COLUMBIA POWER TECHNOLOGIES

power from the next wave

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Version	Date	Summary
1.0	11 June 2015	Critical DLCs for T3 structural optimization
1.1	15 April 2016	StingRAY v3.3, WETS metocean conditions, updated DLCs
2.0	15 July, 2016	2nd DLC issue, formatting update and approval

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1 INTRODUCTION

The overall project objective is to materially decrease levelized cost of energy (LCOE) of the Columbia Power (CPwr) StingRAY v3.3 utility-scale wave energy converter (WEC). This will be achieved by reducing structural material and manufacturing costs and increasing energy output. Structural mass reduction is accomplished by gaining greater knowledge of the WEC structural strength and system loads.

A detailed assessment of WEC loading is critical for the requisite structural analysis of the baseline WEC. A number of design load cases (DLC) will be established. All relevant loads will be considered in the calculations, and both ultimate and fatigue limit states will be considered. The calculation of design loads will be performed using fully-coupled time-domain numerical simulation that accounts for all load contributions simultaneously and for all relevant nonlinearities.

2 LOAD ESTIMATION AND STRUCTURAL ANALYSIS

All relevant loads will be considered in the calculations, including environmental (e.g. waves), permanent (e.g. ballast), functional (e.g. mooring) and accidental (e.g. vessel collision) loads.

Limit states refer to a set of states beyond which the structure can no longer meet its functional requirements. Ultimate limit states (ULS) and fatigue limit states (FLS) will both be evaluated. The ultimate limit state corresponds failure of a critical component due to exceedance of the ultimate strength. The fatigue limit state corresponds to failure of a critical component due to cyclic loading.

The v3.3 WEC consists of two rigid bodies constrained such that the only degree of freedom (DOF) in which relative motion is permitted is pitch. The central body is commonly referred to as the nacelle or the spar, and consists of a nacelle and a damper tank rigidly connected by two spars along with two aft floats rigidly connected to the nacelle. The other body is referred to as the fore float, and is constrained to pitch about the axial centerline of the nacelle. The relative pitching motion between the nacelle and fore float actuates a rotary power take off (PTO) which is the mechanism by which mechanically absorbed wave energy is converted into useful energy. A conceptual schematic is presented in Figure 1.

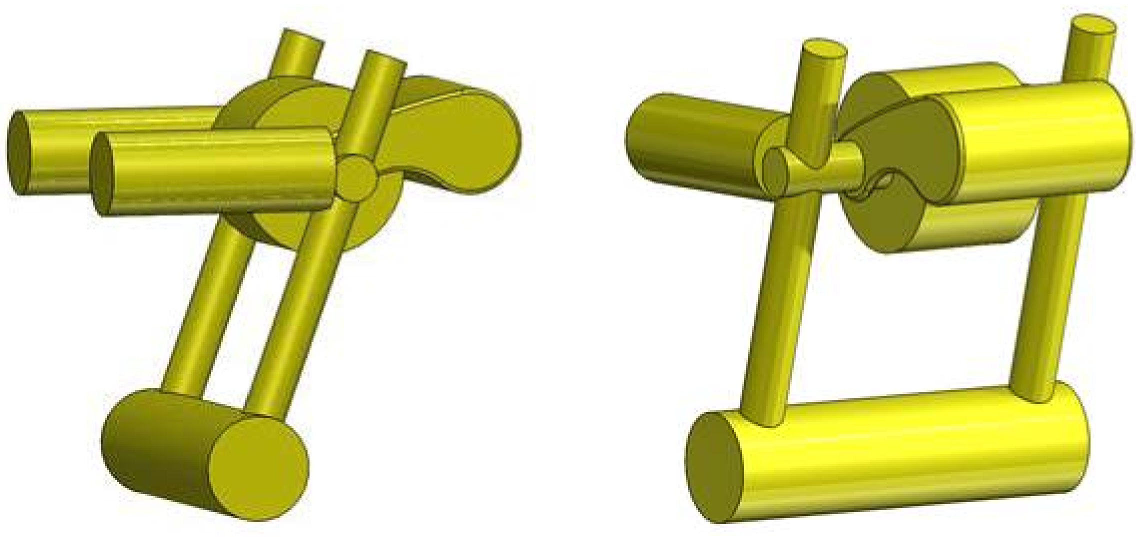

Figure 1 – Conceptual schematic of StingRAY v3.3.

