Development of a marine component testing facility for marine energy converters

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Abstract

High reliability and availability of marine energy devices are key for successful and viable commercial-scale projects. This paper briefly reviews applicability and uncertainties of available component failure rate data and how reliability importance measures could be used as a tool to identify critical system components.

Furthermore two component test facilities currently under development at the Peninsula Research Institute for Marine Renewable Energy (PRIMaRE) group at the University of Exeter are described. The intention is to enable component reliability testing for marine renewable energy converters.

The South Western Mooring Test Facility (SWMTF) is a unique mooring load and response test facility, at large scale in real sea condition and has been recently installed. The Dynamic Marine Component Test facility (DMaC) is capable to perform accelerated component testing under simulated in-service field conditions.

Those two facilities will allow measuring loads that are experienced in the field through prototype testing at the SWMTF and subsequently replicate those load conditions (or information from device developers) at the DMaC for accelerated reliability testing.

The application of component reliability testing can reveal design weaknesses prior to deployment and establish necessary reliability and maintenance information. Components tested under service simulated conditions could be evaluated regarding performance, expected lifetime and subsequently be (cost-)optimised.

Keywords: Component testing, Accelerated test, Failure rate, Mooring, Reliability

1. Introduction

The announcement of large-scale marine energy projects like the planned 1.2 GW installation of wave and tidal devices in the Pentland Firth [1] mark the emergence from the prototype and demonstration stage to commercial deployment of marine energy converters (MECs).

The viability and success of these projects is strongly dependent on the reliability of devices as this determines the amount of generated electricity and the cost for operation and maintenance. System reliability is usually recorded by means of empirical component failure rates. However, at this stage applicable reliability (failure rate) information is scarce. Moreover, the application of proven components and equipment in a new environment and under significantly altered load conditions implies large uncertainties regarding component failure behaviour and frequency. These uncertainties could lead to either costly design safety factors or early field failures.

Reliability testing of critical components could mitigate these difficulties and provide device developers with a possibility to reveal early failures, gain information on lifetime criteria and provide project developers, investors and certification agencies with the required reliability demonstration and evidence of suitable risk control.

2. Applicability and uncertainties of available component failure rate data

The record and analysis of occurring field failures and the exact documentation of associated operating conditions (e.g. wave climate, loads, maintenance schedule, etc.) is crucially important to establish a robust basis for meaningful reliability assessments.

As an example, a comprehensive and insightful reliability analysis conducted in the wind energy industry analysed a dataset of as many as 7,745 turbines with a cumulative operating time of 71,853 turbine years. Although statistical significant conclusions were drawn from this amount of data, it was deemed partially insufficient as a statistical basis for highly detailed analysis (i.e. data breakdown to type of turbine, site conditions, etc.) [2].

In contrast to that, the scarcity of reliability data that could be collected directly from the operating environment of MECs so far entails significant uncertainties of reliability and availability estimates and does not allow a robust reliability analysis. This situation will persist until dedicated test programmes and prototype deployments make this information more accessible [3].

A common approach to overcome the scarcity of data is to use available, often generic failure rate data of similar equipment and components from other industries. Due to significant environmental and operational differences, known failure rates cannot be simply applied to MECs. They have to be adjusted to the dynamic behaviour requirements and associated response modes, possible new failure modes, environmental factors and operational loads and stresses.

Large reliability prediction uncertainties are known to be caused by this combined occurrence of new components, different operating environments and higher stresses [4], as it is the case in the marine renewable application. However, there are approaches (e.g. [5]) that have been developed to account for different environmental and loading conditions using empirical adjustment factors.

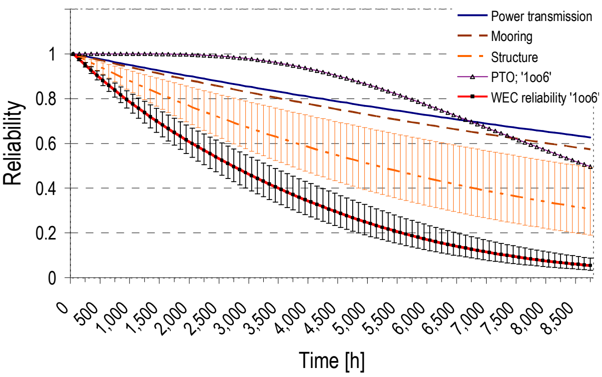

Figure 1: System reliability of a notional WEC and the effect of ±40% variability of the structural failure rate.

