Preliminary Analysis and Selection of Mooring Solution Candidates

M4 & WP3

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M4 & WP3

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Martin Delaney

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Preliminary Analysis and Selection of Mooring Solution Canidates

M4 & WP3

by

Jonas Bjerg Thomsen
Martin Delaney

April 2018

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Preface

This report covers a preliminary analysis of mooring solutions candidates for four large floating wave energy converters. The work is part of the EUDP project "Mooring Solutions for Large Wave Energy Converters" and is the outcome of "Work Package 3: Preliminary Analysis". The report further compose the "Milestone 4: Report on results of preliminary analysis and selection of final candidates.

The report is produced by Aalborg University with input from the partner WECs Floating Power Plant, KNSwing, LEANCON and Wave Dragon. Tension Technology International (TTI) has provided a significant part of the report in terms of buildability concers and cost input. The report was presented and discussed at a workshop in Copenhagen in June 2016.

Aalborg University, May 22, 2018

Contents

1 | Introduction

This report summarises the quasi-static analysis performed on the four WEC: Floating Power Plant, KNSwing, LEANCON Wave Energy and Wave Dragon. The analysis was performed as a part of the EUDP project *"Mooring Solutions for Large Wave Energy Converters"* and covers Task 3.1: *Quasi-Static Analysis of Mooring Solution Candidates"* (Part I). Next the report covers Task 3.2: *"Check of mooring solution candidates for buildability"* (Part II), and finally Task 3.3: *"Selection of final mooring solution candidates for detailed analysis"* (Part III). Combined, the report covers Work Package 3: *"Preliminary Analysis"* and also Milestone 4: *"Report on Results of preliminary analysis including selection of final mooring solutions candidates"*.

The report is structured with the present introduction describing the objectives of the analysis together with overall assumptions and simplifications. This chapter is followed by four chapters, each containing descriptions and results for the analysis of each device. The chapters are very similar in structure and can be read individually. The work is followed by a part which describes buildability considerations for the moorings and is concluded in the final part with selection of a mooring system for each WEC, which will be used in upcoming report and analysis.

1.1 Objective of Quasi-Static Analysis

Based on the mooring solution candidates described in Thomsen et al. [2015b], the present analysis tends to clarify the applicability of each of the candidates. The analysis will not provide fully optimized solutions, and not cover parameter studies for the individual solutions. The outcome of the analysis will be an overview of what solutions that are relevant for further analysis and provide indications on layout, materials, dimensions etc.

The analysis procedure will follow DNV-OS-E301 [DNV-GL, 2015] and cover the ULS, with given design criteria and environmental loads. The calculation procedure follows in great extent Bergdahl and Kofoed [2015] and Pecher et al. [2014]. In the quasi-static analysis, a range of overall assumptions and approximations are made for all four cases.

- Linear potential flow theory is used to find hydrodynamic coefficients by use of the BEM code NEMOH Babarit and Delhommeau [2015].
- The Newman approximation Newman [1967] is used for calculation of second order wave forces.
- Only horizontal motion is considered.
- No dynamic effect of the mooring lines are included.
- Current forces on the lines as result of the movement is not considered.
- Friction on the seabed is not considered.
- There is no bending stiffness in lines.
- The seabed is considered horizontal.
- The mooring lines are considered to be connected in the SWL.

- A frequency domain approach is considered and non-linearities are linearised.
- Only ULS is considered with safety factors from DNV-OS-E301 (cf. Sec. 1.2).
- At present no restrictions on excursion has been specified, hence the design criteria is determined by the tension in mooring lines.

Six mooring solutions candidates are considered.

- CALM system with mooring chains
- Mooring system with synthetic ropes
- SALM system with synthetic ropes
- Turret system with mooring chains
- Turret system with synthetic ropes

The candidates are based on the assessment in Thomsen et al. [2015b] and will be applied to the devices as illustrated in the following table.

Mooring Candidate	**FPP**	**KNSwing**	**LEANCON**	**Wave Dragon**
CALM w/ chains			✓	✓
CALM w/ synthetic			✓	✓
Turret w/ chains	✓	✓		
Turret w/ synthetic	✓	✓		
SALM w/ synthetic	✓	✓	✓	✓

In the analysis, chains manufactured by Vicinay Cadenas [2017], Braidline Nylon ropes by Bridon [2017] and steel wire ropes also by Bridon will be used.

1.2 Mooring System Validation

The mooring system will be validated according to DNV-OS-E301 and its corresponding safety factors and design criteria. In determining design offset and tension, the maximum of the following excursions are used.

$$X_{C1} = X_{mean} + X_{LF-max} + X_{WF-sig} \tag{1.1}$$

$$X_{C2} = X_{mean} + X_{LF-sig} + X_{WF-max} \tag{1.2}$$

Safety factors are listed below.

Consequence Class	Partial safety factor for Mean Tension	Partial Safety factor for Dynamic Tension
1	1.7	
2	2.5	

The strength of each line is validated by:

$$\frac{0.95\ S_{MBS}}{T} \geq 1 \tag{1.3}$$

Part I

Task 3.1
Quasi-Static Analysis of Mooring Solution Candidates

2 | Floating Power Plant

The Floating Power Plant uses the pitching body principle for wave energy harvesting and is additionally equipped with a wind turbine for harvesting of wind energy. The commercial scale device P60 is planned to be deployed at a location at the Belgian Coast, which will be the focus of this analysis. More information and description of the site and environmental conditions can be found in Thomsen et al. [2015b].

2.1 Geometry Description

The P60 device consists of a floating foundation equipped with a system for wave energy absorption and a system for wind energy absorption. The wave energy system consists of a range of floaters and the wind energy system of a Siemens 2.3 MW wind turbine. The P60 device is illustrated in Fig. 2.1-2.3 and geometrical parameters are listed in the following table.

Figure 2.1. P60 device

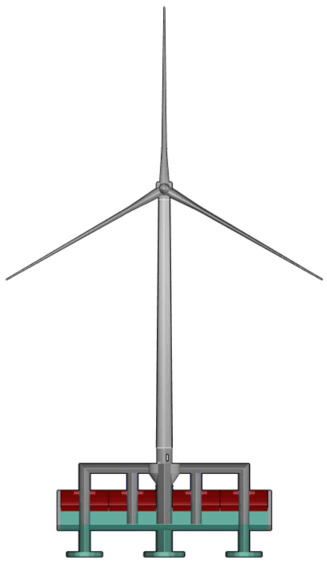

Figure 2.2. Front view of the P60.

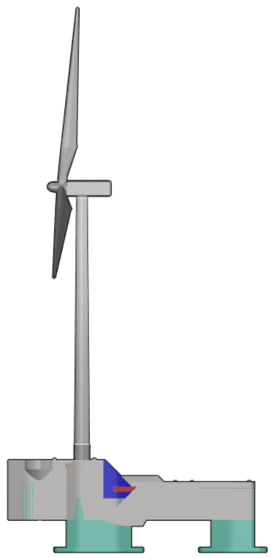

Figure 2.3. Side view of the P60.

Foundation	
Width	60.0 m
Length	72.0 m
Draught	18.6 m
Height above SWL	8.4 m
Wind turbine	
Height	65.0 m
Diameter at found.	4.4 m
Rotor diameter	82.4 m
Blade length	40.0 m

2.2 Environmental Conditions

Environmental conditions are adopted from Thomsen et al. [2015b] and an extreme event with 100-year wind and wave conditions together with 10 year current are analysed.

The following environmental load case will be investigated.

- 100-year wave conditions: $H_s = 6.55$ m and $T_p = 10.25$ s.
- 100-year wind speed: 33.0 m/s
- 10-year current: 1.2 m/s

The mean wind is modelled with a wind profile according to DNV-OS-E301 and since the given wind speed is in a height of 10 m above SWL, the wind speed is calculated in relevant heights when determining wind loads.

The extreme sea state is modelled with a JONSWAP spectrum with the defined H_s and T_p. A peak enhancement factor $\gamma = 3.3$ is chosen.

A water level of 30 m is assumed at the location at the Belgian Coast.

2.3 Analysis Case

The mooring analysis will be performed in the ULS with the specified environmental loads consisting of wind, wave and current. It is assumed that the device is in a survivability mode for both the wave and wind energy absorption systems.

The wind turbine is equipped with a survivability system that pitch the blades and stops the generator at a wind speed of 25 m/s. It is assumed that the wind turbine is in this mode throughout the entire analysis.

The survivability system for the floaters is initiated by ballasting them so that the natural frequency is far from the frequency of the sea state. During the extreme events the sea will consist of long waves, and the radiation can be assumed to be relatively small and diffraction will be dominant. The floaters and the floating foundation are therefore assumed to be one body moving in phase with the incoming waves. A multi body system of the foundation and floaters would be a more sophisticated description of the system, but are for now not considered in this analysis.

2.4 Mean Environmental Loads

The following sections defines the analysed mean environmental loads.

2.4.1 Wind and Current Loads

Mean wind and current loads are estimated from a drag force formulation, as stated in eq. (2.1), where the geometry of the device is simplified into simple geometrical shapes. For each shape a drag coefficient has been defined and a current/wind load calculated.

$$F_{drag} = \frac{1}{2}\,\rho\,C_d\,A\,v^2 \tag{2.1}$$

Based on this simplified calculation the wind load is estimated to $F_{wind} = 400$ kN and the current load to $F_{current} = 450$ kN.

2.5 Mean Wave Drift Loads

The mean wave drift force in the defined sea state has been estimated from results from NEMOH and is determined to 838 kN.

2.5.1 Summary of Mean Environmental Loads

Mean wind load,	$F_{wind} = 400$ kN
Mean current load,	$F_{current} = 450$ kN
Mean wave drift load,	$F_{drift} = 838$ kN
Total mean env. load,	$F_{mean} = 1688$ kN

2.6 Turret System with Mooring Chains

Based on the stated environmental conditions a quasi-static analysis has been performed, resulting in a system as illustrated below.

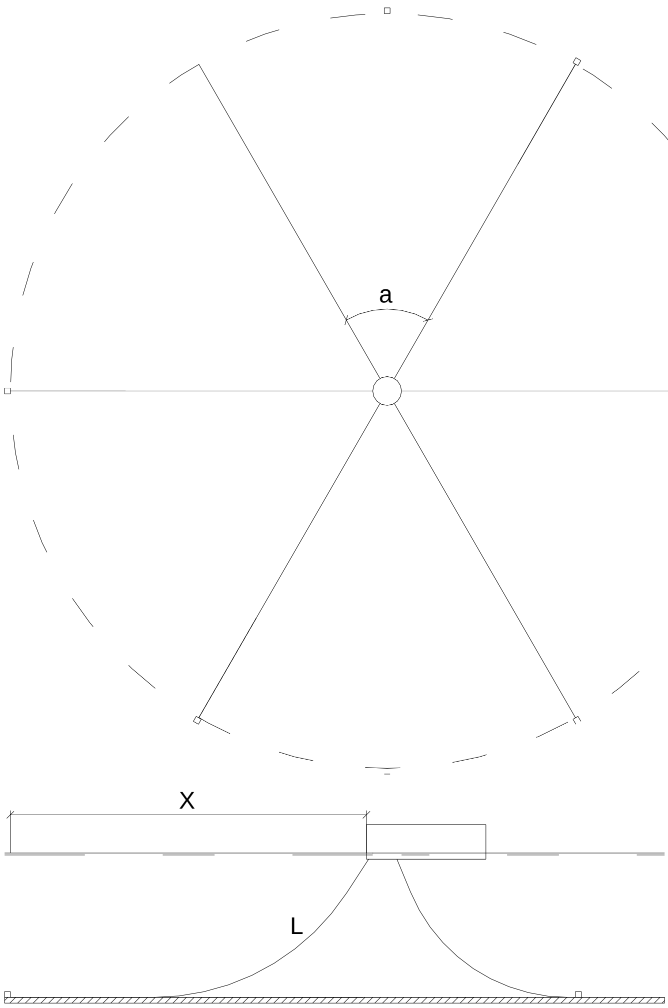

Figure 2.4. Illustration of CALM system.