The StingRAY hull is primarily composed of non-corrosive fiber-reinforced polymer (FRP), which has a high strength-to-weight ratio; the damper tank is composed of reinforced concrete.

Numerical simulation of the WEC and its response to the environment is performed using ANSYS AQWA. ANSYS AQWA is a boundary element method (BEM) solver based on linear wave theory. AQWA LINE is the module that acts as the BEM solver and computes the hydrodynamic coefficients. This must be done once for any given geometry and ballast case. AQWA NAUT is a module that allows simulation in the time domain and allows for nonlinear Froude-Krylov (FK) and hydrostatic force calculation, as well as nonlinear mooring, PTO and viscous drag forces. The radiation and diffraction forces are based on the standard linear assumptions of small–amplitude- motion and waves. Mean drift force in the direction of wave incidence is calculated and applied at the mean water line. The hinged connection is easily implemented and hydrodynamic interactions are accounted for.

Outputs of the numerical simulations include the position, velocity and acceleration of each body, as well as the forces acting upon each body. The hydrodynamic (including hydrostatic) forces are converted to pressure distributed over the wetted hull surface in post processing. The applied PTO torque, bearing and seal friction, and mooring loads are also outputs of the numerical simulations.

3 DESIGN LOAD CASES

3.1 Design load case environmental conditions

The Wave Energy Test Site (WETS) at Marine Corp Base Hawaii in Kaneohe Bay has been selected as the design environment as CPwr is planning a deployment there in early 2018. WETS test Berth B, where CPwr will deploy, is at 80 m water depth. The characterization of the metocean conditions is described in Metocean Report S1-DB-01 v4.1 [1].

A scatter table indicating expected annual occurrence of Hm0-Te sea states is presented in Figure 2, with a resolution of 0.5 m in Hm0 and 1 s in Te. The subset of sea states that will represent normal seas are indicated with a bold border around the bin. These sea states, as well as the design extreme sea state, are tabulated in the Appendix in section 5.

