ADVANCE IN MODELLING AND STRUCTURAL DESIGN OF WAVE ENERGY DEVICES

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ABSTRACT:

Despite the fact that the wave energy is a large resource of energy, the wave energy sector has not still delivered a cost competitive solution. The structural design of wave energy device (SDWED) project aims at accelerating the development of the sector. The project gathers international research communities around the development of design tools and a common design basis for wave energy devices in order to make these devices more competitive. The prospect of an overall wave-to-wire model has the potential of lowering the cost of energy and increasing the reliability of wave energy devices.

1 Introduction

The ongoing debate about climate change, and the decreasing availability of fossil fuels, makes it continuously more relevant to develop renewable energy sources for the future. At present, the wave energy sector has still not delivered cost competitive solutions. However, the sector has already demonstrated that it has the potential to become a major contributor of energy worldwide and various devices, with large potentials to be economical viable, are getting closer to commercialisation.

Wave energy is a developing technological area and a number of technical barriers still need to be overcome. In 2009 the Danish Strategic Research Council granted funding for a strategic research alliance project called “Structural Design of Wave Energy Devices" (SDWED). This project was initiated in 2010 and is ending ultimo 2014. It has aimed at accelerating the development of the wave energy sector towards a reliable and economical industry as well as increase the reliability of wave energy devices (WED), though amongst other, development of wave–to–wire modelling tools.

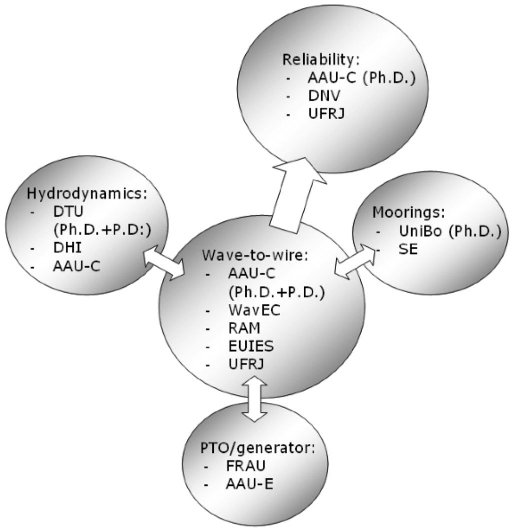

Figure 1: SDWED project overview, definition of the work packages, including interconnections and partner abbreviations.

2 Background

The SDWED project is an international research alliance consisting of 12 main partners (6 Danish and

6 international) which over a five–year period has developed ambitious wave–to–wire models. The wave–to–wire models (WP4) have been focused on bringing together modelling modules providing sufficiently detailed descriptions of parameters related to hydrodynamics (WP1), moorings (WP2) and power take–off (PTO) (WP3) in order to be able to model the resulting behaviour of the device. The topic of wave–to–wire modelling of wave energy devices (WEDs) is not an entirely new concept, but what has been in focus in this project has been development of tools and modules which are the most relevant for WED design and optimisation, recognising the different needs related to operating and extreme conditions, as these are highly related to power production optimisation and the structural design. Since the field of WEDs is very diverse the idea has been to advance the modelling through improvement of the building blocks, the modules, going into the wave–to–wire models, taking into account the complexity, non–linear behaviour and interactions of the systems. Furthermore, as the target of the models is to be able to carry out optimisations, a balance between computational speed and accuracy has been in focus. An additional topic has also focused on enhancing the reliability of WEDs (WP5). The 5 WPs of the project, their internal relations and involved partners are illustrated in the Fig. 1. The developed models have been engaged to model WEDs with increasing complexity, starting out with a fixed structure with one (and later on more) degrees of freedom (DOFs) using the Wavestar as example, going via a floating wave activated body (WAB) hinged–barge type WED with a single DOF, and ending with a floating multi–body WED with variable geometry, using the Weptos WEC as example.