X	401.0 m
L	420.0 m
l_s	37.6 m
α	60°

The system is designed to ensure sufficient strength of the mooring lines and to prevent vertical load on the anchors. Since no specifications on allowable excursion has yet been stated, this has not been a design factor. Specifications on the required chains are stated in the table below.

	Weight in air [kg/m]	**Submerged weight [kg/m]**	S_{MBS} **[kN]**	**Axial stiffness, *EA* [MN]**
Ø117 R4 chain	273.8	238.2	12993	1232

With the given system, the strength of the lines can be validated according to DNV-OS-E301. The table below illustrates the obtained stiffness in the mean position together with calculated offsets and maxmum line tensions. As can be seen it is ensured that the CF factor is >1 and the most exposed line is close to being fully lifted.

Stiffness at mean exc. [kN/m]	**Design offset [m]**		**Max lifted chain length [m]**	**Tension, T [kN]**	**Tension, γ T [kN]**	**Design S_{mbs} [kN]**	**CF [-]**
	X_{c1}	X_{c2}					
761	15.2	17.1	418.4	6896.5	11724.1	12343.4	1.1

For the present system many components as the turret, connections, anchors etc. needs to be designed, but are left out of this analysis.

2.7 Turret System with Synthetic Ropes

A system similar to the system decribed in previous section are analysed, but consisting of six nylon lines instead of the mooring chains. The designed system is illustrated below.

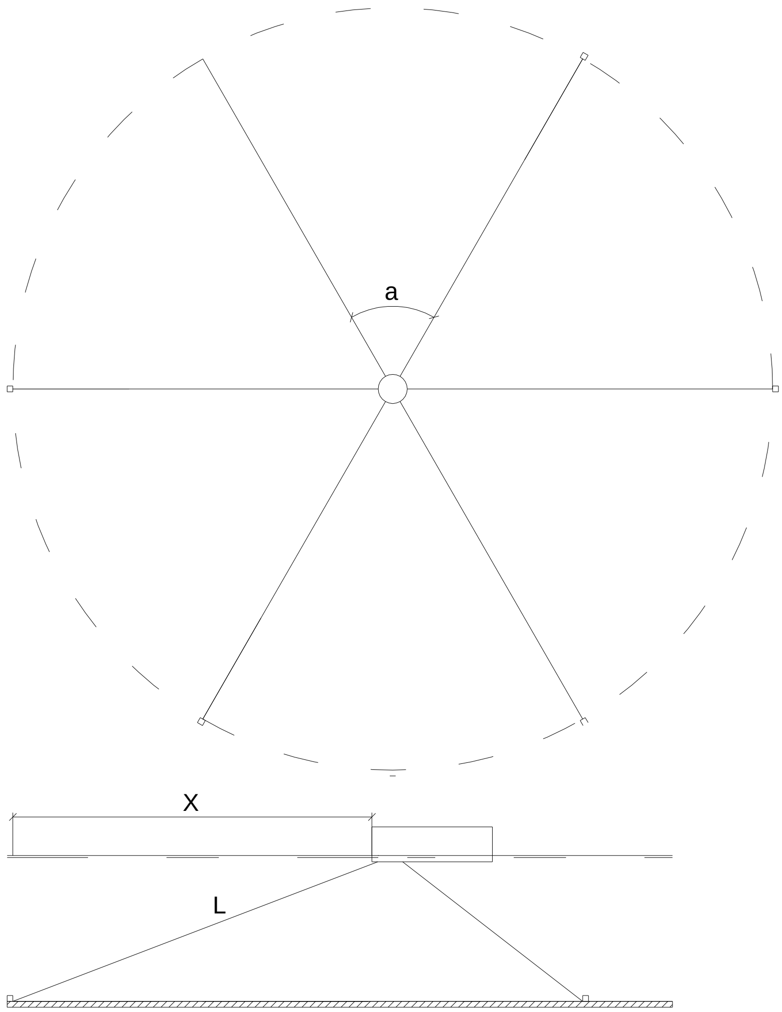

Figure 2.5. Illustration of turret system with synthetic ropes.

X	207 m
L	200 m (unstretched)
α	60°

The system has been designed to ensure sufficient strength in the mooring lines, and similar to the previous case no restrictions on excursion are specified. The required mooring lines are specified below.

	Weight in air [kg/m]	Submerged weight [kg/m]	S_{MBS} [kN]	Axial stiffness, EA [MN]
Ø88 Nylon Rope	4.81	0.46	1795	6.65

The listed specifications are for Bridon Viking Braidline Nylon ropes, and the strength of the lines are validated according to DNV-OS-E301, as illustrated in the table below. For this case the lines will be fully lifted and stretched and an anchor providing both horizontal and vertical strength is needed. For this analysis these are not designed.

Stiffness at mean exc. [kN/m]	Design offset [m]		Max lifted chain length [m]	Tension, T [kN]	Tension, γ T [kN]	Design S_{mbs} [kN]	CF [-]
	X_{c1}	X_{c2}					
100	12.4	14.2	-	789.3	1341.8	1705.3	1.3

2.8 SALM System with Synthetic Hawser

A final mooring solution consisting of a chain tether, nylon hawser and a submerged buoy has been designed, hence a SALM system. The system is illustrated below.

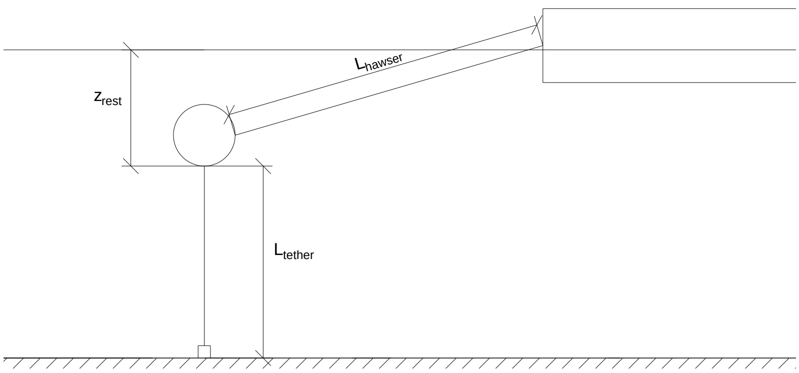

Figure 2.6. Illustration of SALM system.

z_{rest}	7.4 m
L_{tether}	22.6 m
L_{hawser}	40 m
V_{buoy}	236 m^3

To ensure sufficient mooring line strength, components defined in the table below, are used.

	Weight in air [kg/m]	Submerged weight [kg/m]	S_{MBS} [kN]	Axial stiffness, EA [MN]
Ø73 R4 chain	106.6	92.7	5572	479.6
Ø136 Nylon Rope	11.35	1.1	4089	15.1

Nylon lines are of the Bridon Viking Braidline type and validated according to DNV-OS-E301, as shown in the table below.

Stiffness at mean exc. [kN/m]	Design offset [m]		Tension, T [kN]	Tension, γ T [kN]	Design S_{mbs} [kN]	CF [-]
	X_{c1}	X_{c2}				
130.7	19.1	20.9	Tether			
			3001.0	5101.7	5293.4	1.0
			Hawser			
			2284.1	3882.9	3884.5	1.0

3 | KNSwing

The KNSwing is of the I-Beam Attenuater concept and uses a number of OWC chambers for harvesting of wave energy. The full-scale commercial device is intended for deployment in the Danish part of the North Sea. Further information on the site and its environmental conditions can be found in Thomsen et al. [2015b] and relevant parameters are described in the following sections.

3.1 Geometry Description

The KNSwing has a ship-like structure with a number of OWC chambers located along its length. Fig. 3.1-3.3 illustrates the shape and geometry of the device and Table 3.1 defines the geometrical parameters.

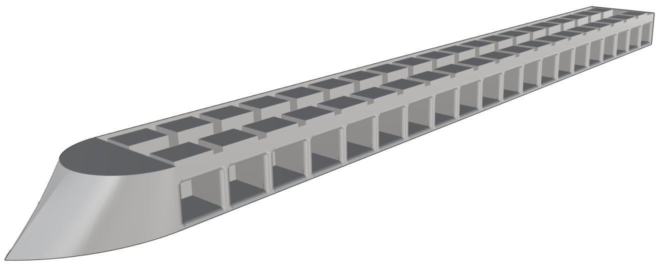

Figure 3.1. Illustration of the submerged part of the KNSwing WEC.

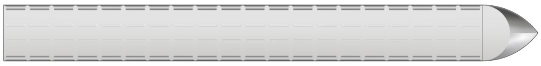

Figure 3.2. Top view of the submerged part of the KNSwing WEC.

Figure 3.3. Side view of the submerged part of the KNSwing WEC.

KNSwing	
Beam	27.6 m
Length	240 m
Draft	13.2 m
Height above SWL	7.0 m

Table 3.1. Geometrical parameters of the KNSwing.

3.2 Environmental Conditions

Environmental conditions are adopted from Thomsen et al. [2015b] and according to DNV-OS-E301, an extreme event with 100-year wind and wave conditions together with 10 year current are analysed.

The following environmental load case will be investigated.

- 100-year wave conditions: $H_s = 9.9$ m and $T_p = 13.1$ s.
- 100-year wind speed: 39.9 m/s
- 10-year current: 1.0 m/s

The mean wind is modelled with a profile according to DNV-OS-E301, and since the given wind speed is in a height of 10 m above the SWL, the wind speed is calculated in relevant heights when calculating the wind loads.

The extreme sea state is modelled with a JONSWAP spectrum, with the defined H_s and T_p. A peak enhancement factor $\gamma = 3.3$ is chosen. The spectrum is illustrated in Fig. 3.4.

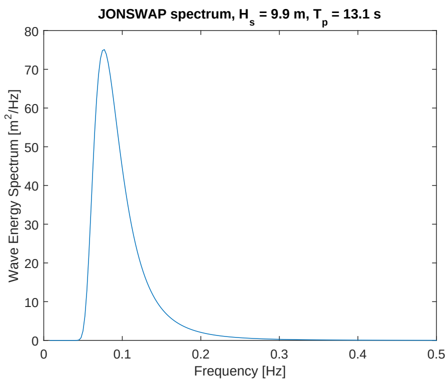

Figure 3.4. Wave spectrum.

Since the dominating directions for all the listed environmental loads are SW, it is assumed that during an extreme event, all loads act in the same direction.

A water level of 40 m is assumed at the location in the North Sea.

3.3 Analysis Case

As defined in the previous section the mooring system for the KNSwing will be analysed in an extreme event with 100-year wave and wind, and 10-year current. The KNSwing is assumed to be in function during the extreme event, hence the influence of the OWC chambers is included in the response analysis. A hydrodynamic analysis and Matlab solver developed by Harry B. Bingham is used to describe the response of the free floating structure. Results from this model have been validated according to small-scale experimental results, and can be upscaled to the full scale model investigated in this analysis.

3.4 Environmental Loads

The following sections defines the analysed environmental loads.

3.4.1 Wind and Current Loads

Mean wind and current loads are estimated from a drag force formulation, as stated in eq. (2.1), where the geometry of the device is simplified into simple geometrical shapes.