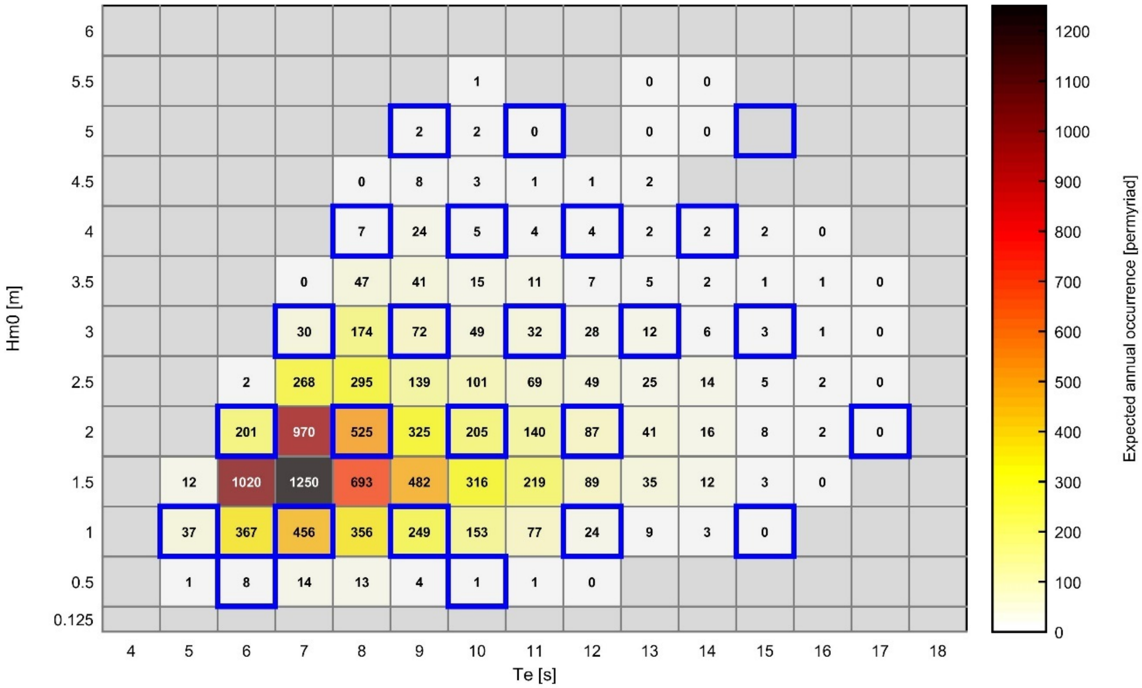

Figure 2 – Design environment occurrence table, with normal sea states indicated.

3.2 Design load case descriptions

Draft IEC Technical Specification on Design Requirements for Marine Energy Systems (IEC 62600-2) [2] recommends consideration of a number of design conditions, appropriately combined with environmental conditions. The design conditions include Normal Operations (including power production, power production plus fault, emergency shutdown, normal startup/shutdown, and idling); Extreme (including extreme environmental conditions, major faults, vessel impact and earthquake/tsunami); Accidental (including loss of stability and loss of station keeping); and Transport/Installation/Maintenance. The environmental conditions include normal and extreme sea states, as well as appropriate wind, current and water level conditions.

A Failure Mode, Effects and Criticality Analysis (FMECA) was performed by CPwr [3] and is used to guide the selection of DLCs. One critical outcome of the FMECA is that system faults lead to a freewheeling PTO. Grid loss leads to ‘islanding mode’ in which the generator damping is very light such that only station power is produced (this small amount of damping is not significantly different from freewheeling). It is possible for faults to lead to reduced generator damping, but if normal generator control and freewheeling are investigated there is no need to also analyze an intermediate state.

Load cases have been considered with respect to the CPwr StingRAY WEC, the design environment, and the objectives of this project. The DLCs have been categorized as either critical, optional or insignificant. Critical DLCs are likely to drive the design and must be analyzed in this project. Optional DLCs may have some significance to the design and will be considered in this project if time allows. Insignificant DLCs are not expected to drive the design and will not be considered in this project. Description of DLCs and justification of their categorization is give in the following subsections.

3.2.1 Critical DLCs

The following DLCs are considered critical, and will be investigated in this project.

3.2.1.1 Normal seas, power production

The WEC is expected to operate in a wide range of sea states day in and day out. While ULS will be analyzed, the primary consideration here is FLS.

Due to data storage and computational time constraints, a limited, but sufficient, number of sea states have been selected. Load effects (e.g. accumulated damage) will be calculated for these sea states and surfaces fit to these data, allowing for interpolation to other sea states.

Due to the weathervaning mooring design, all seas will be assumed to be head on. The PTOs will be controlled for power production. In very energetic sea states the forward float will be pushed over the top of the nacelle and the WEC will operate in 'fore in aft' configuration; for the purposes of DLCs it is assumed that for sea states of Hm0 > 5 m the WEC is operating in fore in aft configuration. The transition is difficult to model and will not be considered in this DLC.

3.2.1.2 Extreme seas, power production

The 50 year return sea state is used to specify this DLC. The WEC is assumed to be in the fore in aft configuration. The seas are assumed head on due to weathervaning. The only significant change that would come from off angle seas would greater loading on the aft mooring tether attachment point; this is not considered design driving and thus is not considered in this DLC.