3 Methodology

In the project the developed models have also been utilised for optimising the WEDs through optimisation of control strategies, not only looking at maximising power production, but also balancing this target against structural wear. The developed models, and modules hereof, have also been subjected to validation studies against performed laboratory tests. This has entailed the need for developing laboratory models enabling use of PTO models were advanced real–time control algorithms can be applied. In the following an overview of the main outcomes, divided for each work package, will be presented together with its capabilities. In each of the work packages significant progress has been made in terms of modelling systems and applying them to real cases.

4 Key Findings

The results and outcomes of the project have continuously been disseminated through scientific publications, public outreach activities, including three project symposia held throughout the project period, Ph.D. courses, researcher exchanges, etc. Most of the produced material has been made available at the project website (www.sdwed.civil.dk), which will be maintained after the end of the project, to ensure its legacy. The website includes lists of publications, thesis, softwares, deliverables and events for all the interested parties. The deliverables cited in the following text can be download at the link reported in the bibliography.

4.1 Hydrodynamics – WP1

This section gives an introduction to the methodologies used to predict the hydrodynamic interaction between a floating object and the passing waves, with focus on the identification of a cost effective solution. Four different levels of analysis exist to describe the wave–body interaction:

Level 1 Linear analysis in the frequency–domain

Level 2 Weakly nonlinear analysis in the time–domain

Level 3 Fully nonlinear analysis without wave–breaking

Level 4 Fully nonlinear analysis including wave–breaking and viscous effects

The models are listed with increasing refinement and computational effort. Level 1 of analysis is based on the solution of the linearised potential flow problem, obtained from boundary element method softwares. Inviscid fluid in irrotational motion and small waves (radiated, diffracted and incident) are the underlying assumptions of the method. The solution to the simplified wave–body interaction problem presents clear benefits. The computational time is kept to a minimum, and for large quasi–static bodies the numerical solution has been proven to be reliable, e.g. naval and Oil & Gas industries. However, some limitations exist that bound the applicability of the method. Especially for small size WEDs, such as Point Absorbers, the large motion induced by the sought resonance condition between floater and wave violate the underlying assumption. On the one hand, the description of non–linear loads, such as hydrostatic and Froude–Krilov, becomes cardinal due to the large displacement of the body from the equilibrium position, while on the other hand, viscous loads are likely to be of paramount importance due to the flow separation caused by the large relative velocity. It is important to bear in mind that “small size" is defined as relative to the characteristic wave length of the deployment location.

Level 2 of analysis is meant to give a description of the non–linear hydrostatic and Froude–Krilov contribution using the linearised Level 1 of analysis as a base for the radiation and diffraction forces. Both non–linear hydrostatic and Froude–Krilov contributions can be put into a convenient form which depends only on the submerged volume of the body bounded by the undisturbed incident surface elevation on the inside of the body, [22].

Level 3 of analysis extends the previous step by incorporating a fully non–linear hydrodynamic description of the incident and radiated problem to the previously defined non–linear hydrostatic and Froude–Krilov contribution, see [2]. The assumption of a potential still hold but the method is still of impractical use due to the capturing and re–griding issues of the moving body and water line to high–order accuracy. An important step toward the fully non–linear solution is presented in D1.3 [3], where a finite–difference based approach to wave–structure interaction is reported which employs the overset approach to grid generation.

Level 4 of analysis assumes only incompressible fluid, without limiting the type of flow around the body. The open source CFD code OpenFoam can be used to solve the incompressible Navier–Stokes equation together with a Volume of Fluid (VoF) technique for capturing the free–surface. The software can capture violent wave–body interactions, but the large Reynolds number associated with the turbulent flow does not allow a full resolution of the problem. The solution is largely affected by the turbulent model used, creating the need for a validation step.

Nevertheless, the viscous load caused by the high velocity of the moving WED can be roughly introduced by using a Morison’s equation type approach on top of either Level 1 or 2 models. From the Morison’s equation only the quadratic viscous drag load is used. Although the approach is convenient from a computational point of view, the main uncertainty lies in the definition of the drag coefficient under oscillatory flow. Both experimental and numerical data set can be used to estimate the magnitude of the coefficient, but only few example are given in the literature so far.