Based on these simplified calculations the wind load is estimated to $F_{wind} = 100$ kN and the current load to $F_{current} = 150$ kN.

3.4.2 Mean Wave Drift Loads

The mean wave drift force is calculated from the wave drift force coefficient, computed by NEMOH.

The mean wave drift is calculated to 1415 kN.

3.4.3 Summary of Environmental Loads

Mean wind load,	$F_{wind} = 100$ kN
Mean current load,	$F_{current} = 150$ kN
Mean wave drift load,	$F_{drift} = 1415$ kN
Total mean env. load,	$F_{mean} = 1665$ kN

3.5 Turret System with Mooring Chains

Based on the stated environmental conditions a quasi-static analysis has been performed, resulting in a system as illustrated below.

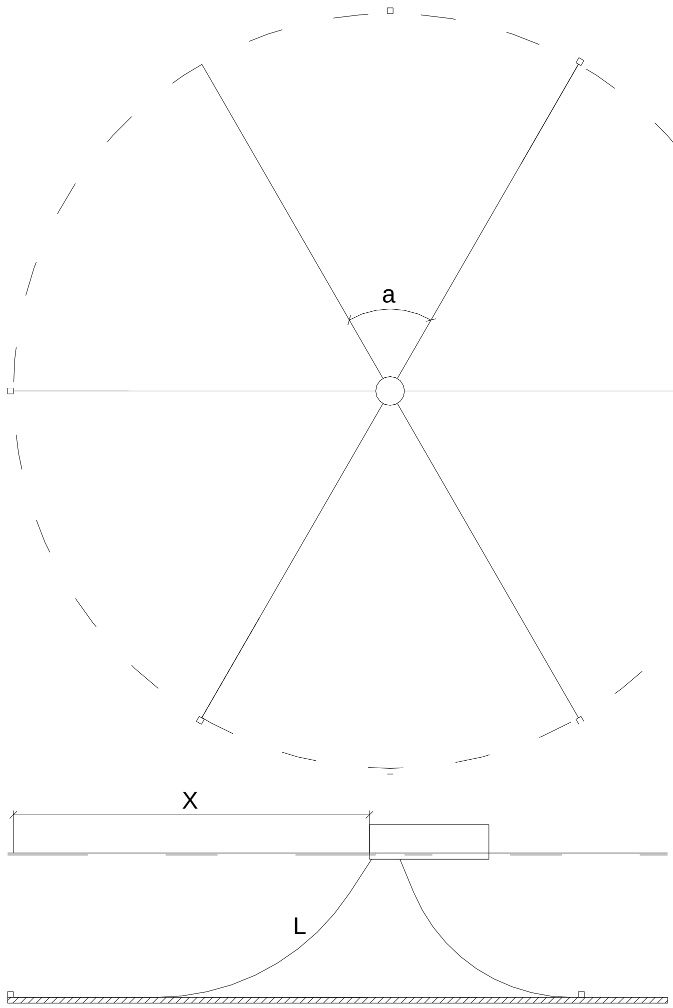

Figure 3.5. Illustration of CALM system.

X	378.7 m
L	420.0 m
l_s	37.6 m
α	60°

The system is designed to ensure sufficient strength of the mooring lines and to prevent vertical load on the anchors. Since no specifications on allowable excursion has yet been stated, this has not been a design factor. Specifications on the required chains are stated in the table below.

	Weight in air [kg/m]	**Submerged weight [kg/m]**	S_{MBS} **[kN]**	**Axial stiffness,** EA **[MN]**
Ø84 R3 chain	141.1	122.8	5866	635

With the given system, the strength of the lines can be validated according to DNV-OS-E301. The table below illustrates the obtained stiffness in the mean position together with calculated offsets and maxmum line tensions. As can be seen it is ensured that the CF factor is >1 and the most exposed line is close to being fully lifted.

Stiffness at mean exc. [kN/m]	Design offset [m]		Max lifted chain length [m]	Tension, T [kN]	Tension, γ T [kN]	Design S_{mbs} [kN]	CF [-]
	X_{c1}	X_{c2}					
351	29.0	29.6	350.1	1195.2	2032.1	5572.2	2.7

For the present system many components as the turret, connections, anchors etc. needs to be designed, but are left out of this analysis.

3.6 Turret System with Synthetic Ropes

A system similar to the system decribed in previous section are analysed, but consisting of six nylon lines instead of the mooring chains. The designed system is illustrated below.

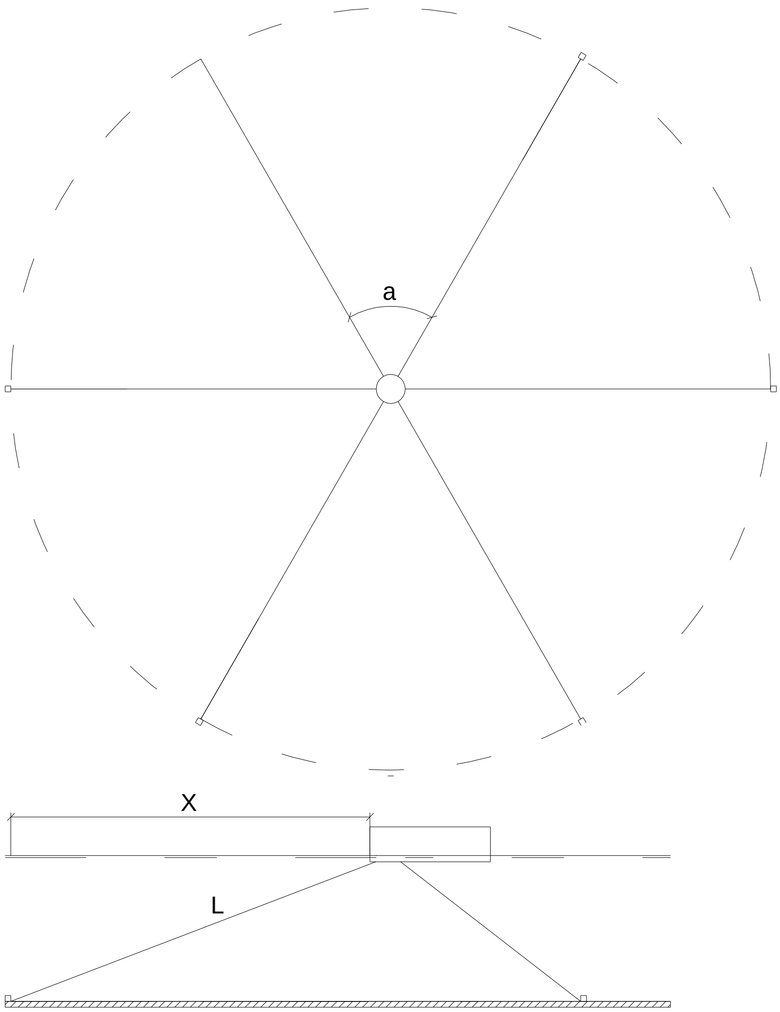

Figure 3.6. Illustration of turret system with synthetic ropes.

X	208 m
L	200 m (unstretched)
α	60°

The system has been designed to ensure sufficient strength in the mooring lines, and similar to the previous case no restrictions on excursion are specified. The required mooring lines are specified below.

	Weight in air [kg/m]	Submerged weight [kg/m]	S_{MBS} [kN]	Axial stiffness, EA [MN]
Ø80 Nylon Rope	3.97	0.38	1491	5.52

The line parameters are for Bridon Viking Braidline Nylon ropes, and the strength of the the lines are validated according to DNV-OS-E301, as illustrated in the table below. For this case the lines will be fully lifted and stretched and an anchor providing both horizontal and vertical strength is needed. For this analysis these are not designed.

Stiffness at mean exc. [kN/m]	Design offset [m]		Max lifted chain length [m]	Tension, T [kN]	Tension, γ T [kN]	Design S_{mbs} [kN]	CF [-]
	X_{c1}	X_{c2}					
88.6	13.2	13.9	-	685.3	1165.3	1416.5	1.2

3.7 SALM System with Synthetic Hawser

A final mooring solution consisting of a chain tether, nylon hawser and a submerged buoy has been designed, hence a SALM system. The system is illustrated below.

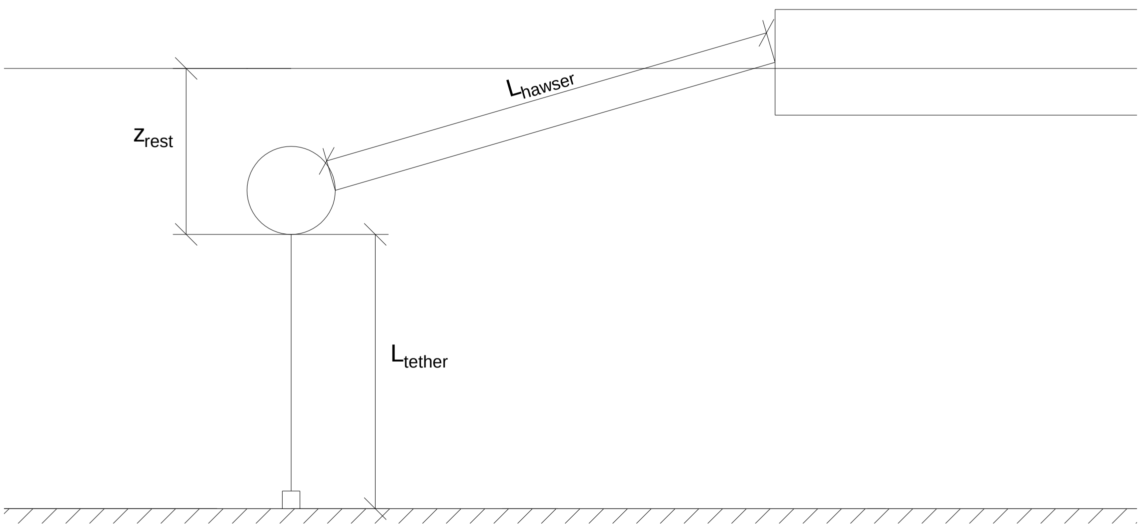

Figure 3.7. Illustration of SALM system.

z_rest	9.4 m
L_{tether}	30.6 m
L_{hawser}	40 m
V_{buoy}	236 m^3

Designing the system to ensure sufficient mooring line strength, components defined in the table below, are used.

	Weight in air [kg/m]	Submerged weight [kg/m]	S_{MBS} [kN]	Axial stiffness, EA [MN]
Ø73 R4 chain	106.6	92.7	5572	479.6
Ø136 Nylon Rope	11.35	1.1	4089	15.1

Nylon lines are of the Bridon Viking Braidline type and validated according to DNV-OS-E301, as shown in the table below.

Stiffness at mean exc. [kN/m]	**Design offset [m]**		**Tension, T [kN]**	**Tension, γ T [kN]**	**Design S_{mbs} [kN]**	**CF [-]**
	X_{c1}	X_{c2}				
174.9	21.6	22.4	Tether			
			2867.2	4874.2	5293.4	1.1
			Hawser			
			1921.0	3265.7	3884.5	1.2

4 | LEANCON

The LEANCON WEC uses the OWC principle for harvesting of wave energy, and consists of two arms on which a number of cylinders are located. The first commercial scale device of this will be the 1:2 model and will be the focus of this investigation. The device will be deployed at the DanWEC test facility, and information on this site can also be obtained in Thomsen et al. [2015b]. In the following section the parameters used in the present study are outlined.

