
- The turbine draft tubes made from black steel and coated with epoxy paint experienced significant marine growth whereas a silicone based antifouling coating inhibited almost all marine growth.
- Maintenance activities on board and accessing the device could only be carried out in calm weather conditions most likely during the summer month.
- For electrical components Ingress Protection Rating IP66 (protected against dust and low pressure jets of water) was not sufficient. The sea water spray overcame existing protections and attacked exposed sealing by corrosion.

B. *Common reliability aspects*

The environmental influences and material phenomena that effect the reliability of wave energy converters have been described by [44] and [45] and a list of the most pertinent aspects is given in Table I. The listed potential failure mechanisms are a result of the operational and environmental factors. Even though most of these phenomena are well known and understood, it appears from the technology review, that the specific application to actual devices is fraught with difficulty and field failures are often not averted.

The different technologies listed above may be separated in two distinct design approaches:

- *New, unproven technology* - As wave energy conversion is an unprecedented energy generation, new technological solutions and components are engineered to suit this application. The invention of the Wells turbine for OWCs and linear generators fall into this approach.
- *Proven technology in new application* - Components and technologies which are widely used and regarded as proven are applied for wave energy applications. Examples are the use of hydraulic systems and water turbines.

Most of the failures and reliability issues described above are due to the fact that actual load conditions in the field are not well understood and the associated reliability is difficult to predict. For proven technologies in new applications it is crucial to understand how the component reliability is affected by the environmental and load conditions. New technology has to be developed and tested appropriately to validate the design and demonstrate its performance.

While new technology always has the association of possible failures while it is being developed, components that have been proven in other fields might be expected to perform to the same standard in the new application. While the former is a reasonable precaution, the latter expectation might not be the case when a proven technology is placed into a radically different operating environment.

The research question emerging from this is to understand how the system reliability can be estimated for new or proven technology in wave energy applications.

TABLE I
ENVIRONMENTAL INFLUENCES AND POTENTIAL FAILURE MECHANISMS FOR WAVE ENERGY CONVERTERS, BASED ON [44], [45]

Environmental influences	Failure mechanism
External water pressure	Corrosion
Damp, saline atmosphere	Fatigue
Temperature variations	Corrosion fatigue
Cyclic motions and accelerations	Stray current corrosion
Inaccessibility	Wear and fretting fatigue
Human factors	Marine fouling
	Impact loading and fracture

III. RATIONALE FOR A NOVEL COMPONENT TEST RIG

The need for extensive component testing as a means to improve the reliability of marine energy devices has been repeatedly emphasised by various authors [1], [4], [45], [46]. In general, component testing promises the opportunity to reveal and investigate occurring failure modes, to optimise the component design and to collect the required data to estimate more appropriate failure rate probabilities, considering the expected operational and environmental loads.

There is a multitude of different reliability tests. A general classification regarding the test *purpose* [47] can be made into:

- Testing of full-scale structures
- Testing of specimens
- Comparative tests
- Model validation testing

A further useful distinction, with a view of how accurate field loads are replicated and how they are accelerated is made in [48].

- Field testing of complete systems with accelerated operating conditions
- Laboratory testing of systems by means of physical simulation of field loads
- Computer simulation of system and field loads

Both classifications can also be associated with a ranked order in terms of cost and complexity. It is certainly the most expensive and most complex operation to test the complete full-scale structure under (accelerated) operating conditions. At the other end of the scale, a virtual, computer-aided test is a less costly alternative but may not provide the required level of assurance. In this respect, an approach to targeted testing that can accommodate full- or large-scale components that are tested under physically simulated and, if possible, accelerated load conditions is presented in the following.

The question of how test type, load acceleration and safety factors are related to each other has been explored by [49]. He suggests that the type of test determines the level of the required safety factor, with high safety factors for highly accelerated single axis tests, medium factors for multiple loading and medium acceleration and low safety factors for service load simulation and in service testing (see Table II). Service simulation testing applies selected field loads to approximate the field load conditions.

Experience in reliability engineering [50] has shown that dedicated component testing is able to improve the accuracy of reliability estimates. Thus, accurate service load simulation tests can contribute to reduce costly safety factors of components and obtain reliability information at the same time. It therefore is a promising test approach for wave energy converters.