4.2 Mooring – WP2

In order to harvest the wave energy content from deep water zones, the design of an efficient and reliable mooring system is of paramount importance for the sector. Deep water zones are associated with higher energy levels as well as lower environmental and visual impacts. In general, the mooring system must be sufficiently rigid to allow station keeping, docking for inspection and maintenance, but at the same time sufficiently flexible to minimise the forces acting on anchors, mooring lines, power transmission cables and on the device itself. Therefore the mooring system is an essential component in the design process and feasibility assessment of the WED installation.

Furthermore, the design of mooring systems has often proved to be insufficiently reliable, leading to the failure of large scale WEDs.

In order to get a first idea of the feasible design options a quasi–static approach can be used. The simple design procedure described in D2.2 [4] can be summarised in the following steps list:

- Metocean data retrieving at the particular site of installation
- Definition of the design weather conditions
- Identification of the mooring layout: number of mooring legs, dimensions of chains, ropes, buoys and clump weights.
- Calculation of the static properties of the mooring system
- Calculation of the mean offset due to wind, current and mean wave drift forces.
- Calculation of the global, horizontal, linearised stiffness of the mooring system around the mean offset position
- Calculation of the horizontal response motion
- Calculation of the mooring loads

The procedure need to be repeated until the standardised design rules are fulfilled. Due to the model simplification adopted, a safety factor need to be applied though.

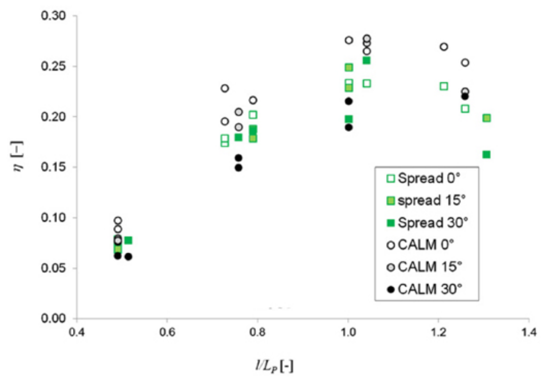

Figure 2: Variation of the system performance in function of the mooring type.

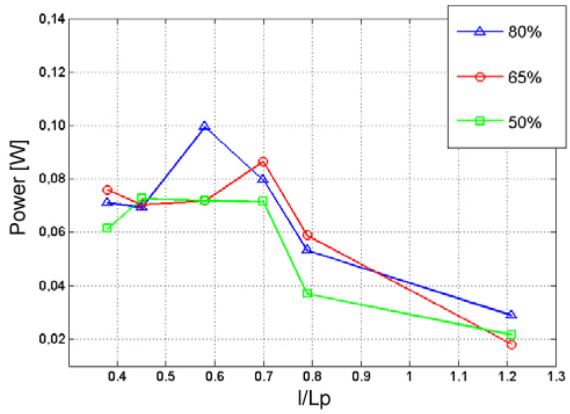

Figure 3: Variation of the system performance in function of the mooring pretension.

Among the others, the identification of the suitable mooring layout is a difficult conundrum. It is important to bear in mind that the design of a mooring system it is not just an exercise of strength calculation. The mooring system affects the motion and the efficiency of the WED, which in–turn is correlated to the economical feasibility of the technology.

Both numerical and physical models should be used to identify some (few) promising configurations, which can then be applied to a detailed design procedure.

An example of the identification of the best mooring configuration using data from the physical model of a floating Wave Activate Body WED is presented in Fig. 2 and Fig. 3, [5, 6]. Fig. 2 presents the comparison between two different mooring configurations: a spread mooring system and a Catenary Anchor Leg Mooring (CALM) system. The efficiency of the WED have been evaluated for different wave directions and wave frequency for both mooring configurations. Fig. 3 presents the comparison between the efficiency of the WEDs in function of the pretension of the chains for the spread mooring layout only.