4.1 Geometry Description

The LEANCON device consists of two arms at which a number of OWC cylinders are located. Fig. 4.1 - 4.3 illustrates the shape and geometry of the device and the following table defines the geometrical parameters.

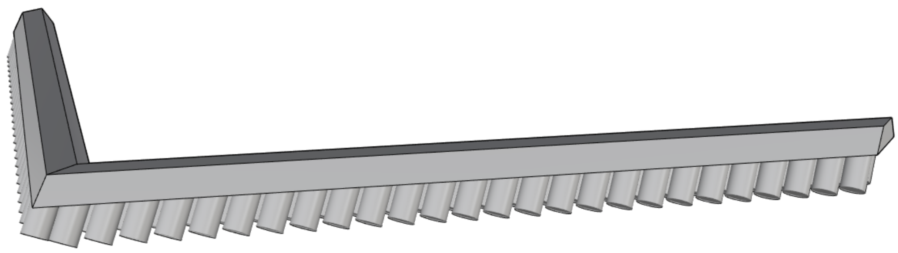

Figure 4.1. The LEANCON WEC.

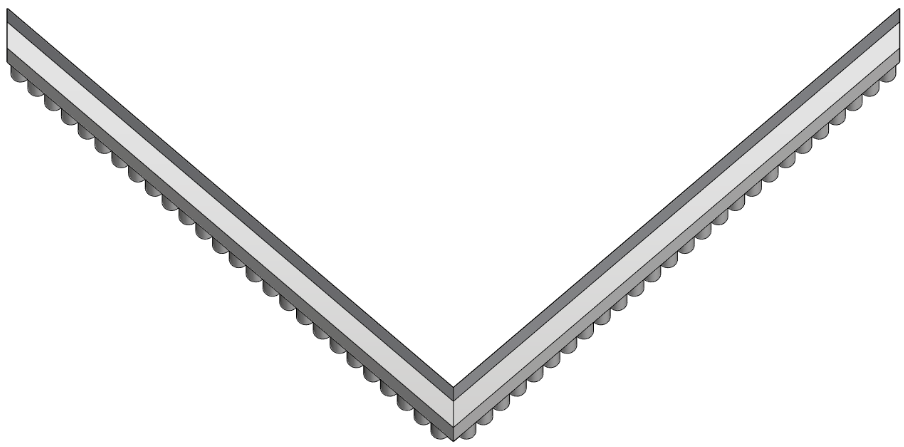

Figure 4.2. Top view of the LEANCON WEC.

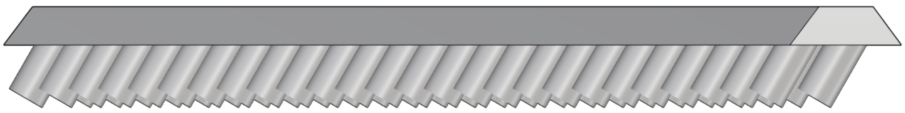

Figure 4.3. Side view of the LEANCON WEC.

LEANCON	
Width	121.6 m
Length	60.0 m
Draught	2.5 m
Draught in Surv. mode	1.25 m
Height above SWL in Surv. mode	5.3 m

4.2 Environmental Conditions

Environmental conditions are adopted from Thomsen et al. [2015b] and according to DNV-OS-E301, an extreme event with 100-year wind and wave conditions together with 10 year current will be analysed.

The following environmental load case will be investigated.

- 100-year wave conditions: $H_s = 8.28$ m and $T_p = 12.92$ s.
- 100-year wind speed: 34.0 m/s
- 10-year current: 1.0 m/s

The mean wind is modelled with a wind profile as defined in DNV-OS-E301, and since the given wind speed is in a height of 10 m above the SWL, the wind speed is calculated in relevant heights when calculating the wind loads.

The extreme sea state is modelled with a JONSWAP spectrum, with the defined H_s and T_p. A peak enhancement factor $\gamma = 3.3$ is chosen. The spectrum is illustrated in Fig. 4.4.

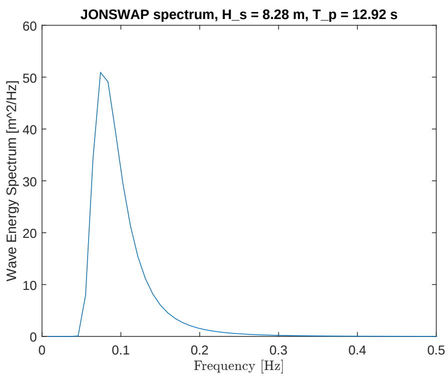

Figure 4.4. Wave spectrum.

Since all the stated environmental parameters are dominating in the same direction, W, it is assumed that during the investigated case, all loads are acting in the same direction.

A water level of 25 m is assumed at the location at the DanWEC.

4.3 Analysis Case

The mooring analysis for the LEANCON device will be performed in the ULS with the extreme case defined in the previous section. It is assumed that the device will be in a survivability mode during this event, in which the device can close the valves of the tubes, resulting in an increase in the buoyancy and therefore an intended decrease in loads on the structure. In this case the device will behave as a rigid floating structure.

4.4 Mean Environmental Loads

The following section defines the analysed environmental loads.

4.4.1 Wind and Current Loads

Mean wind and current loads are estimated from a drag force formulation, as stated in eq. (4.1), where the geometry of the device is simplified into simple geometrical shapes.

$$F_{drag} = \frac{1}{2}\, \rho\, C_d\, A\, v^2 \tag{4.1}$$

Based on these simplified calculations the wind load is estimated to $F_{wind} = 424$ kN and the current load to $F_{current} = 124$ kN.

4.4.2 Mean Wave Drift Force

The mean wave drift force is calculated by NEMOH based on the wave drift coefficients. The LEANCON device is estimated to be exposed to a mean wave drift of 908 kN.

4.4.3 Summary of Mean Environmental Loads

Mean wind load,	$F_{wind} = 424$ kN
Mean current load,	$F_{current} = 124$ kN
Mean wave drift load,	$F_{drift} = 590$ kN
Total mean env. load,	$F_{mean} = 1138$ kN

4.5 CALM System with Mooring Chains

A system consisting of six mooring legs of chains and a hawser of steel wire rope is analysed through a quasi-static analysis. By using the mean environmental loads, an equilibrium position was found and the mooring stiffness in that position was used in a response analysis.

For the present case it was found that a mooring system with chains, could not be designed with respect to minimum breaking strength of chain and the steel wire rope.

Having chains with relatively small diameters increases the compliance of the system, but results in insufficient strength. Using heavier chains can provide some of the strength, but because of the shallow water depths, the stiffness of the systems increases significantly, and induces severe loads in the hawser and the WEC.

4.6 Mooring System with Synthetic Ropes

A system similar to the system described in the previous section is analysed, but consisting of six nylon mooring lines and one nylon hawser instead of the chains and steel wire rope. The designed system is illustrated below.

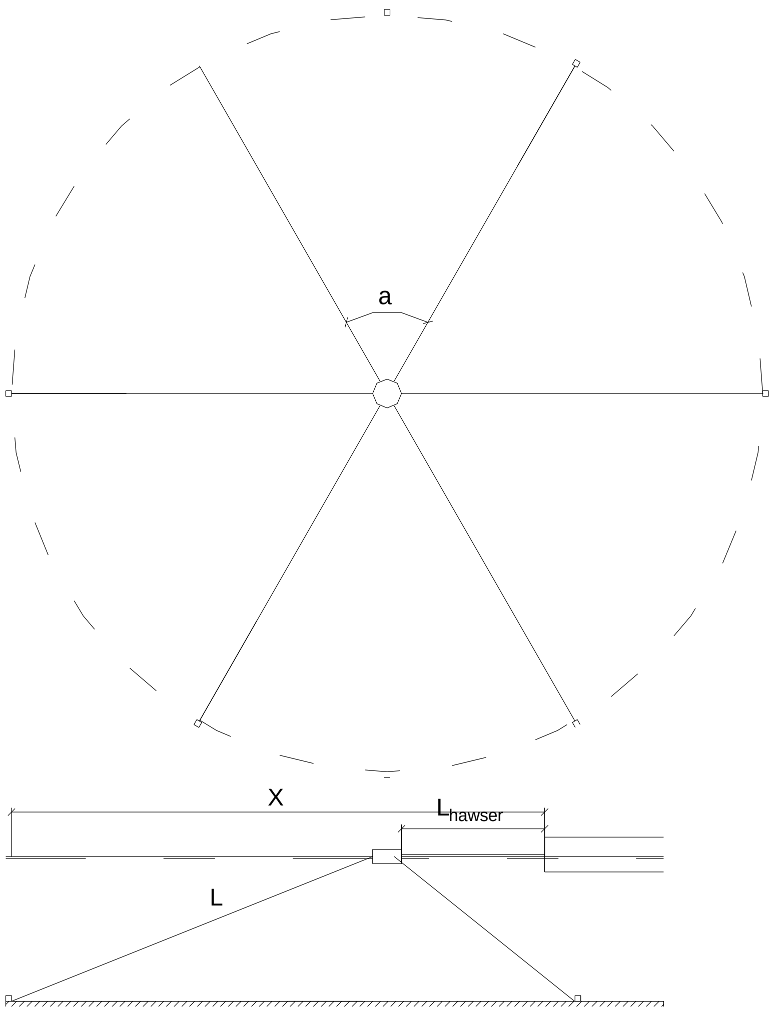

Figure 4.5. Mooring System with synthetic ropes.

X	204 m
L	200 m (unstretched)
l_{hawser}	40 m (unstretched)
α	60°

The system has been designed to ensure sufficient strength in the mooring lines, and no restrictions on excursion are specified. The required mooring lines are specified below.

	Weight in air [kg/m]	**Submerged weight [kg/m]**	S_{MBS} **[kN]**	**Axial stiffness, EA [MN]**
Ø128 Nylon Rope (mooring lines)	9.85	0.95	3570	13.22
Ø192 Nylon Rope (hawser)	28.5	2.75	9807	36.3

The specifications are for Bridon Viking Braidline Nylon ropes, and the strength of the lines are validated according to DNV-OS-E301, as illustrated in the table below. For this case the lines will be fully lifted and stretched and an anchor providing both horizontal and vertical strength is needed. For this analysis these are not designed.

Stiffness at mean exc. [kN/m]	**Design offset [m]**		**Tension, T [kN]**	**Tension, γ T [kN]**	**Design S_{mbs} [kN]**	**CF [-]**
	X_{c1}	X_{c2}				
244.0	14.3	22.9	Mooring lines			
			1991.5	3385.6	3391.5	1.0
			Hawser			
			5207.0	8851.9	9316.7	1.1

4.7 SALM System with Synthetic Hawser

A final mooring solution consisting of a chain tether, nylon hawser and a submerged buoy has been designed, hence a SALM system. The system is illustrated below.

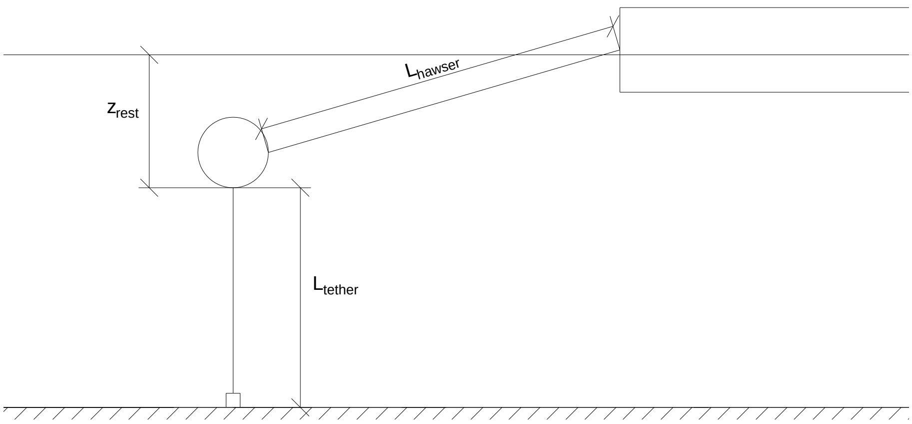

Figure 4.6. Illustration of SALM System.

z_rest	9.1 m
L_{tether}	15.9 m
L_{hawser}	60 m
V_{buoy}	402 m^3

Designing the system to ensure sufficient mooring line strength, components defined in the table below, are used.