3.2.1.3 Extreme seas, freewheeling

This DLC is identical to power production in extreme seas except the PTOs are freewheeling. This DLC is considered critical as faults (leading to freewheeling) are more likely to occur in extreme seas conditions.

3.2.2 Optional DLCs

The following DLCs are considered optional, and will be investigated in this project if resources allow.

3.2.2.1 Normal seas, freewheeling

This DLC is identical to power production in normal seas except the PTOs are freewheeling. If the WEC is expected to operate for a significant amount of time idling, and the loads while idling differ significantly from damped PTOs, then this DLC may be important in fatigue analysis. While damping the PTOs clearly affects the WEC's response, and thus has an influence on loading and fatigue, it is not expected to be so great a change as to warrant the additional analysis at this time. If resources allow, this DLC will be investigated.

Note that this DLC covers idling, islanding mode, faults (that lead to idling) and grid loss.

3.2.2.2 Bimodal and bidirectional seas

This DLC considers loading from bimodal and/or bidirectional sea states, with the WEC operating normally. This DLC could also include different spectral shapes and directional spreadings. If resources allow, this DLC will be investigated.

3.2.2.3 Damaged stability

Damaged stability includes cases in which a) the WEC operates with a flooded compartment, or b) a single mooring line failure. This DLC could include normal and extreme sea states, though the loading in extreme seas is likely to be more significant to design. Of the two categories, the single mooring line failure is likely to be more significant. If resources allow, this DLC will be investigated.

3.2.2.4 Float overtopping, slamming

This DLC considers the forward float slamming into the sea surface after going over the top of the nacelle. When the float was observed to overtop in 1:33 tank testing, the float appeared to move with the wave crest and so it is unclear whether or not the float is likely to slam into the sea surface in any scenarios. If resources allow, this DLC will be investigated.

3.2.3 Insignificant DLCs

The following DLCs are considered insignificant and will not be investigated in this project.

3.2.3.1 Other environmental conditions

Wind loading is not expected to be significant for the StingRAY WEC, due to its low profile.

Tidal level is not expected to be significant due to the compliant mooring.

Current loading is not expected to be significant for the selected WETS design environment, although for some sites it is conceivable that the mooring attachment points would need to be reinforced to deal with current loading.

3.2.3.2 Other extreme events

Ship impact is not considered to be design driving; safety protocol and design will mitigate risk.

There is no expectation of deployment where ice impact is a threat.

The WEC will be deployed offshore in deep water where tsunamis manifest as very low amplitude and very long period.

3.2.3.3 Other normal operation events

Startup and shutdown, including emergency shutdown, have no structural implications. The transition is always made at zero speed (for which PTO torque is zero).

3.2.3.4 Transport, installation, maintenance and repair

These DLCs involve scenarios over which the operator has a large degree of control. For example, additional blocking can be used during transport to distribute loads.

4 REFERENCES

[1] "Metocean Report," Columbia Power Technologies, S1-DB-01 v4.1, Jun. 2015.

[2] "Design requirements for marine energy systems (draft)," IEC 62600-2, 2015.

[3] "StingRAY Failure Mode, Effects and Criticality Analysis," Columbia Power Technologies, S1-FMECA-1000 v3.0, Sep. 2014.

5 APPENDIX – TABULATED DESIGN LOAD CASES

5.1 Critical DLCs

5.1.1 Normal Seas, Power Production

Design load case:	1.1a
Mode of operation:	Power Production
Wave conditions:	Normal
Type of analysis:	Fatigue/Ultimate
Total cases:	24
Analysis length:	40 minutes
Spectral shape:	PM
Direction:	Head on
Priority:	Critical