This approach, namely the parts-stress analysis method has been applied to a notional hydraulic MEC in [6] who estimated the system reliability by means of reliability block diagrams. It was found that crude adjustments were necessary which lead to rather unfavourable, pessimistic reliability predictions, subject to large uncertainties (see also Figure 1). Hence there is a clear need to establish more accurate and appropriate failure rate estimates for the marine energy application.

3. Identify critical components

Regarding the multitude of MEC systems and the limited resources available, it would be beneficial to target the testing and improvement of components toward those who are deemed as most critical.
Currently, there is no clear agreement which components are most crucial, as there are numerous devices based on different working principles and energy conversion mechanisms and a technology convergence to a few standard converter types has not taken place, yet. Beyond that, the number of failure modes that must be considered is diverse, ranging from marine fouling to fatigue and the loading regimes (type and frequency) for MECs can be significantly different from those experienced by the naval and offshore industries.

In general a prioritisation of components can be carried out in a qualitative or quantitative way.

Bittencourt [7] proposes a qualitative prioritisation from a reliability perspective, using a risk ranking methodology. It rates possible incidents according to their expected frequency and consequence, covering function, safety, environment, operation and assets as impact areas. Each area is rated on a scale from 1 (low risk) to 5 (high risk). Such a risk matrix approach is a useful tool to identify the high risk components of a prototype/device but has not been published yet for any marine energy device.

Another attempt to qualitatively assess and prioritise marine component technologies from an innovation and development point of view [8] was based on three criteria:

- Contribution to device costs
- Cost reduction potential
- Unlikelihood that cost reductions are realised in other industries.

The study identified several key components for further research and testing which should contribute to make MECs more viable. The findings are grouped into sub-system categories (see Table 1), covering structural materials, powertrain and mooring components. Even though this study gives an indication on which area of sub-systems and components to focus for further improvement, it is limited to the three criteria mentioned above, and does e.g. not account for reliability implications or O&M costs.

	Sub-system	Component
Wave energy	Structural Materials	Floats and device body, Offshore substation platform
	Powertrain	Generator, Power Converter (AC/DC/AC)
	Mooring	Mooring tethers, Anchors, Device connection
Tidal stream	Rotor	Rotors
	Structural	Off-shore Substation Platform
	Powertrain	Gearbox, generators, associated equipment
	Mooring	Mooring components

Table 1: Prioritised wave energy and tidal stream component technologies [8]

A quantitative risk prioritisation of components could take the following parameters into account:

- Level and uncertainty of failure probability
- Consequence (cost) of failure

4. Reliability importance measures

The concept of reliability importance measures is used to identify the weakness of a system and to quantify the impact of component failures on overall system reliability. It provides a numerical rank to decide which components are more important with regard to system reliability improvements or more critical towards system failure. Hence importance indices are a valuable tool to rank and identify the most critical components and subsequently prioritise reliability improvement efforts [9].

4.1 Birnbaum importance measure

The Birnbaum measure I_i^B ranks components after the resulting change in system reliability for incremental changes of component reliability [10]. Equation (1) describes the partial derivative of the system reliability function h with regard to the specific component reliability. The same approach is used in sensitivity analysis, i.e. if $I_i^B(i|t)$ is large the component i has a large impact on the overall system reliability in the case of small variations of i. Hence, for large values the components would be assigned a higher importance. As a characteristic of the partial derivative, Birnbaum's importance measure quantifies the effect of failure rate variations on system reliability.

$$I_i^B(i \mid t) = \frac{\partial h(p(t))}{\partial p_i(t)} \quad \text{for i=1,2, … n} \qquad (1)$$

where h is the system reliability function and p(t) represents the probability of failure of a component.

The Birnbaum measure has two vital implications [11]:

- The reliability importance (rank) of a component does not depend on the failure probability itself, but on the effect a change of this failure rate has on the system.
- Generally speaking, the weakest component is most important in a series system, and the strongest component is most important in a parallel system.