Numerical models are also important in the screening phase of different mooring layout. In contrast with naval and Oil & Gas industries where a quasi–static description of the mooring system is often pertinent due to the large system inertia, for WEDs in order to predict the loads acting on the mooring system a dynamic solver should be used. In fact, WEDs are often meant to move at high velocity, leading to a possible important dissipation of energy throughout the mooring lines. Fig. 4 shows the comparison between the load time series predicted by a dynamic solver (blue line) and the quasi–static solution (black line) and the measured data (red line). Even though the magnitude of the mooring load is well described by both the numerical solution, there is a clear phase error in the quasi–static solution, which can lead to a very different body response. The D4.6 [7] presents few examples of the utilisation of the dynamic cable solver MOODY, developed by Chalmers University [21]. As summarised in Fig. 4, the solver presents an interesting accuracy, but at the actual stage of development it is still too slow (in term of computational time) to be applied in a (fast) wave–to–wire model, which is one of the task of the project.

4.3 Power Take–Off – WP3

Apart from special applications, e.g. sea water desalination, WEDs are intended to produce electrical energy and thus an electrical generator is a key element of the system. The selection of an appropriate generator together with the whole power take–off system highly depends on the WED type and working principle.

Overtopping and oscillating water column WEDs fit the utilisation of rotary electrical machines, since the primary actuator is a rotating turbine. In contrast, WEDs of the Wave Activated Body type are usually associated either with a low rotational speed or linear motions, giving rise to the need for diverse power take–off architectures.

For the latest case both rotary and linear electrical machines can be used. On the one hand, for the former type of electrical machines an intermediate conversion step, such as rack and pinion, overrunning clutch, hy-

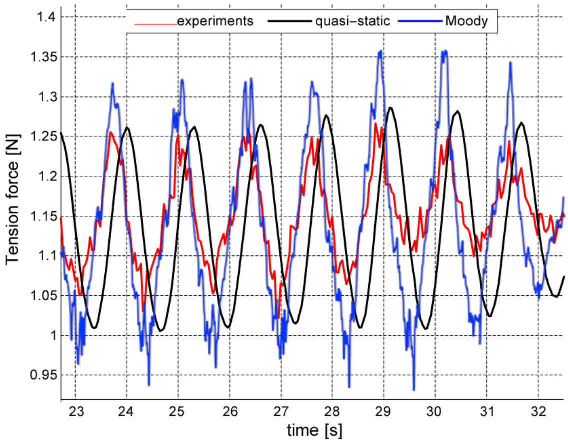

Figure 4: Tension force at the fair–lead of cable 2 from quasi–static analysis, experiments and MOODY.

draulic, etc., need to be interposed between the moving body and the generator. These transformations introduce a loss of energy and involve a reduction of the overall reliability of the system due to the higher number of component involved. On the other hand, using a linear electrical machine greatly simplify the overall system complexity, but some consideration need to be made regarding the electrical machine itself.

Rotating electrical machines are used in many applications, i.e. industry, transportation and conventional and renewable energy production. In the power range of interest today several off–shelf solutions are already available. Linear electrical machines in the power range of interest are tailored machines, resulting in higher engineering effort, costs and development risks. Furthermore, in consequence of the high forces and low speeds exerted by the WED, only heavy and expensive machines can be used.

As no long term experiences with such systems from offshore installations exist their reliability, exposed to millions of load cycles per year, is sometimes questioned. Similar conclusion can be sketched for both rack and pinion and overrunning clutch systems.

Hydraulic systems coupled with rotating generator gives a reliable and robust layout, but the actual overall efficiency is still low. This is subject to current research and significant improvements can be expected in the future.

Considering the requirements in WED applications, there is a range of rotating electrical generators that are technically adequate for these applications. Possible candidate generator systems are:

- Doubly fed induction generators (DFIG),
- Asynchronous Generators (ASG),
- Permanent magnet synchronous generators (PMG),
- Separately excited synchronous generators (SG).