Id	Hm0 [m]	Te [s]	s-index	Fore float
1.1a.1	0.5	6	3	fore
1.1a.2	0.5	10	3	fore
1.1a.3	1	5	5	fore
1.1a.4	1	7	4	fore
1.1a.5	1	9	4	fore
1.1a.6	1	12	9	fore
1.1a.7	1	15	22	fore
1.1a.8	2	6	7	fore
1.1a.9	2	8	5	fore
1.1a.10	2	10	8	fore
1.1a.11	2	12	15	fore
1.1a.12	2	17	18	fore
1.1a.13	3	7	6	fore
1.1a.14	3	9	6	fore
1.1a.15	3	11	15	fore
1.1a.16	3	13	23	fore
1.1a.17	3	15	31	fore
1.1a.18	4	8	7	fore
1.1a.19	4	10	9	fore
1.1a.20	4	12	17	fore
1.1a.21	4	14	31	fore
1.1a.22	5	9	9	fore
1.1a.23	5	11	9	fore
1.1a.24	5	15	21	fore

5.1.2 Extreme Seas, Power Production

Design load case:	1.1b
Mode of operation:	Power production
Wave conditions:	Extreme
Type of analysis:	Ultimate
Total cases:	1
Analysis length:	180 minutes
Spectral shape:	PM
Direction:	Head on
Priority:	Critical

Id	Hm0 [m]	Te [s]	s-index	Fore float
1.1b.1	7.57	10.6	9	aft

5.1.3 Extreme Seas, Freewheeling

Design load case:	6.1b
Mode of operation:	Freewheeling (Idling or Fault)
Wave conditions:	Extreme
Type of analysis:	Ultimate
Total cases:	1
Analysis length:	180 minutes
Spectral shape:	PM
Direction:	Head on
Priority:	Critical

Id	Hm0 [m]	Te [s]	s-index	Fore float
6.1b.1	7.57	10.6	9	aft

5.2 Optional DLCs

5.2.1 Normal Seas, Freewheeling

Design load case:	6.1a
Mode of operation:	Freewheeling (Idling or Fault)
Wave conditions:	Normal
Type of analysis:	Fatigue/Ultimate
Total cases:	24
Analysis length:	40 minutes
Spectral shape:	PM
Direction:	Head on
Priority:	Optional

Id	Hm0 [m]	Te [s]	s-index	Fore float
1.1a.1	0.5	6	3	fore
1.1a.2	0.5	10	3	fore
1.1a.3	1	5	5	fore
1.1a.4	1	7	4	fore
1.1a.5	1	9	4	fore
1.1a.6	1	12	9	fore
1.1a.7	1	15	22	fore
1.1a.8	2	6	7	fore
1.1a.9	2	8	5	fore
1.1a.10	2	10	8	fore
1.1a.11	2	12	15	fore
1.1a.12	2	17	18	fore
1.1a.13	3	7	6	fore
1.1a.14	3	9	6	fore
1.1a.15	3	11	15	fore
1.1a.16	3	13	23	fore
1.1a.17	3	15	31	fore
1.1a.18	4	8	7	fore
1.1a.19	4	10	9	fore
1.1a.20	4	12	17	fore
1.1a.21	4	14	31	fore
1.1a.22	5	9	9	fore
1.1a.23	5	11	9	fore
1.1a.24	5	15	21	fore

5.2.2 Extreme Seas, Bidirectional

Wave conditions:	Extreme, bimodal
Type of analysis:	Ultimate
Total cases:	1
Analysis length:	180 minutes
Spectral shape:	PM
Direction:	Wind and swell separated by 90 deg (+- 45 deg of mean)
Priority:	Optional

Id	Hm0 [m]	Te [s]	s-index	Fore float
1.3b.2	7.57 (5.35 wind, 5.35 swell)	10.6 (8.0 wind, 13.2 swell)	9 wind, 21 swell	aft

5.2.3 Extreme Seas, Unidirectional

Mode of operation:	Power production
Wave conditions:	Extreme
Type of analysis:	Ultimate
Total cases:	1
Analysis length:	180 minutes
Spectral shape:	PM
Direction:	Head on
Priority:	Optional

Id	Hm0 [m]	Te [s]	s-index	Fore float
1.3b.1	7.57	10.6	UD	aft