4.2 Improvement potential

The *improvement potential* I_i^{IP} is a further importance measure, which assesses the level of system reliability enhancement that could be achieved in the theoretical case of a perfectly reliable component, i.e. $p_i(t) = 1$ (see equation (2)).

$$I_i^{IP}(i \mid t) = h(1_i, p) - h(p) \quad \text{for i=1,2, … n} \qquad (2)$$

where h is the system reliability function and p(t) represents the probability of failure of a component.

Aven and Nøkland [12] state that the improvement potential is frequently employed during the system design whereas the Birnbaum measure is usually applied during system operation.

The improvement potential measure could hence be used during the device design to prioritise and identify those components which would yield a large reliability improvement for the overall system. Considering the cost of possible reliability improvements a decision can then be made which components qualify for a reliability enhancement programme.

An application of the Birnbaum measure could provide information to answer the question which components need the utmost maintenance attention to avoid detrimental effects for the overall system reliability. Obtaining such a ranking would ensure that the maintenance effort has the largest benefit for the system reliability.

5. Component testing

The described scarcity of failure rate data for the marine renewable application could be mitigated through targeted component testing under simulated field conditions. The need for extensive component testing as a means to improve the reliability of marine energy devices has been repeatedly emphasised by various authors [3], [13]-[15].

By means of dedicated component testing, occurring failure modes can be revealed and investigated, the design can be optimised and ultimately more informed failure rate probabilities can be established considering the expected operational and environmental loads.
Components tested under such service simulated conditions could be evaluated regarding performance, expected lifetime and subsequently be (cost-)optimised.

The PRIMaRE test facilities described in the following are aiming to replicate the dynamic movements of mooring assemblies and other components/sub-systems in order to assess the reliability implications of operational field loads.

This follows a service-simulation test approach commonly applied in other industries (automotive, aviation, offshore structures. Load-time sequences are established through field measurement (observing both operational conditions and component/system loads/responses) which are then synthesised to representative test loads that can be replicated and accelerated on dedicated test rigs. Details on how the methodology has been applied in other industries can be found in [16], [17].

It is intended to apply this service simulation test approach presented approach in conjunction with the facilities of the Peninsula Research Institute for Marine Renewable Energy (PRIMaRE) research group [18]:

- The operational conditions will be measured using wave buoys and acoustic Doppler current profileometers (ADCPs) [19].
- Real time load data of various mooring configurations will be measured using the South Western Mooring Test Facility (SWMTF).
- The Dynamic Marine Component Test facility (DMaC) will be used for specimen and accelerated component testing.

5.1 South Western Mooring test facility (SWMTF)

The SWMTF is a world first mooring load and response test facility, at large scale in real sea condition. It comprises a generic 2t buoy (Figure 2), that has been recently installed in Falmouth Bay. It is instrumented to gather data relating to the response of the buoy and the mooring line loads due to external loads [20]. The influences of wave action, tidal currents, wind blown surface currents and wind are being measured by the following instrumentation:

- On the bouy:
  - Six degree motion measurement system
  - Differential Global Positioning System (DGPS)
  - Structural stress measurements
  - Directional wind data on buoy
- Mooring system:
  - Tri-axis top-end load cell
  - In-line load cells
  - Anchor point load cells
  - Mid-line load cells
- Environmental condition monitoring:
  - Multiple acoustic Doppler systems for waves/current (ADCPs)
  - Onshore weather station
  - Water quality measurements

Processing of the data will allow a detailed analysis of the effectiveness of each mooring system at holding the buoy on station in a variety of conditions and will give a thorough understanding of the loads imposed on the system. Initial sway test measurements are shown in Figure 3.

Figure 2: South Western Mooring Test Facility (SWMTF) buoy; launch operation (left); in operation on site (right)