TABLE II
TEST TYPE AND REQUIRED SAFETY FACTORS, AFTER [49]

Test	Acceleration	Loading	Safety factor
In-service	None	Actual	Low
Service simulation	Low	Selections true load	Low
Cyclic multi axis	Medium	Multiple level	Medium
Cyclic single axis	High	Single level	High

However, most test efforts that have been reported for wave energy systems are mainly concerned with demonstrating the power take-off performance. An implicit assumption may be that the reliability behaviour of the components will be similar to that experienced in other application fields. Yet, it is important to consider the particular problems imposed when components are incorporated into a WEC system. For example, the mooring system or the marine power cable will be exposed to unusual load time histories as part of the dynamic system which will impact on the component reliability. Component failures described in the technology review in section II-A had a common issue, that field load conditions were not anticipated for allegedly reliable components.

An example where extensive component testing is performed to avoid unexpected failures in a marine environment are offshore moorings. Specific operational conditions like the tension-torsion fatigue behaviour of wire ropes is carried out by [51], while [52] engages in detailed examination and tensile testing for internal wear and [53] tests damaged mooring ropes to determine their damage-tolerance behaviour. These tests apply traditional tension testing to determine component reliability under specified load conditions.

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] [54], [55], suggests that at least three degrees of freedom are required to replicate the dynamic mechanical load regime that a floating system is subjected to. The component test rig described in the following aims to replicate the dynamic movements of mooring assemblies and other components/sub-systems in order to assess the reliability implications of operational field loads.

From simulation tests in the automotive and other industries [56] identifies four key steps:

- Measuring realistic load data
- Identifying representative loading regimes
- Testing a (representative) sample on a laboratory test rig
- Root cause analysis and statistical evaluation of test results

Realistic load data is ideally measured in situ, for example the loads that a component is subjected to in operation at the installation site of the device. As field deployments incur considerable installation cost, alternative data sources for realistic loads may be real sea test facilities, large scale tank tests or numerical models. Once representative load data is established, the most severe load cycles can be used to derive a loading regime for the laboratory testing. Standardised load spectra and load-time histories have been generated for a range of industries to assess the fatigue behaviour of structures and components [57]. An attempt to estimate the annual load spectrum for mooring lines in a wave energy application has been made in [58]–[60].

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 [61].

Reference [62] distinguishes four general possibilities that can be applied to accelerate reliability tests, by increasing the following characteristics:

- Use rate of the component, e.g. increased load cycle frequency
- Radiation exposure intensity, e.g. increased UV radiation
- Ageing 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

The development and implementation of a purpose built marine component test rig that is capable to perform service simulation tests is described in the following section while the results for initial tests with a marine power cable is reported in section V.

The service simulation test approach can be summarised in four steps (see also Fig.2):

1) Characterise the environmental climate of a specific installation location
2) Measure realistic load and response characteristics for component
3) Analyse and extract representative/severe load cycles and combine load segments according to environmental conditions

4) Conduct laboratory component testing with established load spectrum

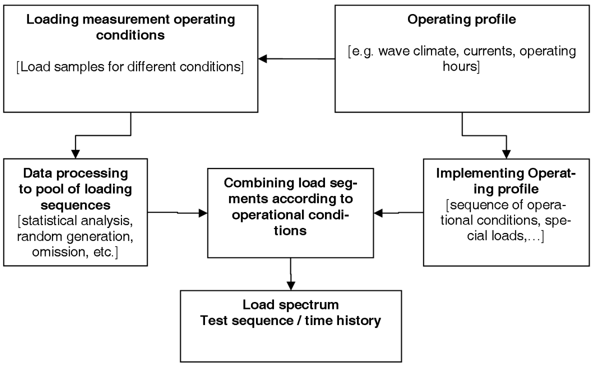
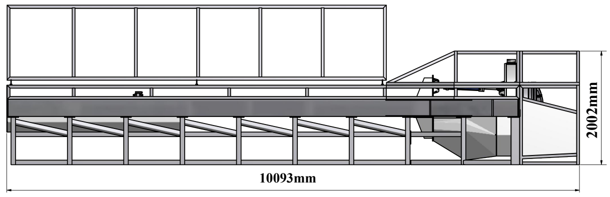
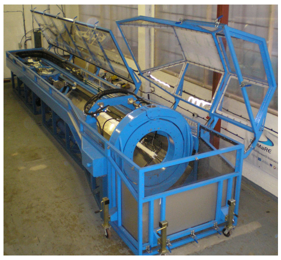


Fig. 2. General simplified approach for the generation of standardised load-time histories for service simulation testing (based on [57])



(a) Side view, dimensions in (mm)



(b) Assembled machine

Fig. 3. Dynamic Marine component test rig

IV. Development Dynamic Marine Component test rig

A. Design Requirements and concept design

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 (...)" [63].