Independently of the type of generator used, the generator has to be coupled to the grid by a frequency converter (FC) to achieve a variable speed system. The study analyses the specific characteristics of the different types of generators and general aspects of the state–of–the–art of generator systems. Further details about the identification and discussion about generators suitable for the wave energy sector can be found in D3.2 [9] and D3.3 [10].

A further aspect, receiving increasing consideration, is the need for energy storage systems (ESS) in WEDs, D3.1 [8].

Various energy storage techniques for WED have been investigated, including e.g. fly–wheel, hydraulic/air accumulator and super–capacitor, etc. The energy is stored in various energy forms and is placed at different locations in the WED systems. Each technique has its benefits and disadvantages when evaluated from many different aspects, such as system complexity, efficiency and cost. In general, from the efficiency and cost point of view, locating the energy storage system at the front end (the terminal that is close to the wave energy absorber) will provide smooth energy to all the following WED components in the wave–to–grid path. This avoids oversizing these components since they do not need to handle the peak power, which could be several times higher than the average power. Therefore, the system efficiency could be increased and all the components will work at close–to–rated conditions with optimised performances. Fig. 5 shows an example of the expected efficiency trend in function of accumulator size and hydraulic motor displacement for fixed accumulator pressure, generator size and sea state. Generally speaking, three key parameters need to be carefully designed:

- accumulator size – the maximum allowable accumulator gas volume.
- hydraulic motor capacity – the maximum hydraulic pump/motor displacement, and
- system pressure – system maximum allowable pressure.

The increasing of accumulator size and system pressure has the same purpose to increase the energy storage capability of the system. In order to ensure the hydraulic motor to work in the high efficiency range, the system pressure should match the required rated pressure difference of the hydraulic motor. After determining the system pressure, suitable accumulator size can then be found, in order to obtain sufficient energy storage capability. It should be noticed that it is not always good to increase the accumulator size to pursue higher energy storage capability. Big accumulator size will lower the system pressure and reduces the efficiency of the hydraulic motor. Therefore, a suitable accumulator is better than a large accumulator when designing hydraulic energy storage system. Hydraulic motor capacity can influence the system performance in different ways:

- Large hydraulic motor capacity can transmit the input hydraulic energy to the mechanical energy in a short time. It reduces the requirement on system energy storage capability. Therefore, smaller accumulator and lower system pressure can be applied, and the cost of accumulator and connecting lines is reduced. However, a large electric generator is then needed to absorb the large instantaneous power transmitted by the hydraulic motor. The cost of hydraulic motor and electric generator will be increased.
- Small hydraulic motor capacity can only transmit limited hydraulic power in a short time. Large accumulator and system pressure is required to provide sufficient energy storage capability. The inrush hydraulic power is stored in the accumulator and is used to drive the hydraulic motor after the inrush. Hydraulic motor has a continuous input, and it will have higher average efficiency and more smooth output torque/power.

For those applications in which the energy input is allowed to experience a large variation, e.g. different sea states in an energetic wave location, the chosen system parameters should balance different input profiles to obtain the highest possible average system efficiency. Relative low hydraulic motor capacity and high system pressure is preferred for such application. Such combination can ensure that the hydraulic motor works with a relative high average efficiency and give much smooth output torque. The electric generator should be selected to meet the output characteristic of the hydraulic motor. The generator should be able to absorb the inrush power from hydraulic motor, so that hydraulic motor capacity will not be limited by generator over torque protection (torque PI regulator),

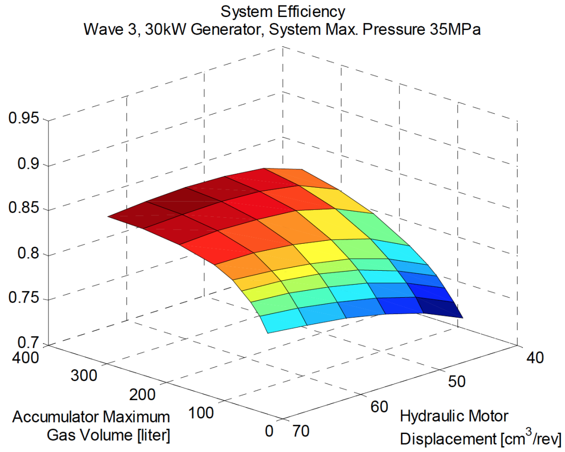

Figure 5: System efficiency optimisation at a moderate sea state (30kW generator).

and ensure that the hydraulic motor works in the high efficiency range.

