The Role of Accelerated Testing in Reliability Prediction

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***Abstract* - The transition from the early stages of marine renewable energy (MRE) device development towards pre-commercial status involves rigorous design validation before full-scale testing. The main aim of Technology Readiness Levels (TRLs) 4-6 is to prove that the concept can deliver the required power production performance and also that a level of system reliability is achieved to ensure sufficient availability. Both of these metrics are crucial to obtaining a competitive levelised cost of energy (LCOE).**

The current state of the MRE sector means that reliability data are sparse or commercially sensitive. Device developers are therefore forced to base reliability predictions on physical testing, detailed numerical analysis or in the absence of these, generic (and potentially unsuitable) failure rate databases. Generic data will only provide a crude estimate of component or subsystem reliability unless modified to suit the application.

More accurate estimates of component and subsystem reliability are possible through accelerated testing. As part of the DTOcean (Optimal Design Tools for Ocean Energy Arrays) project, results from physical tests involving synthetic ropes and shackles are used to demonstrate how quantitative accelerated testing can be used to bridge the gap between generic failure rates and those which are applicable to MRE mooring applications.

***Keywords* - Reliability prediction; Accelerated testing; Bottom-up statistical method; Reliability block diagram**

I. Introduction

The importance of reliability for marine renewable energy (MRE) has long been recognised [1-3], but is now gaining increased attention among all stakeholders. The Technology Innovation Need Assessment [4] for Marine Energy estimates that approximately 25% of the estimated cost of energy can be reduced through reliability related measures. Public funding has increasingly sought the explicit improvement of device reliabilities in order to make MRE a competitive form of electricity generation. Recent examples include the OCEANERA-NET call [5] and the H2020 low-carbon energy (LCE) call, demanding "(…) high levels of reliability and survivability for at least 20 years in harsh conditions" [6].

The two fundamental approaches used to consider and improve reliability [7] are:

i) The failure rate approach aims to estimate the number of failures over the life of a component under given environmental and operational conditions.

ii) The component test approach employs extensive testing and analysis to identify and mitigate all potential failure modes for the given conditions.

The reliability of sub-systems and components in demanding applications can be effectively assessed and improved by accelerated testing. It offers the capability to identify potential failure modes that may arise during the operation of MRE systems. The mitigation and avoidance of failures will be critical in order to make MRE a commercially viable technology.

Accelerated testing seeks to increase component stress levels with the assumption that the damage accumulates over the lifetime of the component. The objective is to accelerate the time needed to observe failure modes by using test regimes which are representative of the conditions expected in the field.

Two types of accelerated tests can be distinguished [7]:

i) Qualitative tests aim to assess if the capacity of the component regarding the damage model of interest provides sufficient safety margins over and above the expected field damage. The likelihood of component failure during the lifetime is not quantified.

ii) Quantitative tests relate the failure probability to the different stress levels that the component is subjected to during the test.

In the next section the open-source Tool being developed in DTOcean project is introduced and the selected method of reliability assessment. Two case studies of accelerated testing are provided in Section 3 in the context of informing reliability calculations.

II. The DTOcean Tool

A. Background

DTOcean (Optimal Design Tools for Ocean Energy Arrays: www.dtocean.eu) is a collaborative project funded by the European Commission under the FP7 call ENERGY 2013-1. The consortium comprises 18 partner organisations from 11 countries including industrial partners, universities and research institutes. The main outcome of the project will be to produce an open-source design Tool which will be able to assess the i) economics (i.e. LCOE), ii) reliability and iii) environmental impact of the first generation of wave or tidal energy arrays in order to accelerate their deployment. Several key aspects will be analysed and optimised within the Tool including; array layout, electrical system architecture, mooring and foundation systems, lifecycle logistics as well as system control and operation. Within the project the Offshore Renewable Energy group at the University of Exeter is responsible for the development of reliability assessment methods and is also lead partner of the mooring and foundation work package.