	Weight in air [kg/m]	**Submerged weight [kg/m]**	**S_{MBS} [kN]**	**Axial stiffness, EA [MN]**
Ø120 R4 chain	288	250.6	13573	1300
Ø192 Nylon Rope	22.57	2.18	7826	30.0

Nylon lines are of the Bridon Viking Braidline type and validated according to DNV-OS-E301, as shown in the table below.

Stiffness at mean exc. [kN/m]	**Design offset [m]**		**Tension, T [kN]**	**Tension, γ T [kN]**	**Design S_{mbs} [kN]**	**CF [-]**
	X_{c1}	X_{c2}				
167.5	18.9	29.2	Tether			
			5174.9	8797.0	12894.4	1.5
			Hawser			
			3880.3	6596.5	7434.7	1.1

5 | Wave Dragon

The Wave Dragon device harvest wave energy by use of overtopping stored in a reservoir at the main body of the device. The 1.5 MW device is intended to be deployed at DanWEC test facility outside Hanstholm. Details on the site and its condition can be found in Thomsen et al. [2015b] and relevant parameters will be described in the following.

5.1 Geometry Description

The Wave Dragon consists of a main body equipped with a reservoir for storing of the overtopping. Two reflector arms are attached for pointing the waves towards the main body. The Wave Dragon is illustrated in Fig. 5.1 - 5.3 and geometrical parameters are listed in the table below.

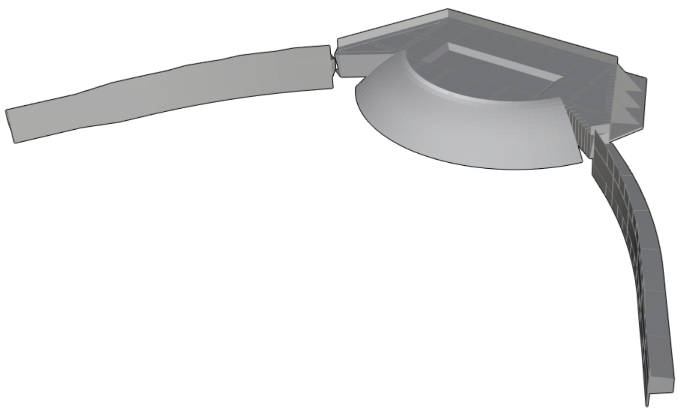

Figure 5.1. The Wave Dragon WEC.

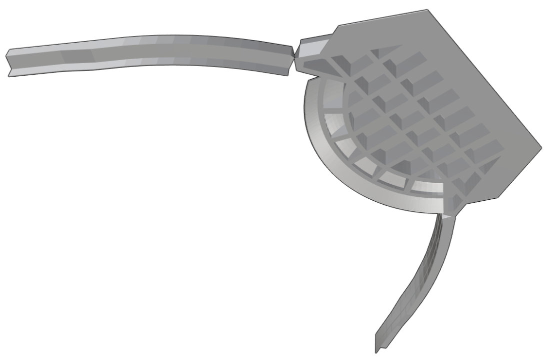

Figure 5.2. Bottom view of the Wave Dragon WEC.

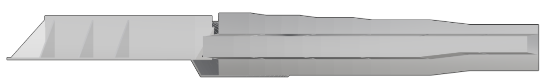

Figure 5.3. Side view of the Wave Dragon WEC.

Wave Dragon	
Width	152 m
Length	94 m
Draft	6 m
Height above SWL	1.7 m

5.2 Environmental Conditions

Environmental conditions are adopted from Thomsen et al. [2015b] and according to DNV-OS-E301, an an extreme event with 100-year wind and wave conditions together with 10 year current will be analysed.

The following environmental load case will be investigated.

- 100-year wave conditions: $H_s = 8.28$ m and $T_p = 12.92$ s.
- 100-year wind speed: 34.0 m/s
- 10-year current: 1.0 m/s

The mean wind is modelled with a wind profile as defined in DNV-OS-E301, and since the given wind speed is in a height of 10 m above the SWL, the wind speed is calculated in relevant heights when calculating the wind loads.

The extreme sea state is modelled with a JONSWAP spectrum, with the defined H_s and T_p. A peak enhancement factor $\gamma = 3.3$ is chosen. The spectrum is illustrated in Fig. 5.4.

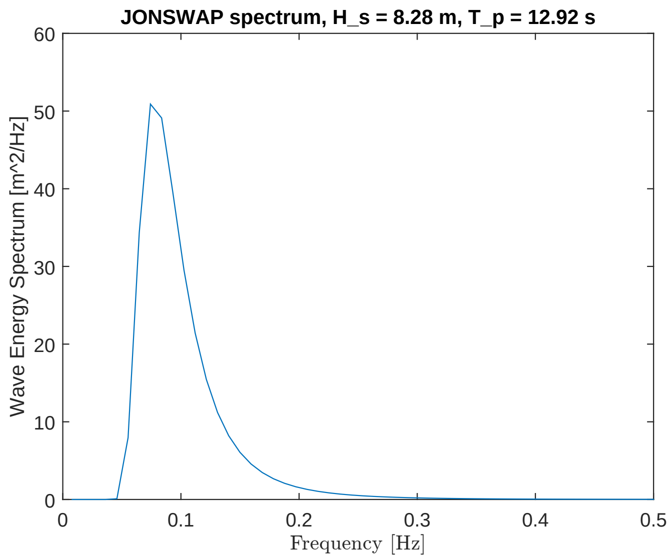

Figure 5.4. JONSWAP spectrum for 100-year sea state at the DanWEC test facility.

Since all the stated environmental parameters are dominating in the same direction, W, is it assumed that during the investigated case, all loads are acting in the same direction.

A water level of 25 m is assumed at the location at the DanWEC.

5.3 Analysis Case

The Wave Dragon will be analysed in an extreme event according to the environmental conditions listed in the previous section. As illustrated in Fig. 5.2 the device is equipped with a range of air cushions, which can be used to modify the draft of the device, thereby both optimize energy absorption but also modify loads on the structure.

In survivability mode the air cushions are emptied (now filled with water) and the maximum draft of 6 m is achieved. In this situation the overtopping reservoir is fully submerged and no power production takes place.

For the present analysis it is assumed that the device is in survivability mode, and therefore no effect from air cushions and PTO systems are modelled.

5.4 Mean Environmental Loads

The following section defines the analysed environmental loads.

5.4.1 Wind and Current Loads

Mean wind and current loads are estimated from a drag force formulation, as stated in eq. (5.1), where the geometry of the device is simplified into simple geometrical shapes.

$$F_{drag} = \frac{1}{2} \rho \, C_d \, A \, v^2 \tag{5.1}$$

Based on these simplified calculations the wind load is estimated to $F_{wind} = 100$ kN and the current load to $F_{current} = 750$ kN.

5.4.2 Mean Wave Drift Force

The mean wave drift force is calculated by NEMOH based on the wave drift coefficients. The Wave Dragon device is estimated to be exposed to a mean wave drift of 1360 kN.

5.4.3 Summary of Mean Environmental Loads

Mean wind load,	$F_{wind} = 100$ kN
Mean current load,	$F_{current} = 750$ kN
Mean wave drift load,	$F_{drift} = 1360$ kN
Total mean env. load,	$F_{mean} = 2210$ kN

5.5 CALM System with Mooring Chains

Based on the defined CALM system with six mooring lines, a quasi-static analysis has been performed.

For this type of system it was found that designing a realistic system is not possible. As a result of the environmental loading, large tension is present in the mooring lines. To ensure sufficient strength, chains with large diameter are needed, resulting in a stiff system with severe tension in the hawser and WEC. To design a system that can withstand the loads, an unrealistic length of lines are needed together with a significant nominal diameter. A more compliant system is needed.

5.6 Mooring System with Synthetic Ropes

A system of six lines and a hawser of nylon is analysed. The designed system is illustrated below.

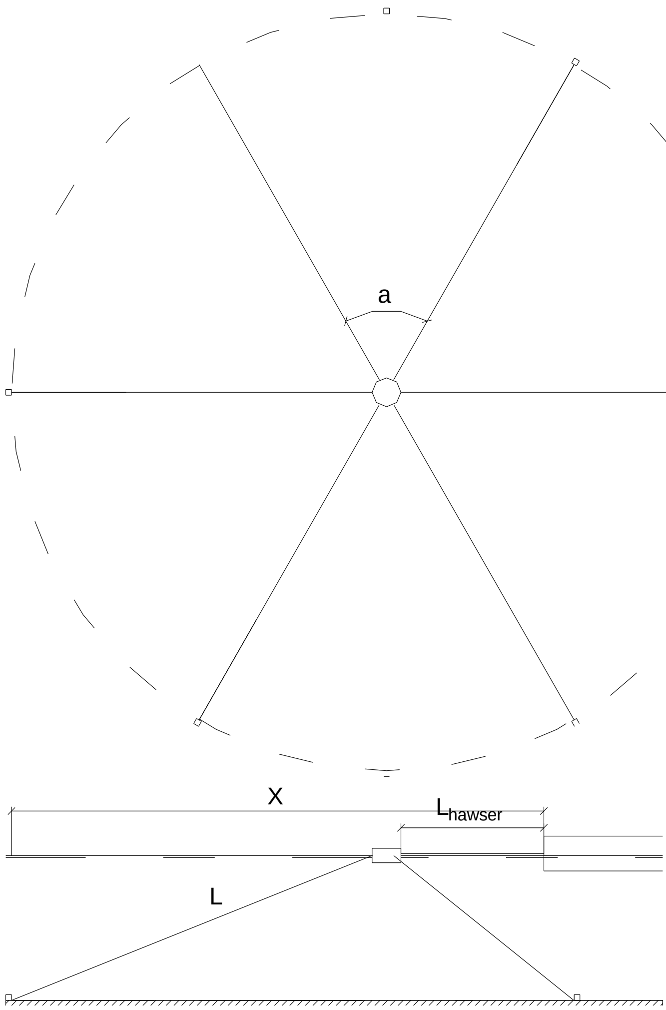

Figure 5.5. Mooring system consisting of synthetic ropes.

X	203 m
L	200 m (unstretched)
l_{hawser}	40 m (unstretched)
α	60°

The system has been designed to ensure sufficient strength in the mooring lines, as no restrictions on excursion are specified. The required mooring lines are specified below.

	Weight in air [kg/m]	Submerged weight [kg/m]	S_{MBS} [kN]	Axial stiffness, EA [MN]
Ø128 Nylon Rope (mooring lines)	9.85	0.95	3570	13.22
Ø192 Nylon Rope (hawser)	28.5	2.75	9807	36.3

The line specifications are for Bridon Viking Braidline Nylon ropes, and the strength of the the lines are validated according to DNV-OS-E301, as illustrated in the table below.

For this case the lines will be fully lifted and stretched and an anchor providing both horizontal and vertical strength is needed. For this analysis these are not designed.