The utilisation of PTO models with a high level of detail is generally avoided within the framework of a (fast) wave–to–wire model. Nevertheless, it is possible to model the main influence by means of simplified and calibrated linear and non-linear models.

4.4 Wave to wire modelling – WP4

The three subsystem introduced so far describe the most important elements for the determination of WED performances. Several others are indeed present but their contribution to the overall system design is, in general terms, of secondary importance. In order to optimise the design of a WED, the analysis of the motion and forces based on the three subsystems is of paramount importance. The assessment is typically based on software simulations of the full–scale WEC design and/or on reduced–scale experimental studies in wave tanks. Numerical models simulating the full energy conversion system from the wave energy resource to the power production are often referred to as wave–to–wire models. A growing number of commercial software packages which can perform such calculations exist, but recently also free alternatives have become available, see D4.10 [11]. However, existing state of the art methods suffer from shortcomings when it comes to realistically reproducing the behaviour of WEDs, thereby leading to large uncertainties in the cost of, and the electrical energy production from, the devices.

In order to mitigate the large uncertainty in the

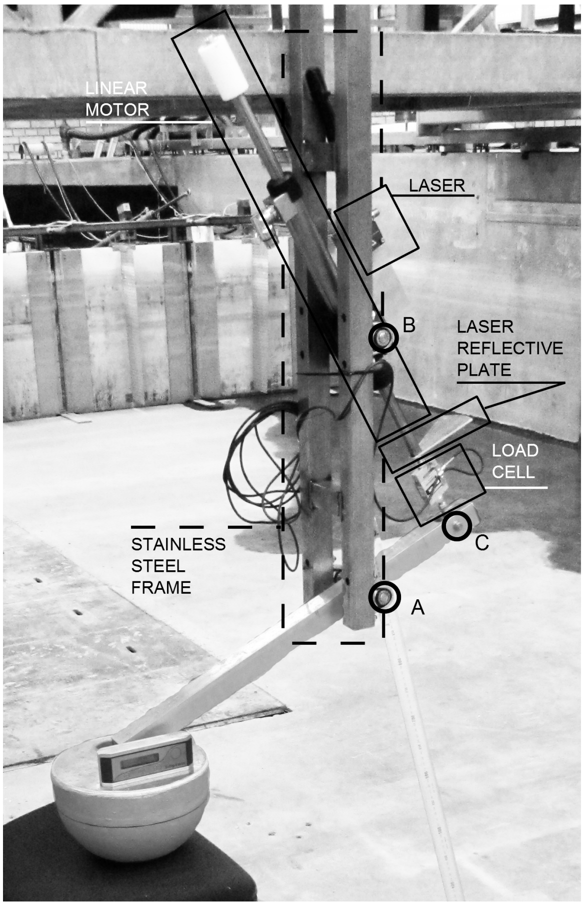

Figure 6: Physical model of the Wavestar device single floater, with advance PTO system.

model output experiment data sets can be adopted as a benchmark solution (validation). Experimental testing in wave tanks of small–scale WEDs can provide valuable knowledge about the hydrodynamic behaviour of the device, D4.1 [1]. The Froude model law provides good accuracy for scaling the waves, forces and motions up to real scale. Unfortunately, realistic PTOs cannot be scaled down for direct use in small–scale model tests. A solution is to equip the device with a mechanism that imitates the behaviour of the real PTO. Fig. 6 shows an example of a physical model of WED, the Wavestar device single floater at scale 1:20 developed at the Civil Engineering Department of Aalborg University, (wave energy research group). The physical model enables real time control of the PTO feedback force making application of advance control algorithms possible at lab. scale. A detailed description of the system is given in D4.1 [1].