B. Reliability Assessment Within the Tool

Mean time to failure (MTTF) is a widely used metric for assessing the reliability of systems on a global, sub-system and component level. It is based on the reliability function $R(t)$ which describes the probability that reliability will continue from a particular point in time:

$$MTTF(T) = \int_0^\infty R(t)\, dt \qquad (1)$$

Reliability functions are based on statistical probability density functions (PDFs) which are generated from data acquired from physical tests or sophisticated numerical models. An exponential PDF can be representative of the constant rate of random failures which tend to occur during the 'useful' or operational life of the component or sub-system. In this case the MTTF can be estimated as follows:

$$MTTF(T) = \int_0^\infty R(t)\, dt = \int_0^\infty \left[\int_t^\infty f(\tau) d\tau\right] dt \int_0^\infty e^{-\lambda t} = \frac{1}{\lambda} \qquad (2)$$

Where λ represents the failure rate and τ is time interval of interest. High failures occurring during the early or later life stages of the component or sub-system are not adequately represented by an exponential PDF and alternatives must be sought (i.e. the Weibull distribution is often used to represent end-of-life failures). Reliability assessment in the DTOcean Tool will focus on the operating period of array devices where failure rates are assumed to be constant for the following reasons:

- The Tool database will be preprogramed with a set of failure rates and in the absence of MRE-specific data, failure rates from other relevant sources will be used, the majority of which are based on long periods of operation. The user will also be able to include relevant reliability data if available to override the preprogramed values.
- The operating period of array devices is likely to be considerably longer than the periods of early failure or wear-out. If particular components or subsystems are susceptible to these failure intervals, the user will be able to include their own reliability data.

In the first instance the priority for the Tool design modules (Array Layout, Electrical System Architecture, Mooring and Foundation Systems) will be to find a suitable solution which has the lowest capital cost. The calculation of system reliability will be based on a reliability function generated from each design solution and based on the relationship between each component and subsystem contained therein (e.g. Figure 1). In order to provide a full assessment of reliability, the user will be able to include other subsystems (e.g. power take-off system, structure and condition monitoring systems) with user-interaction provided via a Reliability Block Diagram. In addition to providing an overall statistical-based MTTF of the system, the time to failure (TTF) of each component or assembly will be utilised by the System Control and Operation module. Within this module time-domain stochastic (Poisson process) simulations will be conducted to plan maintenance actions, drawing from information regarding operational logistics, weather window availability and other maintenance strategies.

In order to find an optimal system configuration, the Tool will instruct the design modules to reconsider a different solution if the associated LCOE, reliability or environmental impact are deemed to be unacceptable (i.e. if they do not meet criteria pre-defined by the user).

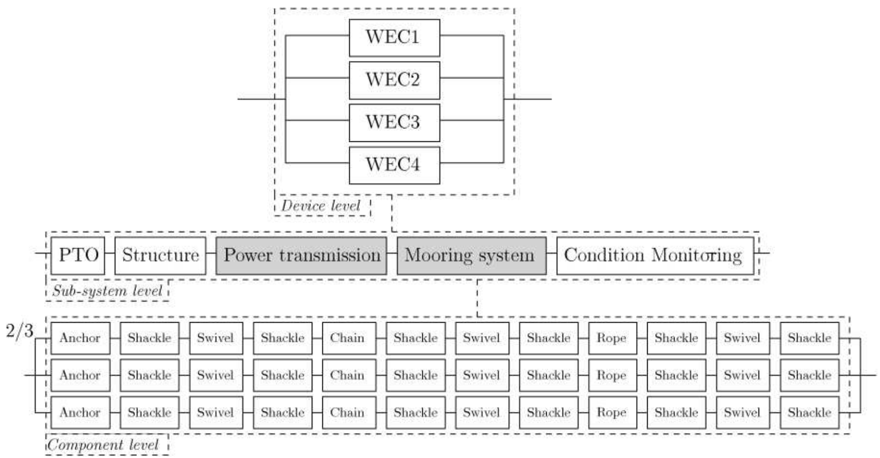

Fig. 1 Reliability Block Diagram for an array of four generic wave energy converters each with three mooring lines