Stiffness at mean exc. [kN/m]	**Design offset [m]**		**Tension, T [kN]**	**Tension, γ T [kN]**	**Design S_{mbs} [kN]**	**CF [-]**
	X_{c1}	X_{c2}				
			Mooring lines			
155.0	13.2	15.2	1398.6	2377.6	3391.5	1.4
			Hawser			
			3664.9	6230.4	9316.7	1.5

5.7 SALM System with Synthetic Hawser

A final mooring solution consisting of a chain tether, nylon hawser and a submerged buoy has been designed, hence a SALM system. The system is illustrated below.

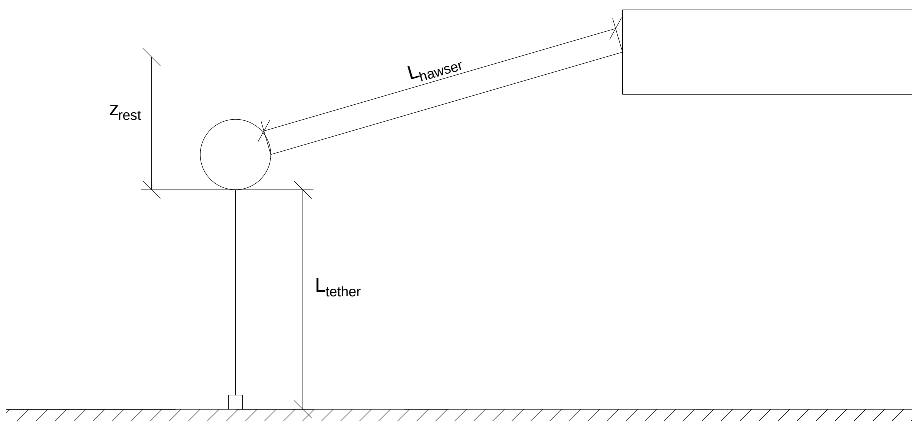

Figure 5.6. SALM system.

z_rest	9.1 m
L_{tether}	15.9 m
L_{hawser}	40 m
V_{buoy}	402 m^3

In designing the system to ensure sufficient mooring line strength, components defined in the table below, are used.

	Weight in air [kg/m]	**Submerged weight [kg/m]**	**S_{MBS} [kN]**	**Axial stiffness, EA [MN]**
Ø120 R4 chain	288	250.6	13573	1300
Ø192 Nylon Rope	22.57	2.18	7826	30.0

Nylon lines are of the Bridon Viking Braidline type and validated according to DNV-OS-E301, as shown in the table below.

Stiffness at mean exc. [kN/m]	**Design offset [m]**		**Tension, T [kN]**	**Tension, γ T [kN]**	**Design S_{mbs} [kN]**	**CF [-]**
	X_{c1}	X_{c2}				
			Tether			
251.3	13.4	15.4	5000.2	8500.3	12894.4	1.5
			Hawser			
			3732.0	6344.4	7434.7	1.7

Part II

Task 3.2
Check of Mooring Solution Candidates for Buildability

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EUDP Project

"Mooring Solutions for Large Wave Energy Converters"

Project Task 3.2

Buildability Review

Date	Rev.	Description	Prepared by	Authorised by
28-08-15	00	Draft Issue	M. A. Delaney	

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CONTENTS

GLOSSARY

EUDP	Energy Technology Development & Demonstration Programme
MSLWEC	Mooring Solutions for Large Wave Energy Converters
AAU	Aalborg University
TTI	Tension Technology International Ltd.
WEC	Wave Energy Converter
SPM	Single Point Mooring
CALM	Catenary Anchor Leg Mooring
SALM	Single Anchor Leg Mooring
DNV	Det Norske Veritas (now DNV-GL)
MBS	Minimum Break Strength (rope/chain/wire)
HMPE	High Modulus Polyethylene
DEA	Drag Embedment Anchor

REFERENCES

1. Aalborg University Collaborative Agreement Regarding Public Research (The Collaborative Agreement) between AAU and the seven participant organisations as signed by all in December 2014, together with Appendices 1 to 6 defining the Standard Terms, Work Packages, Schedule and Financial arrangements for the Project.

2. Aalborg University Department of Civil Engineering Wave Energy Research Group, "Current Mooring Design in Partner WECs and Candidates for Preliminary Analysis CM1 & M.3", DCE Contract Report No.163, May 2015.

3. Aalborg University Department of Civil Engineering Wave Energy Research Group, "Preliminary Quasi-Static Analysis", DCE Contract Report No.???, May 2015.

4. Det Norske Veritas Offshore Standard DNV-OS-E301, Position Mooring, October 2008, amended October 2009.

5. Det Norske Veritas, "Offshore Fibre Ropes", Offshore Standard DNV-OS-E303, February 2013.

1 INTRODUCTION

1.1 Project Background

The EUDP Project is titled as follows:

"Mooring Solutions for Large Wave Energy Converters"

The objectives of the project are to design, test and develop cost efficient mooring solutions for large, slack moored, floating Wave Energy Converters (WECs), and to build Danish national competences in design and modelling of mooring systems for WECs.

This is a collaborative project involving seven partner organisations working together to undertake defined work packages and achieve the project goals. Partial funding and support for the project is being provided by EUDP. The project is being led by Aalborg University and the project details, work packages and partner contributions are set out in the Collaborative Agreement (Reference 1).

1.2 Project Task 3.2

Project Task 3.2 requires a check on "buildability" of the mooring solution candidates.

The scope of the work is to provide commentary on buildability matters relating to the mooring solutions proposed for each of the four partner's WECs (as listed below):

- Floating Power Plant - P60.
- LEANCON - 1:2 scale (up-scaled design).
- Wave Dragon - 1.5 MW.
- KNSwing - ??

1.3 Buildability Review Approach

Firstly, it should be recognised that anything is potentially "buildable". Therefore, in practice, the considerations for buildability are really a question of keeping the costs for materials and construction within realistically achievable bounds.

It is further noted that the mooring solutions for the Partner WECs are generally at early concept design stage so there are no construction drawings, material schedules, detailed specifications, deployment site information and other detail on which to base a specific review of buildability for each WEC.

The approach adopted for the buildability review is therefore to review the design concepts and provide a generalised commentary to highlight the issues that are likely to impact on cost and buildability and should be addressed to ensure practical mooring designs.

2 WEC MOORING SOLUTIONS

2.1 Mooring Solutions - General

The project partners proposed or intended mooring designs as defined in early project work packages WP1 and WP2 (Reference 2) are considered in the buildability review.

In addition, the review commentary will address the mooring solutions that have been shown to be viable by the preliminary quasi-static analyses (Task 3.1) which produced the matrix shown as Table 1 below (from Reference 3).

Table 1 – Generic Mooring Solutions

	Floating Power Plant	LEANCON	Wave Dragon	KNSwing
CALM - Chain Lines		x	x	
CALM - Synthetic Lines		✓	✓	
Turret – Chain Lines	✓			✓
Turret – Synthetic Lines	✓			✓
SALM – Synthetic Lines	✓	✓	✓	✓

Notes: CALM designs use a synthetic hawser from the WEC to the SPM buoy.
SALM designs use a chain tether from the anchor to the submerged buoy.

As indicated in the above table, the analysis work found that an all chain CALM type mooring could not be designed for the LEANCON and Wave Dragon WECs.

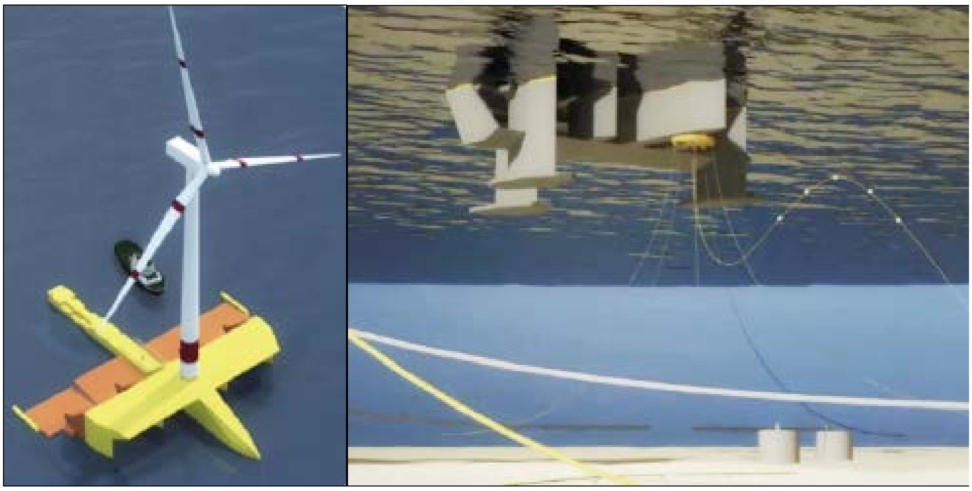
The mooring solutions for each of the four partner WECS are further detailed in the following sections.

2.2 Floating Power Plant

Quoting from the Floating Power Plant website; "The platform is anchored using standard mooring technology that has been proven, and is still used, by the oil and gas industry. The system is a disconnectable turret mooring system with slack (catenary) anchor chains. The combination of the mooring system, the platform design and the high wave energy absorption ensures that the platform weathervanes 360 degrees in order to face the incoming waves. The mooring turret is the grid connection point (hub) from which the platform can be disconnected and towed away."

Graphic views are presented in Figure 1 below. The disconnectable turret mooring at the forward end is shown by the underwater view.

Figure 1 – Floating Power Plant and Above Water and Underwater Views



As part of WP1 and WP2 of the project, Aalborg University defined the current mooring solution used by each partner WEC (Reference 2). The current mooring solution for Floating Power Plant has been based on the mooring system used for the P37 prototype device deployed at a test site but scaled up for the larger P60 size device. The mooring spread layout from the turret with details of lines and anchors is summarised in Figure 2 below.

Figure 2 – Floating Power Plant Current Mooring Solution

Floating Power Plant – Current Mooring Solution…

Water depth at Mooring Site: 30 metres

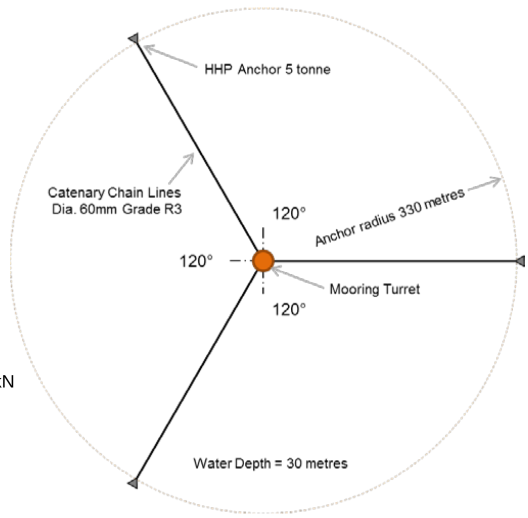
Extreme Mooring Design Load: 1177 kN

Mooring concept:
Turret Mooring with Chain Catenary Legs

On-board Equipment:
Mooring Turret (built into WEC)

Mooring Lines:
3 × 350 m Ø60 mm studless chain (72 kg/m)
R3 Proof / Breaking load: 2201 / 3147 kN

Anchors:
3 No. Flipper Delta Anchor, 5 tonne mass
Holding Capacity: 1178 kN



Subsequent work under WP3 of the project involved undertaking preliminary quasi-static analyses for several different mooring design concepts applied to each of the four partner's WECs. This work has been carried out by Aalborg University and is reported in Reference 3.