Once the uncertainties of the wave–to–wire to model have been quantified by comparison with experimental data, the model can be used within an optimisation loop. The first level of optimisation can be achieved by controlling the PTO force acting on the WED. Several different strategies have been proposed, with a theoretical improvement of a factor 2–3 in constrained conditions if compared with a simple passive PTO control strategy, D4.3 [12, 13]. The same approach can be extended to an array of WED as presented in D4.4 [13]. In this case the effect of nearby body interacting with the waves reduce the efficiency of the single machine, but the application of a control strategy with interaction coefficients can damp this effect out. In order to highlight the importance of the validation of the numerical results with experimental data, a set of experiments has been run with a simple WED (single floater Wavestar scale 1:20), D4.2 [14]. In general, for a simple WED the numerical simulation agree with the experimental solution in case of a simple controller.

The main drawback of this first level of optimisation is the absence of the influence of the control loads into the structural design of the WED. When an advanced control strategy is adopted, the PTO loads can be up to ten times larger than the simple controller case. This entails not only that the PTO system should be design for larger loads, but also that the structure will be affected by the enlarged stress levels. D4.8 [15] shows the analysis of the influence of the control loads into the fatigue response of the single floater Wavestar system. The topic is also analysed with the PhD project presented in [17, 16].

Software to assist in the modelling of wave energy converters has been developed in the SDWED project. The software can be freely downloaded using the links at the project website, and it may assist or, in other ways, help wave energy developers to design or optimise specific WEDs using “low budget" software solutions. The main part of the software is toolboxes written in Matlab and Simulink, so these programs are required in order to use the software. The software is provided "as is" without warranty of any kind. No support from the authors can be expected, but anyone is welcome to modify, adjust and use the software as desired.

4.5 Reliability – WP5

Along with the identification of the productivity of the different WEDs, the identification of the systems' reliability contributes to the overall assessment of the devices and sector feasibility. In traditional deterministic

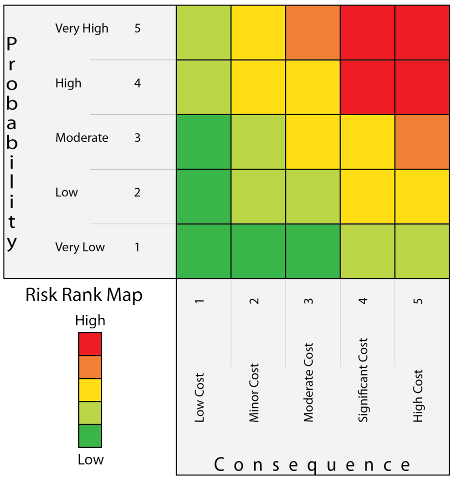

Figure 7: Risk matrix

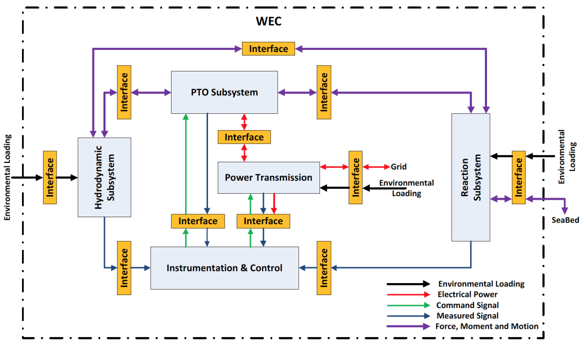

Figure 8: Exemplification of the system breakdown for the Wavestar device.

approach the design parameters are determined by the value of the safety factors, which reflect the uncertainties of the design methodology. Improved design with a consistent reliability level for all the components can be obtained by use of probabilistic design methods.

The first act in a probabilistic design method is the identification and quantification of the different risks associated with the device, see Fig. 7. The risk assessment is a fundamental step, particularly for new application of novel nature, where new uncertainties and technical challenges, which are not covered by conventional standards, can arise. The full description of the risk based design method specialised for WEDs is presented in SDWED deliverable 5.2 [18].