III. Accelerated Testing

A. Motivation

The bottom-up statistical reliability approach utilises adjustment factors (i.e. relating to manufacturing quality; π_Q, operational environment; π_E or application; π_A) to an existing or base failure rate (λ_B) in the absence of failure rates which are specific to the application of interest:

$$\lambda_P = \lambda_B \pi_Q \pi_E \pi_A \quad (3)$$

Although this is a well-established approach the use of factors is not ideal as it can have a significant effect on the overall calculated reliability. For example Mil-Hdbk-217F [8] specifies a factor of 18 to adapt the failure rate of a synchronous motor from ground benign to naval sheltered conditions (Table 1). Assuming a base failure rate of 0.011 failures/10^6 hours (operating at 70°C [8]), the MTTF of the motor in both scenarios would be $90.91\text{x}10^6$ hours and $5.05\text{x}10^6$ hours. This simple example illustrates the inherent uncertainty with applying factors to adapt failure rates for very different situations and the potential cumulative effect of inaccurate reliability estimations on maintenance scheduling for arrays comprising 100s or 1000s of devices.

TABLE I
Environmental influence factors for synchronous motors adapted from Mil-Hdbk-217F [8]

Environment	Factor	Description
Ground, benign	1.0	Non-mobile, temperature and humidity controlled environment, readily maintainable
Naval, sheltered	7.0	Sheltered or below deck conditions
Naval, unsheltered	18.0	Unprotected, surface equipment exposed to weather conditions and salt water immersion

Plugging the knowledge gap between generic failure rates and direct experience is not a trivial task for device developers at low TRLs with a limited number of operating hours in the field. At the time of writing developers at higher TRLs have already clocked up significant operational times (e.g. [9]) but concerns in the sector over intellectual property and disseminating device performance data have hampered the sharing of reliability data across the sector. It is likely that the need to improve device designs will drive the creation of a MRE reliability database. This is likely to follow a similar format to the Offshore REliability Data (OREDA®) database [10] which has been developed by several prominent oil and gas operators over the past 34 years. Although reluctant to share reliability information at first, concerns over confidentially were overcome by anonymizing the data and categorizing it into generic subsystems. Similar collaborative endeavors for reliability data collection and modelling have recently been started for tidal energy; TiPTORS (Tidal Turbine Power Take-Off Reliability Simulation programme, [11]) and offshore wind; SPARTA **(**System performance, Availability and Reliability Trend Analysis, [12]).

In the absence of field data accelerated testing provides a cost effective means of assessing component and subsystem performance and durability in a controlled environment. In conjunction with numerical analysis, experimental testing allows designs to be improved in order to reduce the risk of failure occurring in the field, where failures are often costly and difficult to rectify. Funding programmes such as the Marine Renewables Infrastructure Network (MARINET, e.g. [13]) have enabled free-of-charge access to particular test facilities, often for this purpose.

One of the key requirements of accelerated testing is to ensure that (within practicable limits) the test conditions used are representative of those experienced by the component in the field. In this section two case studies involving synthetic mooring ropes and shackles are presented to demonstrate how standardized accelerated test procedures can inform the reliability assessment of components and subsystems. In addition initial tests were recently conducted using the University of Exeter's Dynamic Marine Component test facility (DMaC) to investigate the feasibility of time-accelerated tests for synthetic ropes [13].

B. Background

Synthetic ropes have been used for the past two decades by the offshore industry for a range of permanent and temporary mooring applications. With this track record and favourable properties it is unsurprising that these materials have been adopted by MRE device developers keen to specify mooring components which are both economic and durable [14]. Extensive testing programmes have been developed by the offshore industry to characterise the performance and durability of these materials, two aspects which are key in the potentially harsh operating environments synonymous with offshore oil and gas exploration platforms. Two standardised test procedures [15] that are used to determine the durability of ropes and yarns include the thousand cycle load level [16] test (which is used to obtain a first indication of tension-load cycle or T-N curves) and yarn-on-yarn abrasion tests [17]. In this paper yarn-on-yarn abrasion tests focusing on one failure mode, abrasion wear, are reported.

Shackles are typically specified by a working load limit (WLL) and a minimum break load (MBL), with yield and tensile strengths provided by the manufacturer upon request. For what is a widely used component, stress-load cycle (S-N) curves are often difficult to obtain and this makes fatigue analysis problematic. DNV-OS-E301 [18] recommends the use of B1 curve parameters from DNV-RP-C203 [19] to determine the fatigue life of long-term mooring shackles associated with a 97.7% probability of survival:

$$\log(N) = \log(a_D) - m\log(s) \quad (4)$$

where N is the number of cycles to failure, a_D and m are the intercept parameter and slope of the S-N curve respectively and s is the stress range (double amplitude) in MPa.