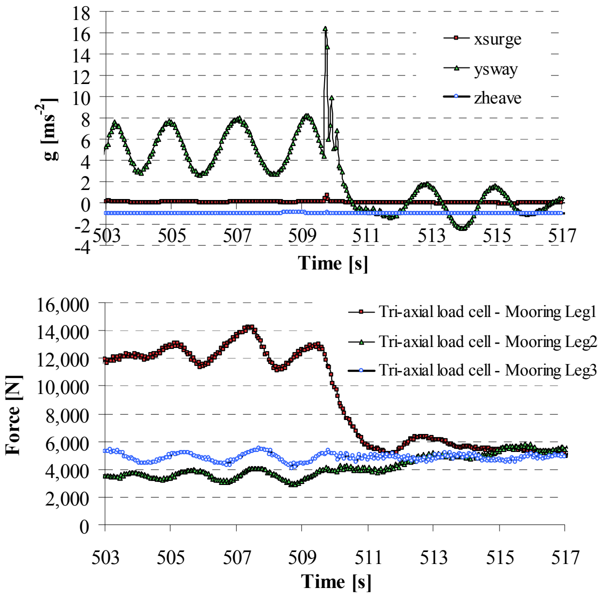

Figure 3: Sway test measurements at the SWMTF; linear motion of buoy after release (a); resulting forces measured by tri-axial load cell (b).

5.2 Dynamic Marine Component Test Facility

The Dynamic Marine Component Test facility (DMaC) will provide the ability to the group to perform accelerated component testing. Whilst the SWMTF provides the ability to perform component testing in a realistic environment, including observation by ROV, the outcomes from these nearshore tests can be replicated in an accelerated manner in the DMaC to improve performance and develop suitable components for the marine offshore industry.

The DMaC test rig will have unique features that are relevant to the component testing of components for marine renewable energy devices, allowing the dynamic testing in a wet environment. The three features allowing such advanced testing are:

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

These features will allow a dynamic testing of components in large scale under a controlled environment, applying realistic motion characteristics. A 3DOF moving headstock is intended to be used that are commercially available and typically are being used in specific component reliability testing. Furthermore, linear hydraulic actuators are also well established and applied within the field of material testing. The unique feature of this test rig is to combine these two test methods in dynamic loading under immersed conditions.

To be able to replicate the motion and forces experienced by a MEC, or sub component, the test rig will provide a pulling and pushing force representative of wave motion (termed the Z actuator in the tailstock position) and a headstock with 3 degrees of freedom (namely pitch, roll and yaw); shown in principle in Figure 4. A preliminary conceptual design is shown in Figure 5.

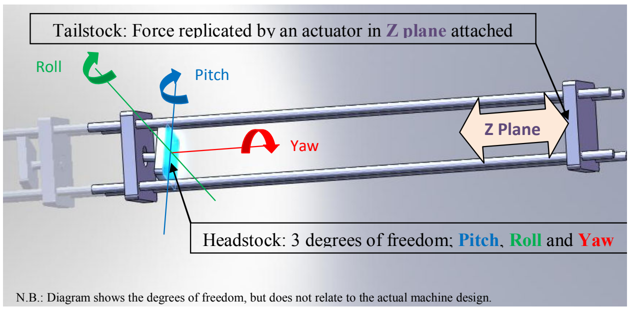

Figure 4: Functional illustration of the DMaC

Figure 5: Preliminary design of the DMaC test rig

The technical capability of the rig has been specified as follows:

- Z actuator: 30t, capable to replicate compound waves, e.g. sine waves of different frequencies superimposed; as defined by Table 1.
- Test bed: 6m working length
- Headstock Pitch: +30° to -30° in 2 sec
- Headstock Roll: +30° to -30° in 2 sec
- Headstock Yaw: continuously
- Headstock test bed: diameter of 600mm with component mounting arrangement

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

Table 2: Functional specification of Dynamic Marine component test facility (DMaC)

6. Conclusions

This paper has given a brief account of the applicability of failure rates and efforts to identify critical components of marine energy devices.

Component reliability testing could be used to evaluate field failure rates more accurately and reveal possible failure modes/design weaknesses of critical components.

The capability of two facilities developed by the PRIMaRE research group has been described. Loads that are experienced in the field through prototype testing, or through information from MEC developers, could be used to accurately replicate load conditions for accelerated testing and ultimately evaluate the operational failure rates of component.

Adopting such a testing approach provides a possibility to accurately assess and demonstrate the component reliability of MECs before they are deployed in the field where cost of failures would be prohibitively high, in particular in the case of array configuration with numerous devices. For the marine renewable energy sector to emerge successfully from the research and development phase toward commercial-scale deployment, confidence in the economic operation of large arrays is fundamental. Properly specifying the reliability of devices is a key element and the testing of marine components must be an essential goal.

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