The key points of the methods are the technology and risk assessment. The system breakdown, shown in Fig. 8, is used to perform the technology assessment. The WED is divided in subsystems and for each of them a technology class is identified. Following, from the definition of the probability and consequence classes the subsystem risk is quantified. The probability is defined from the failure probability and the technology class, while the consequence class is derived from the quantification of the direct cost, plus the accessibility of the device.

The assessment of the detailed reliability level comes after the identification of the components associated with a high level of risk. For the assessment different design load cases are used. For example for the case of extreme loads four different cases are used: extreme loads in operation, extreme loads in operation with fault, extreme loads in parked position and extreme loads during installation and transportation. An example of extreme loads in fault mode is given in D5.3 [19]. Along with extreme loads also fatigue loads have an impact on the overall system reliability, [20].

The other two steps needed before performing the reliability assessment are the identification of the input uncertainties, (wave states and wave model uncertainties) and the definition of the maximum annual probability of failure of structural components, as described in D5.3 [19]. In general, some uncertainty levels can be inherited from nearby industries, but there are other wave energy specific uncertainties, e.g. wave model that need to be quantified by applying probabilistic methods. Due to the absence of specific standardisation for WED it is a good procedure to consider the same probability level of the wind turbines, given that a major failure does have low environmental and human impacts.

An application of the reliability assessment is presented in D5.4 [20], in which the method is used to calibrate the fatigue design factor for a WED. The fatigue design factors are used to account for uncertainties that are not explicitly included in the deterministic design process, and their level is affected by the presence and nature of the inspection.

Whether the details are inspected or not the calibration method uses a different approach and model in order to include the inspection information in the identification of the state of the system.

As shown in D5.4 [20] the fatigue design factor characteristic for the wave energy sector are similar to the one of the off–shore wind sector. Further, it is important to highlight that the design factor can be reduced to a level 1 if annual inspections are planned on the structure. The focus has been given so far at the Wavestar device, in consequence of its simplicity, but in order to extend the method to a standardisation procedure its application to other WEDs is a fundamental step.

5 Conclusion

The need for new renewable energy solutions leads the debate around the utilisation of the wave energy resource. The SDWED project is an international research alliance aiming at the acceleration of the development of the wave energy sector.

The main outcomes of the SDWED projects are publicly available at the website www.sdwed.civil.aau.dk, where the full list of the deliverables and software can be retrieved.

Within the period of five years of the project four PhDs and two PostDocs has been funded, and had resulted in about 80 scientific publications with contributions from all the partners in the project consortium. Further, the acquired knowledge has been disseminate though three project symposia and provided PhD courses.

Another important contribution of the SDWED project is the creation of a productive international network of people and research groups, which resulted in a number of derived project, such as DTOcean (www.dtocean.eu), Digital Hydraulic Power Take–Off for Wave Energy, and Mooring Solution for Large Wave Energy Converters.

Furthermore the SDWED project is providing inputs for the ongoing standardisation effort within the framework of IECTC–114.

6 Acknowledgements

The authors gratefully acknowledge the financial support from the Danish Council for Strategic Research under the Programme Commission on Sustainable Energy and Environment (Contract 09-067257, Structural Design of Wave Energy Devices) which made this work possible.

The authors want to acknowledge and thank all the partners of the project for their valuable contribution: Aalborg University, Dept. of Civil Engineering, Wave Energy Research Group (Denmark), DHI Water and Environment (Denmark), DTU Mechanical Engineering (Denmark), Det Norske Veritas (England), University of Bologna, DISTART Idraulica (Italy), Federal University of Rio de Janeiro/COPPE, Ocean Structures Underwater Technology, Rambøll Oil Gas A/S (Denmark), WavEC (Portugal), Aalborg University, Institute of Energy Technology (Denmark), Sterndorff Engineering (Denmark), Edinburgh University, Institute for Energy Systems (Scotland), Fraunhofer (Germany), and also the Department of Shipping and Marine Technology of Chalmers University of Technology (Sweden), who have been involved in WP2 as a subcontractor in the project.

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