The MRE sector can draw upon existing offshore experience and design practices, and clearly mooring system requirements for both applications are equally challenging. However the requirements for MRE mooring systems are potentially unique, due to differences in the mass and size of the moored equipment, consequences of mooring line failure, dynamic response characteristics and operating water depth. At one end of the spectrum commonality may exist between the mooring load cases of existing offshore equipment and floating wind turbines or large multi-use systems (e.g. the Poseidon Floating Power Plant [20]) because these systems are designed to provide a stable platform. At the other end of the spectrum, motion-dependent devices actively encourage dynamic responses for the purpose of energy extraction (such as Carnegie Wave Energy's CETO 5 device [21]), resulting in highly dynamic mooring loads. Over the lifetime of a device deployment (i.e. usually envisaged to be between 20-25 years) any type of mooring system will be subjected to a large number of fatigue load cycles and several studies have used load cycle counting techniques to predict component lifetimes (e.g. [22, 23]). Therefore it is crucial that reliability analysis, supported by physical component tests using realistic loading conditions, is carried out in order to ascertain component durability over these time-scales.

C. Nylon yarn-on-yarn abrasion tests

As part of the Marine Energy in Far Peripheral and Island Communities (MERiFIC) project rope and yarn tests were conducted at the University of Exeter and L'Institut français de recherche pour l'exploitation de la mer (IFREMER), the findings of which are reported in a number of papers (including [14, 24-26]).

One of the main degradation mechanisms of synthetic ropes in dynamic marine applications is friction-induced abrasion wear occurring between contacting fibres. In order to mitigate this effect, marine finishes are applied to yarns during rope manufacture [27] and yarn-on-yarn cyclic tests are used to determine the effectiveness of these finishes in prolonging the fatigue life of yarns. Using the methodology described in [28] and equipment shown in Figure 2, 16 new and 16 aged nylon yarn samples were cycled until failure at IFREMER. The aged yarn samples originated from the outer sub-rope of a 44mm parallel stranded rope deployed at sea for 18 months on the South West Mooring Test Facility (SWMTF, [29]). The new and aged yarns were subjected to four different mean loads whilst immersed in natural sea water.

TABLE II
NUMBER OF CYCLES TO FAILURE FOR THE RESULTS PRESENTED IN FIG. 2

Yarn condition	Average load [g/dTex]	Log_{10} cycles to failure		
		Minimum	**Maximum**	**Average**
New	0.12	4.69	5.09	4.87
	0.21	3.62	4.26	4.06
	0.31	3.24	3.71	3.45
	0.40	2.61	3.04	2.81
Aged	0.12	3.4	4.95	4.07
	0.21	1.48	3.22	2.17
	0.31	1.30	2.79	1.79
	0.41	1.34	2.15	1.74

Fig. 2 Yarn-on-yarn abrasion test machine at IFREMER set up ready for testing (from [25])

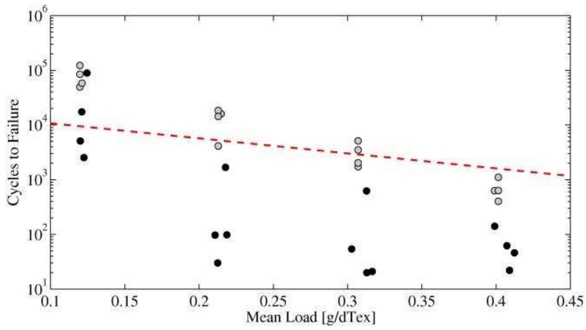

Fig. 3 Yarn-on-yarn abrasion tests of new and aged yarns (grey and black markers respectively, from [25]). Mean loads have been normalised by dTex, a measure of mass per unit length (units: g/10km). Minimum cycles to failure as defined in Flory [27] are shown as a dashed red line

From the results presented in Table II and Figure 3 it is possible to define linear trend lines to describe the relationship between mean load (*T*) and number of cycles to failure (*N*).