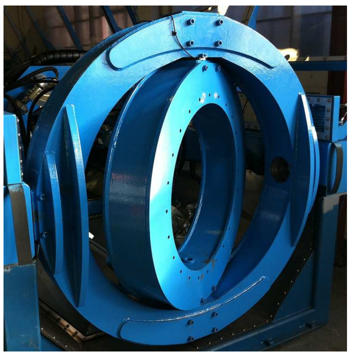
As such the objective for the Dynamic Marine Component test rig (DMaC) is to replicate the marine environmental load conditions as closely as possible, to enable a service simulation approach. The test rig should facilitate the dynamic testing of components in large scale within a controlled environment applying realistic motion characteristics. The distinct features allowing such advanced testing are:

1) Constructing the test rig with a system to immerse the tested component
2) Construction of a three degree of freedom (3DOF) moving headstock to allow replication of dynamic response as seen by components in realistic application
3) A linear hydraulic actuator at the far end to provide necessary axial loading.

B. Implementation and capabilities

An overview of the overall dimensions and layout of the test rig is shown in Fig. 3. The forces generated and applied through the four degrees of freedom are fully reacted by the frame. The frame itself is approximately 10m in length and hosts a test bed of maximal 6m in length. The length of the test bed, i.e. the distance between the two force application points, is adjustable between 1-6m. The frame itself is surrounded by a sealed outer housing which enables a test operation under wet conditions, where the item is submersed in fresh water.

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. Fig.4(a) 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.



(a) Gimble system, tilted inner ring

(b) Linear actuator, short test bed position

Fig. 4. Load application points of Dynamic Marine Component test rig

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 $\pm 30°$, 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 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, see Fig.4(b). 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 III. The main limiting factors are the maximum displacement stroke of 1m and a maximum applicable force of 45 tonnes in static conditions and 30 tonnes under dynamic conditions.

TABLE III
FUNCTIONAL CAPABILITIES AND DIMENSIONS OF HYDRAULIC ACTUATOR SUPPLYING FORCE AT TAILSTOCK OF DYNAMIC MARINE COMPONENT TEST RIG

Parameter	Value
Maximum stroke	1m
Rod diameter	70 mm
Bore	160 mm
Maximum Dynamic Force	30 tonnes
Maximum Static Force	45 tonnes
Servo-hydraulic control valve	462 l/min
Pre-load force	14 tonnes
Maximum specimen length	6 m
Maximum specimen diameter	800 mm
Maximum specimen weight	1000 kg

The test rig is connected to a 130kW electrical supply with a voltage of 415V which supplies the hydraulic power pack unit. The hydraulic power is generated with two variable displacement pumps that supply the pressure to both the hydraulic actuator circuit (140 bar) and the pilot circuit (210 bar) to operate the hydraulic control valves. The maximum achievable flow rate is about 362 l/min (see also Table IV).

TABLE IV
RATED POWER OF ELECTRICAL SUPPLY AND HYDRAULIC POWER SYSTEM FOR DYNAMIC MARINE COMPONENT TEST RIG

Electrical Power Supply		Hydraulic Power Unit	
Parameter	Value	Parameter	Value
Power	130 kW	2 x Induction motors	55kW each
Voltage	415 V	2 x variable displacement pumps	
		Drive Circuit Pressure	140 bar
		Flow Rate	362 l/min
		Pilot Circuit Pressure	210 bar

The control and measurement capabilities are listed in Table V. 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. For the tests presented here the linear actuator was force-controlled while the moving headstock was displacment (angle) controlled. The position control frequency reaches up to 120kHz. The data acquisition system offers 32 analogue inputs, 8 differential inputs for strain gauges together with a total of 32 digital and 16 analogue outputs. The maximum sampling frequency is 250kHz.