This work found that three types of mooring arrangement can be designed for the use with the disconnectable turret of the Floating Power Plant P60 size at its intended site (30m water depth) as follows:

- Six leg chain catenary - anchor radius 401 metres, 6 x 420 metres of 117 mm dia. grade R4 studless chain MBS 12993 kN.
- Six leg taut synthetic - anchor radius 207 metres, 6 x 200 metres of 88 mm dia. Bridon Viking Braidline Nylon rope MBS 1795 kN.
- Single Anchor Leg buoy mooring - 22.6 metres of 73 mm dia. tether chain grade R4 MBS 5572 kN, Submerged buoy 2370 kN net uplift, 40 metres of 136 mm dia. Bridon Viking Braidline Nylon hawser MBS 4089 kN.

2.3 LEANCON

As part of WP1 and WP2 of the project, Aalborg University defined the current mooring solution used by each partner WEC (Reference 2). The current mooring solution for the LEANCON WEC has been based on the system designed by the WEC developer for mooring the 1:10 scale prototype that will be deployed at a test site during summer 2015 but scaled up for a larger 1:2 size device. The mooring is of a SALM type with details of the system summarised in Figure 3 below.

Figure 3 – LEANCON Current Mooring Solution

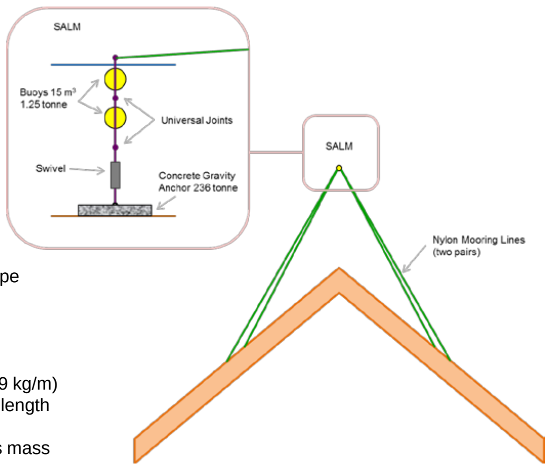
LEANCON – Current Mooring Solution…

Water depth at Mooring Site: 22.5 metres

Extreme Mooring Design Load: 774 kN

Mooring concept:
SALM Mooring With Nylon Rope Tethers

On-board Equipment:
?? Fairleads and Padeyes ??
Mooring Lines:
2 × 257 m Ø90 mm Double Braid Nylon rope
(6.19 kg/m), Breaking load: 2113 kN
SALM Leg:
2 No. 15 m3 buoy, 1.25 tonnes mass
1 No. Swivel (Cable Twister)
18.75 m Ø100 mm stainless steel rod (62.9 kg/m)
In 3 pieces of 7.25, 6.0 & 5.5 metres length
Anchor:
1 No. Concrete Gravity Anchor 236 tonnes mass



Subsequent work under WP3 of the project has involved undertaking preliminary quasi-static analyses for several different mooring design concepts applied to each of the four partner's WECs. This work has been carried out by Aalborg University and is reported in Reference 3.

This work found that only two types of mooring arrangement can be designed for the LEANCON 1:2 scale WEC device at its intended site (25m water depth) as follows:

- Single Point Mooring with six taut synthetic legs - anchor radius 204 metres, 6 x 200 metres of 128 mm dia. Bridon Viking Braidline Nylon rope MBS 3570 kN, SPM buoy, 40 metres of 216 mm dia. Bridon Viking Braidline Nylon hawser MBS 9807 kN.
- Single Anchor Leg Mooring - 15.9 metres of 120 mm dia. tether chain grade R4 MBS 13573 kN, Submerged buoy 4040 kN net uplift, 60 metres of 192 mm dia. Bridon Viking Braidline Nylon hawser MBS 7826 kN.

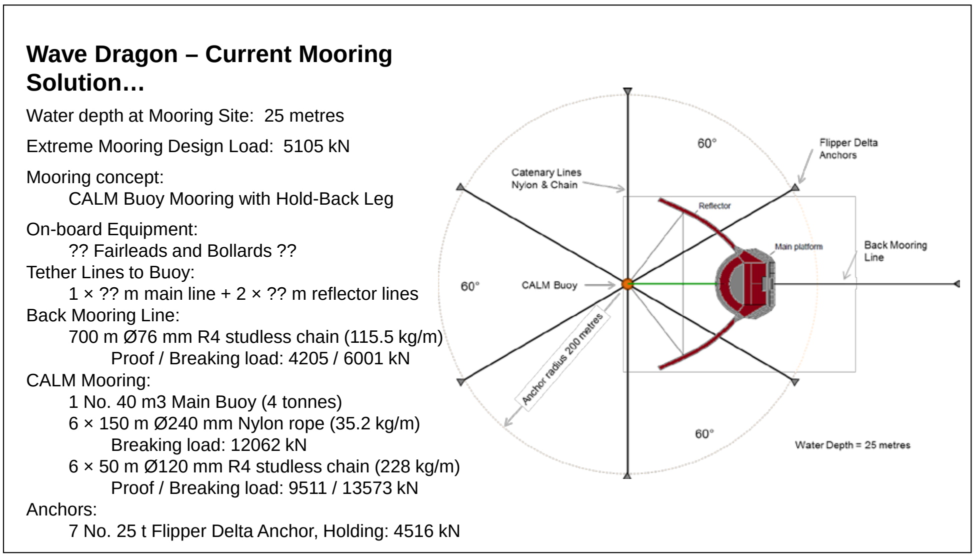
It was found that a CALM type mooring (which is an SPM with chain catenary anchor legs) could not be designed for the LEANCON WEC in this water depth.

2.4 Wave Dragon

As part of WP1 and WP2 of the project, Aalborg University defined the current mooring solution used by each partner WEC (Reference 2). The current mooring solution for the Wave Dragon WEC has been based on the system proposed by the WEC developer following work commissioned from their mooring design consultants.

The mooring is of a CALM type with two part chain and synthetic rope mooring legs. A synthetic rope hawser connects the WEC to the mooring buoy. A hold-back mooring line is used to restrict the weathervaneing rotation to less than +/- 60° so that the mooring buoy does not need a fully rotatable bearing. Details of the mooring arrangement are summarised in Figure 4 below.

Figure 4 – Wave Dragon Current Mooring Solution



Subsequent work under WP3 of the project has involved undertaking preliminary quasi-static analyses for several different mooring design concepts applied to each of the four partner's WECs. This work has been carried out by Aalborg University and is reported in Reference 3.

This work found that only two types of mooring arrangement can be designed for the Wave Dragon WEC device at its intended site (25m water depth):

- Single Point Mooring with six taut synthetic legs - anchor radius 203 metres, 6 x 200 metres of 128 mm dia. Bridon Viking Braidline Nylon rope MBS 3570 kN, SPM buoy, 40 metres of 216 mm dia. Bridon Viking Braidline Nylon hawser MBS 9807 kN.
- Single Anchor Leg Mooring - 15.9 metres of 120 mm dia. tether chain grade R4 MBS 13573 kN, Submerged buoy 4040 kN net uplift, 40 metres of 192 mm dia. Bridon Viking Braidline Nylon hawser MBS 7826 kN.

It was found that a CALM type mooring (which is an SPM with all chain catenary anchor legs) could not be designed for the Wave Dragon WEC in this water depth.

2.5 KNSWing

As part of WP1 and WP2 of the project, Aalborg University defined the current mooring solution used by each partner WEC (Reference 2). The mooring design of the KNSwing was found to be in a conceptual state with no design detail although indicative mooring loads and motions are available from scale model tests.

The current mooring solution for the KNSwing WEC has therefore been based on a turret mooring similar to the Floating Power Plant, but with the 6-leg mixed chain and synthetic line spread mooring as designed for Wave Dragon. The mooring details are summarised in Figure 5 below.

Figure 5 – KNSWing Current Mooring Solution

KNSWing – Current Mooring Solution…

Water depth at Mooring Site: 40 metres

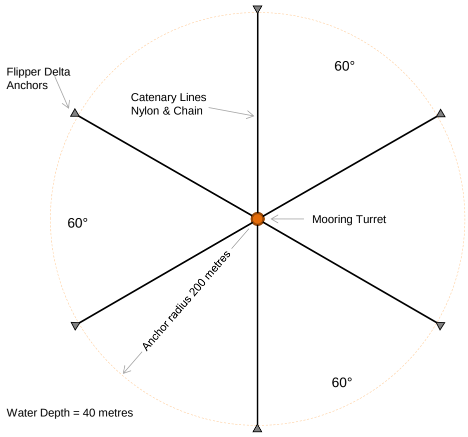
Extreme Mooring Design Load: ??

Mooring concept:
Turret Mooring with Chain Catenary Legs

On-board Equipment:
Mooring Turret (built into WEC)

Mooring Lines:
6 × 150 m Ø240 mm Nylon rope (35.2 kg/m)
Breaking load: 12062 kN
6 × 50 m Ø120 mm R4 studless chain (228 kg/m)
Proof / Breaking load: 9511 / 13573 kN

Anchors:
6 No. Flipper Delta Anchor, 25 tonne mass
Holding Capacity: 4516 kN



Subsequent work under WP3 of the project has involved undertaking preliminary quasi-static analyses for several different mooring design concepts applied to each of the four partner's WECs. This work has been carried out by Aalborg University and is reported in Reference 3.

This work found that three types of mooring arrangement can be designed for the use with the turret of the KNSWing at its intended site (40m water depth):

- Six leg chain catenary - anchor radius 401 metres, 6 x 420 metres of 117 mm dia. grade R4 studless chain MBS 12993 kN.
- Six leg taut synthetic - anchor radius 208 metres, 6 x 200 metres of 80 mm dia. Bridon Viking Braidline Nylon rope MBS 1491 kN.
- Single Anchor Leg buoy mooring - 30.6 metres of 73 mm dia. tether chain grade R4 MBS 5572 kN, Submerged buoy 2370 kN net uplift, 40 metres of 136 mm dia. Bridon Viking Braidline Nylon hawser MBS 4089 kN.

3 BUILDABILITY ISSUES

3.1 Turret Mooring Systems

Rotating turret systems as used by Floating Power Plant and KNSwing WECs will require sophisticated engineering and manufacture by a specialist company and will therefore be a high cost component of the WEC structure.

Design of the mooring line connections to the turret will need to consider the following issues:

- Method to be used for hooking-up and (if necessary) disconnecting the WEC from the pre-deployed spread mooring.
- Requirement for, and the means of achieving, mooring line length adjustments to facilitate correct pre-tensioning of the mooring lines.
- The means of securing / locking the mooring lines at their ultimate attachment points.
- Selection and design of any fairleads / sheaves / trumpets to protect and guide the mooring lines to their attachment points (especially for synthetic rope lines).
- Provision for any instrumentation such as line tension measurement systems (load-cells, etc.).

It is believed that Floating Power Plant intend to use a disconnectable turret design where the spread mooring lines are attached to a buoy that is separate from the WEC structure but can be winched up, mated and locked into the slewing bearing part of the turret which is built into the WEC hull. The buoy with all mooring lines still attached can also be unlocked and lowered so that the WEC is disconnected from the moorings.

A disconnectable turret system has clear advantages in simplifying the initial hook-up installation of the WEC offshore and in facilitating periodic disconnection so that the WEC can be towed inshore for maintenance or repair. However, the buildability issues mentioned above need to be considered and there are some other aspects that should be considered in relation to this type of mooring:

- Size and weight / buoyancy of the disconnectable part so that separation from the WEC is achievable and the independent mooring system that remains on site is not susceptible to damage, can survive the environmental extremes and then be readily retrievable for reconnection of the WEC.
- Method to be used for installation of the mooring spread, hook-up of lines to the disconnectable buoy and the achievement of correct pretensions in the lines.