New yarns (R^2 = 0.9345):

$$\log_{10}(N_{new}) = -7.2396T + 5.6824 \quad (5)$$

Aged yarns (R^2 = 0.5542):

$$\log_{10}(N_{aged}) = -7.7221T + 4.479 \quad (6)$$

Cordage Institute minimum cycles to failure (adapted from [27]):

$$\log_{10}(N_{MCF}) = \log_{10}(20220e^{-6.332\mathrm{T}}) \quad (7)$$

Scatter in the aged yarn results is significant, as reflected through a much lower coefficient of determination (R^2) than the new yarns. The generally poor and more variable yarn performance of aged yarns also observed in break and cyclic tension tests has been attributed to wear and structural rearrangement occurring in service [25]. It is interesting to note that the slopes of plots of applied load versus cycles to failure in the yarn abrasion tests are similar to T-N plots for ropes [30]. Flory noted in [27] greater fatigue performance of rope and yarn samples coated in a marine finish compared to untreated samples. However, further fatigue testing is required in order to fully determine if the lifetime of a rope can be accurately predicted based on yarn performance.

D. Mooring shackle tests

As part of a review of safety factors used in mooring design, a set of B.S. 3032 galvanised steel shackles (WLL: 24.5kN, MBL: 122.6kN) was subjected to break and fatigue tests. The break tests were used to identify the elastic range of the medium strength shackles and hence inform the load ranges specified for fatigue testing. Only the fatigue tests are reported in this paper, but for further details about the study the reader is directed to [31]. The shackles were subjected to constant amplitude cyclic loads ranging from 10-90kN at a frequency of 2Hz using the DMaC test facility (Figure 4, [32]). Three different exposure levels (or number of load cycles) were used to compare the effect of aging on fatigue performance. The purpose of this was to induce fatigue cracking and create fatigue failures.

It should be noted that the focus of the study was to investigate the effect of pre-aging on the ultimate strength and fatigue performance of the shackles, not to fully define shackle fatigue behaviour in the standardised S-N curve format. In order to do this a minimum number of 15 samples must be tested using at least three stress ranges [33].

Fig. 4 Shackle setup in the DMaC test facility (from [31])

TABLE III
NUMBER OF CYCLES TO FAILURE FOR EACH SHACKLE

Shackle	**Exposure level**	**Failure type and location**	**Log_{10} load cycles**
10	Low	None	3.70
11	Low	None	3.70
4	Medium	None	4.29
5	Medium	None	4.29
6	Medium	Break (bow)	4.29
7	High	Fatigue crack (pin)	4.39
8	High	Fatigue crack (pin)	4.39
9	High	Break (centre of pin)	4.39

The results listed in Table III indicate that a range of failure modes were observed (e.g. Figure 5), the locations of which were different from the break tests but correspond with areas of weakness identified by Finite Element Analysis [26]. Dye penetrant testing was used to locate fatigue cracks in the pins of shackles 7 and 8.

Fig. 5 Comparison of (*left*) failed shackle 6 and (*right*) undamaged shackle (from [26])

Following fatigue testing some of the aged shackles were deployed along with new shackles on the SWMTF for almost 6 months. The maximum mooring tensions measured during this period were low (just over 10kN) and as expected, no failures were observed nor further fatigue cracks.

TABLE IV
B1 S-N CURVE PARAMETERS FOR SHACKLES IN AIR [19]

Log_{10} load cycles	***m***	a_D
≤ 7	4	15.117
> 7	5	17.146

The shackles failed at approximately 11% of the number of cycles expected according to the DNV S-N curve for shackles in air (defined by the B1 parameters listed in Table IV and Equation 4). It is thought that the lower performance of the shackles was due to the fact that the mean load (and stress) were non-zero due to the applied pretension, which is contrary to the fully reversed fatigue loading assumed in the S-N curves. Further discussion regarding this point is provided in [31]. Manufacturing defects could have also contributed to the early failures observed and further testing with larger sample sizes is required to confirm if this is the case.