TABLE V
MEASUREMENT AND CONTROL CAPABILITIES OF DYNAMIC MARINE COMPONENT TEST RIG

Item	Description
Programmable test design	Force or Displacement driven control
Data acquisition and control channels, National Instruments Compact RIO / Labview system	32 analogue inputs, 8 differential strain gauge inputs, 64 digital inputs, 32 Digital Outputs, 16 Analogue Outputs
Sampling frequency (combined)	250 kHz
Position control frequency	120 kHz

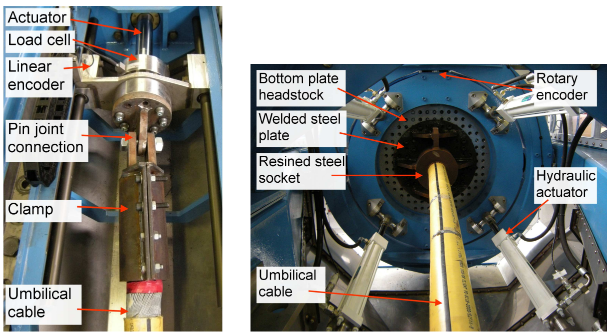
V. SERVICE SIMULATION TESTING OF MARINE POWER CABLE

The major objective of the service simulation test with a marine power cable presented here, is to demonstrate the capability of the DMaC to replicate the operational load conditions which would be expected for components in a wave energy application. As such, only a short load signal with a duration of 5 minutes was employed in the tests presented here, rather than to fatigue test the cable, which is beyond the scope of this paper.

A. *Experimental setup and input parameters*

Figure 5 shows the experimental set-up with the cable fitted to the test rig. The rig is instrumented with the following measurement equipment:

- Force load cell measuring the tensile/compressive force that the specimen experiences at the end of the linear cylinder.
- Linear displacement encoder measuring the stroke position of the linear actuator.
- Rotary encoder measuring the angle of the x-bend and y-bend plane.
- Pressure transducers at each of the hydraulic actuators.



(a) Linear actuator (b) Moving headstock

Fig. 5. Experimental set-up with marine power cable fitted to test rig

The input load data was computed 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 [64]. 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, as detailed in Table VI:

- Effective Tension
- Angle between cable section and adjacent section plane (resolved for angle with zx-plane (Ezx), which corresponds to y-bend; and zy-plane (Ezy), corresponding to x-bend).

TABLE VI
STATISTICAL PROPERTIES INPUT PARAMETERS FOR MARINE POWER CABLE, 5MIN SIGNAL

Type	Tension force [N]	y-bend angle Ezx [°]	x-bend angle Ezy [°]
Minimum	-2813	-16.4	-12.6
Maximum	-5324	12.4	14.5
Mean	-4058	-0.7	1.2
SD	444	4.8	5.3
Range	2511	28.8	27.1

B. Test results and simulation accuracy

Within the scope of this paper only the headstock angles are presented, which are governing the resulting bending moment on the cable and thus need to be replicated accurately.

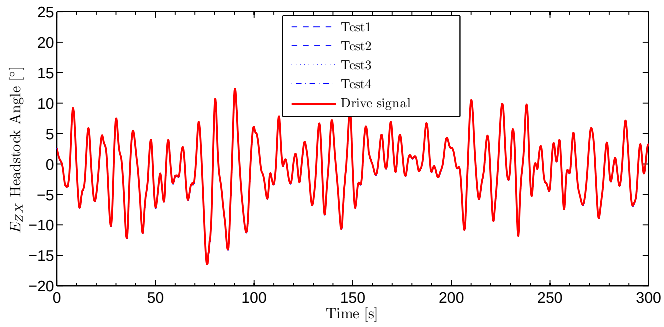
As a first, qualitative measure the data is visually examined through two types of plots:

- A simple time series plot which shows both, the desired input signal and the measured signal. This plot allows an instant impression of the simulation accuracy. It is however, only practical for short time series.
- Entire time series can be conveniently compared when the measured data X is plotted against the desired input signal Y. Together with the line that indicates a perfect correlation, i.e. $Y = X$, this plot allows a visual assessment of larger data sets. The vertical distance from the ideal line directly shows how well the signal is reproduced.

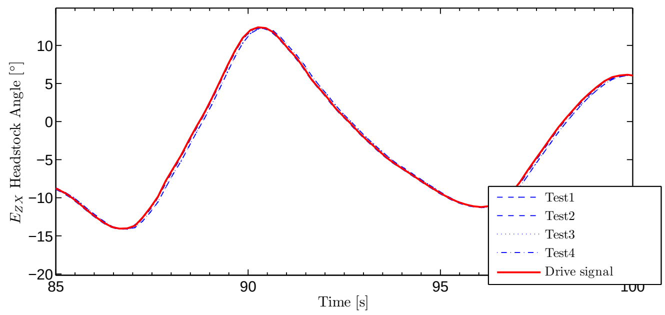
In the following plots are only shown for the y-bend angle as it has the larger range of $28.8°$, but the results for the x-bend angle are similar.