The lowest cost anchoring option is to use Drag Embedment Anchors (DEAs). However, the selection and design depends on the nature and composition of the seabed at the deployment location. The drag distance needed to achieve full embedment is uncertain so the mooring design and installation procedures must accommodate this uncertainty in the line lengths and ensure there is sufficient adjustment capability to achieve correct line pretensions. Other anchoring options include hammer piles, suction piles, plate anchors and gravity anchors; each having pros and cons to be considered.

3.2 CALM Mooring Systems

CALM is an acronym for "Catenary Anchor Leg Mooring" and refers to a spread mooring of chain catenary lines attaching to a surface mooring buoy that has a rotating turntable for attaching hawser lines from the moored vessel (WEC in this case). It is therefore classed as a Single Point Mooring (SPM) along with SALM "Single Anchor Leg Mooring" and similar mooring arrangements that allow vessel weathervaning.

The preliminary analysis work conducted by Aalborg University has shown that CALM mooring systems with all chain lines are not feasible for the relatively shallow water depths in which it is intended to moor the partner WECs. It is shown that viable mooring solutions require the use of synthetic rope mooring lines. Synthetic rope lines have very low weight in water so do not hang in a defined catenary like chain lines and the mooring compliance derives from the axial stretch of the lines. The term CALM mooring is therefore not strictly accurate and it is preferable to use the more generic SPM name to define this type of mooring.

An SPM buoy with a rotating turntable is needed to facilitate 360degree weathervaning of the WEC. As for a turret mooring, this will require sophisticated engineering and manufacture by a specialist company. This LEANCON WEC does require full rotation but Wave Dragon has a stern mooring line designed to control rotation to within +/- 60° so a turntable with a slewing bearing may not be needed and the heading changes could simply be accommodated by designing the mooring system to tolerate this range of twist.

The lowest cost anchoring option is to use Drag Embedment Anchors (DEAs). However, the selection and design depends on the nature and composition of the seabed at the deployment location. The drag distance needed to achieve full embedment is uncertain so the mooring design and installation procedures must accommodate this uncertainty in the line lengths and ensure there is sufficient adjustment capability to achieve correct line pretensions. Other anchoring options include hammer piles, suction piles, plate anchors and gravity anchors; each having pros and cons to be considered.

In summary, the buildability issues relevant to the CALM type mooring are the following:

- Requirement for weathervaning of the WEC around the SPM buoy and, if needed, engineering of a rotating turntable for the hawser attachment point(s).
- Anchor type and selection appropriate to the seabed at the deployment location.
- Method to be used for installation of the mooring spread, hook-up of lines to the SPM buoy, locking off and adjusting to achieve correct pretensions in the lines.
- Selection and design of any fairleads / sheaves / trumpets to protect and guide the mooring lines and hawser(s) to their attachment points (vital for synthetic rope lines).
- Means of attaching and securing the mooring hawser(s) at their ultimate attachment points on the WEC.

- Provision for any instrumentation such as line tension measurement systems (load-cells, etc.) for the spread mooring lines at the SPM buoy and/or the hawser(s) at the WEC.

3.3 SALM Mooring Systems

SALM is an acronym for "Single Anchor Leg Mooring" and refers to a Single Point Mooring (SPM) which has a single leg supported in a vertical position by buoyancy and restrained at the base by a single seabed anchor point. A hawser is used to moor the vessel / WEC to the top of the riser leg. The SALM provides a readily disconnectable mooring arrangement.

Unless the moored vessel is restrained from weathervaning (e.g. using a back mooring as Wave Dragon), full rotational freedom may need to be provided. This could be at the anchor attachment, within the body of the riser leg or at the hawser connection point. The manner in which any swivel is designed and implemented could significantly impact the buildability and cost of the mooring system.

Simple SALM designs use a vertical leg of steel chain connected to a buoy at the top end but the anchor leg may be designed as a single rigid structure or an assembly with hinged joints. The simple chain leg design has been used for the preliminary analysis work conducted by Aalborg University which shows that this type of mooring can be designed for all four Partner WECs (Reference 3).

LEANCON is the only partner WEC where the designer proposes to use a SALM and the design comprises a leg of three rigid sections with universal joints rising from a concrete gravity anchor. Buoyancy elements are attached to the upper two leg sections. The WEC is moored to the top of the SALM by synthetic hawsers.

An important issue for design and buildability of SALM moorings is the requirement for the seabed anchoring point to resist considerable vertical loads in addition to the horizontal loading. The selection, design and installation of anchoring that can effectively handle such loading depend on the nature and composition of the seabed at the deployment location. It could be that a SALM solution is effectively infeasible at a particular location because of this buildability issue.

The generic solution of gravity base anchoring as used in the LEANCON mooring design has particular buildability issues around achieving the required mass within a reasonable volume and the manufacture, transportation and installation onto the seabed of such heavy and bulky components.

3.4 Synthetic Rope Lines

The mooring solutions for partner WECs as presented in the Aalborg reports (Reference 2 and Reference 3) indicate that, where used, synthetic rope mooring lines are all "Bridon Viking Braidline" with rope properties taken from the Bridon Fibre Brochure 04/2011 Edition 3, Page 13.

However, there is a buildability issue with using "braidline" rope construction as it is not considered the most appropriate for long-term moorings due to the need for frequent replacement during the mooring lifetime. Much enhanced fatigue endurance is achievable with parallel sub-rope type constructions. Designers of the mooring systems should also note that parallel sub-rope constructions are generally stiffer than braidline ropes (by around one third).

Many different types of synthetic fibre can be used to construct ropes; those most commonly used for mooring applications being Polyester, Nylon and HMPE. Each fibre has different stiffness and durability characteristics so selection of the fibre and rope construction is of vital importance to ensure that mooring lines perform as required and deliver a buildable mooring system for a particular WEC.

There is a long history of synthetic ropes being used as hawsers for mooring of large vessels (predominantly oil tankers) to single point moorings (CALM / SALM) so many of the buildability issues for such arrangements are well understood and the engineering solutions should be readily transferable to WEC moorings. It should be remembered that spread moorings have a level of pre-tension to control the slackening of lines but hawsers generally do not have such control and may therefore suffer more rapid strength deterioration and provision should be made for periodic replacement of hawsers.

The spread mooring proposed by the Wave Dragon designer uses mixed material lines comprising heavy chains from the anchors joined to synthetic ropes which lead up to the SPM buoy. Mixed lines comprising ground chains from the anchors connected to synthetic ropes are a viable mooring solution however, mooring lines which combine synthetic ropes and wire ropes are extremely difficult to engineer due to torque balance issues and are best avoided.

In any mooring that uses synthetic rope lines, care must be taken in engineering the mooring system to avoid buildability issues, which include the following:

- Synthetic ropes are more vulnerable (than chain) to physical damage such as cuts and abrasion so protective jacketing / sheathing should be provided in prone areas such as the end terminations.
- Synthetic ropes should be protected by filter cloth layers within the rope construction to prevent the ingress of soil particles in regions where they may potentially contact the seabed.
- Rope end terminations (spliced eyes, etc.) and the associated connecting hardware need careful design and manufacture appropriate to the rope construction and the installation and service requirements.
- The installation of mooring systems exposes synthetic line components to potential damage so installation arrangements and planned sequences of operations need to be developed to mitigate the potential for such damage.

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Part III

Task 3.3
Selection of Mooring Solutions Candidates for Detailed Analysis

6 | Selection of Mooring Solution Candidates

Based on the quasi-static analysis and the buildability assessment, the most important conclusions are that use of a catenary chain system is problematic and infeasible in the investigated water depths and sea conditions. Similar considerations were found in Thomsen et al. [2016].

In general, it is evident that much lighter systems will be obtained by use of synthetic lines, cf. Table 6.1. Even though synthetic lines are 4 times as expensive as chains pr. tonne, the overall average mass of the line materials in the found chain systems are 57 times heavier than the material in the synthetic systems. In addition to the indication of significant component cost in the synthetic system, it is evident that installation and decommissioning of a lighter system will be influencing the mooring cost in a positive direction. This further makes the SALM system an attractive solution, despite it being a relatively unexplored system for permanent moorings of this type of structure. While the investigated SALM system in this report treats a synthetic hawser and a chain tether, it is of great interest to also consider using only synthetic materials, thereby inducing even greater compliance and reduction of mass.

	CALM with chains	Mooring with synthetic lines	SALM
Average mass	522.8 t	9.1 t	4.5 t
Indicative line cost	4,140 €/t	16,100 €/t	-

Table 6.1. Average mass of the systems found in the quasi-static analysis, together with indicative costs for line materials.

Taking its basis in the previous quasi-static analysis of the mooring systems for the four large WECs and the requirements from the respective WEC developers, the following sections briefly lists the chosen solutions for each device, which will be investigated and optimized more detailed in coming reports.

6.1 Floating Power Plant

Floating Power Plant originally considered the use of a catenary turret system with mooring chains and drag embedded anchors. Following the conclusions made in Chapter 2, the main focus for this device will be aimed at the use of synthetic lines. Due to the structure of the device, the solution will continue using a turret system which allows for weathervaning and disconnectability.

6.2 KNSwing

The KNSwing mooring system, similar to Floating Power Plant, will be composed of a turret system with synthetic lines. The device might consider the use of a back anchor to limit the rotation to $\pm 90°$. From laboratory tests, it has been shown that oblique waves might increase power production, inducing the need for the back anchor. For early stages, however, this will not be considered. A SALM system was considered possible for this device due to its small seabed interference and high compliance. Due to concerns regarding redundancy, it was found insufficient, and the synthetic turret is chosen for further analysis.

6.3 LEANCON

The LEANCON device initially considered a SALM system with two submerged buoys, a deformable steel tether and synthetic hawser. CALM systems could also be considered, but due to the novelty of using a SALM system, this solution will be considered in future investigation and design. At present, the small-scale solution uses a gravity based anchor, which might cause problems when up-scaled. Similarly, the handling of the power cable can be a topic of further research.

6.4 Wave Dragon

The Wave Dragon WEC aims at using synthetic lines in following analysis, due to the desire of avoiding chain in the mooring. This is based on the present analysis, together with previous considerations. It is not a requirement at present that the device can weathervane 360° due to deployment at a near-shore location, where the dominating wave direction spreading is within $\pm 60°$.

7 | Conclusion

The present report used a simple quasi-static analysis procedure to analyse and design three mooring concepts for four large floating WECs. The design process considered deployment sites for the individual devices, in shallow/intermediate water depths, and considered design criteria found in relevant design standards. It is paramount to note that at this early stage in the design process, no limitations on e.g. motions etc. have been considered. The main purpose of the analysis is, therefore, to highlight solutions which are infeasible in these conditions and identify those that are most promising.

The main conclusions are:

- Mooring chain is infeasible in shallow/intermediate water depths when considering these types of WEC.
- SALM systems potentially provides a light and compliant system.
- Use of synthetic lines provide the necessary compliance to achieve a feasible design.

Based on these conclusions, it has been decided to use the following mooring systems in future analysis:

- SALM with synthetic lines.
- SPM with synthetic lines.
- Turret with synthetic lines.

Due to the high desire to obtain compliant mooring systems for this type of WECs (discussed in e.g. Thomsen et al. [2015a]), the use of nylon lines are highly beneficial and will form the focus for coming analysis. Further description of this can be found in Thomsen et al. [2016].

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