E. Application and suitability of the Pålmgren-Miner rule

For a given set of environmental conditions it is possible to estimate the long-term damage sustained by a component using linear damage accumulation methods such as the Pålmgren-Miner rule. In the case of a mooring component, counting techniques such as rainflow analysis [22] are used to discretize the simulated or measured tension time-series (which corresponds to a set of design environmental conditions) into a number of tension or stress cycles. By convention T-N plots tend to be used for synthetic ropes, with the y-axis representing the ratio of tension range to MBL (e.g. [34]). S-N plots are typically used for all other mooring components where the y-axis represents to nominal stress range (e.g. [18]). Typically T-N and S-N design curves are based on the mean of data minus 2 standard deviations. The Pålmgren-Miner rule is used to calculate the overall damage sustained by the component by combining all of the damage contributions at each stress magnitude or tension ratio.

Although widely used this technique has two key drawbacks [35] which must be acknowledged:

1. Damage is accumulated by discrete events (i.e. load history and its effect on material state are not considered).
2. The rate of damage accumulation is independent of stress or load level.

The yarn-on-yarn fatigue test results and characteristic formulae presented in this paper can be used to estimate the abrasion damage experienced by a set of yarns subjected to different mean loads. It should be noted that whilst T-N curves exist for synthetic ropes (e.g. [34]) the experimental data that these curves are based upon are likely to be influenced by several fatigue mechanisms, not just abrasion wear. Shackle test results have also been presented in this paper, with the occurrence of several failure modes observed in response to harmonic loading. In reality, the tensions experienced by mooring components are stochastic in nature and hence vary not only in terms of mean load but also load rate and amplitude. Therefore whilst these results can give an indication of damage accumulation, the influence of load rate and amplitude is not considered. A potentially more suitable approach for dynamically responsive moored equipment would be the application of simulated or measured tension time-series which is representative of operational and extreme conditions instead of repeated harmonic loading [25].

F. Implications for Reliability Assessment Within the Tool

The value of component fatigue test data to reliability assessment is that it defines a benchmark which must be met by a component for all expected operating conditions. Furthermore it provides insight into the mechanisms through which failure occurred. If the proposed operating conditions are not known or fully described (such as the number of cycles for each tension or stress range), then a statistical approach can be used in conjunction with fatigue data to provide a fast estimate of component reliability. This is a suitable approach for early stage designs as it provides more detail than single, generic component failure rates, particularly those which have been adapted using unvalidated application factors. By identifying a dominant stress or tension range (or mean load) the number of cycles to failure could be estimated from a fully defined fatigue curve. For example with the yarn-on-yarn results, the independent variable; mean load is analogous with the application factor described in Section 2. Combining this with an estimate of the number of cycles expected for a given time interval would lead to an estimation of the TTF of the component. It is acknowledged that this would not provide as accurate an estimate of component reliability as full damage accumulation analysis because not all of the discretized cycles would be considered.

IV. Conclusions

A suite of design tools are being developed as part of the DTOcean (Optimal Design Tools for Ocean Energy Arrays) project to accelerate the deployment of the first generation of MRE arrays. Each design solution will be assessed in terms of LCOE, environmental impact and reliability. In this paper the reliability assessment method which will be used by the Tool has been introduced.

A general lack of long-term deployment experience within the MRE sector presents a very real problem for developers wishing to predict the reliability of their own device or array of devices. A large knowledge gap exists because either a particular design or component has never been used in this application, or if it has the sharing of performance data is restricted by concerns over intellectual property. Adapting generic failure rate data will produce an estimate, but it will be at best crude and at worst wildly inaccurate. The implications of reliability uncertainties are large and will have a direct impact on the LCOE of each device, with this problem further compounded by scaling up to commercial arrays.

The combination of component reliability testing and numerical modelling is pivotal to reducing reliability uncertainties. By conducting tests in a controlled environment which is representative of the expected operating conditions the aforementioned knowledge gap can be reduced. At low TRLs this process provides a cost effective way of assessing component performance. At later TRLs it can be used to ‘iron out’ design flaws in order to improve whole system reliability. Two case studies have been presented in this paper to demonstrate how accelerated testing can contribute not only to understanding how components fail, but also when failures can be expected to occur and under which conditions. Although many failure mechanisms are complex and involve multiple factors, the time to failure of components can be readily estimated from this data. This allows suitable design solutions to be quickly identified prior to detailed design and analysis.

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