The timeseries plots for the headstock angle (y-bend) is shown in Fig. 6, which depicts the input drive signal and the measured angles for four independent tests and consists of 2 subplots for the full 300s timeseries and an excerpt of 15s. There is very good agreement between the drive signal and the measured angles.

The correlation plots of the headstock angles for all 4 tests are given in fig. 7. 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 there is very good agreement with all measured points close to or on the ideal line, confirming the close replication of the input signal which was shown in the simple timeseries plots.



(a) Full signal



(b) Excerpt

Fig. 6. Marine power cable service simulation test, time series comparison of input and measured y-axis (Ezx-angle) signal

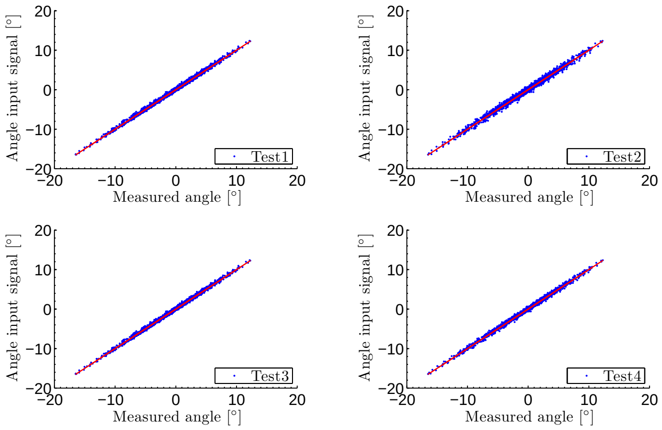


Fig. 7. Correlation of input signal and measurement for Ezx-angle (y-axis)

As a second step, quantitative measures have been calculated to assess the simulation accuracy of the test rig. Two suitable parameters to quantify the accuracy depicted in the scatter plots above are the Pearson correlation coefficient r, defined in Equation 1, and the mean absolute error (MAE), Equation 2.

$$r = \frac{\sum_{i=1}^{n}(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \bar{X})^2}\sqrt{\sum_{i=1}^{n}(Y_i - \bar{Y})^2}} \quad (1)$$

Where X_i, Y_i denote the individual sample points and $\bar{X}$, $\bar{Y}$ are the means for each sample set, n denotes the number of sample points.

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|X_i - Y_i| \tag{2}$$

Where X_i, Y_i denote the individual sample points.

The Pearson correlation coefficient r is given in Table VII. The bending angles have very high correlation values close to $r = 1$, indicating an accurate replication of the given input signals.

TABLE VII
CORRELATION COEFFICIENT FOR SERVICE SIMULATION TEST RESULTS, CORRELATING MEASURED SIGNAL AND INPUT LOAD SIGNAL

Test Nr.	y-bend angle (Ezx)	x-bend angle (Ezy)
1	0.998	0.998
2	0.995	0.996
3	0.998	0.998
4	0.998	0.998

For the second quantitative measure the MAE has been calculated and is tabulated in Table VIII. The MAE computed for the angles are all significantly smaller than $0.5°$. The relative error of the maximum angle is in the order of ±2%.

TABLE VIII
MEAN ABSOLUTE ERROR (MAE) OF SERVICE SIMULATION TEST RESULTS, COMPARING MEASURED PARAMETER AND INPUT LOAD SIGNAL

Test Nr.	y-bend angle (Ezx) [°]	x-bend angle (Ezy) [°]
1	0.26	0.31
2	0.38	0.43
3	0.25	0.28
4	0.27	0.31

VI. CONCLUSION

This paper has provided a rationale for a service simulation component test approach and presented the development and capabilities of a novel test rig that facilitates this approach. The objective is to gain a better understanding of the reliability of components and devices that can be expected in the field and to avoid unknown failure modes during deployments. It was shown that the Dynamic Marine Component test rig (DMaC) is able to replicate the motions of floating marine applications with high accuracy. This will provide the basis for further specific component testing. This paper has shown that simulated load data can be replicated to a high degree of accuracy, so further work will aim to use load profiles of measured field data to improve the service simulation. The service simulation test approach will prove useful for a range of stakeholders involved with MRE technologies, including device developers, component manufacturers, certification agencies, insurance companies and project developers in order to develop and assess cost-effective, yet robust and reliable components and devices.

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