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Full Dynamic Analysis of Mooring Solution Candidates - First Iteration

T4.3 & M6

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DEPARTMENT OF CIVIL ENGINEERING
AALBORG UNIVERSITY

Full Dynamic Analysis of Mooring Solution Candidates – First Iteration

T4.3 & M6

Jonas Bjerg Thomsen
Francesco Ferri

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Aalborg University
Department of Civil Engineering
Wave Energy Research Group

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Full Dynamic Analysis of Mooring Solution Candidates – First Iteration

T4.3 & M6

by

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Francesco Ferri

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Contents

1 | Introduction

This report covers the initial steps in the full dynamic analysis of the wave energy converters (WECs) in the project *"Mooring Solutions for Large Wave Energy Converters"*: Floating Power Plant, KNSwing, LEANCON and Wave Dragon.

The content of the report deals with a very fist iteration in finding a suitable mooring solution for each of the WECs. In [3] a solutions was found using a simplified quasi-static analysis, and this will form the baseline for this dynamic analysis. The work tends not to optimize greatly on the layouts found previously and, hence, does not find any optimal solution. The main purpose of the report is to investigate if a solution can be found, and what parameter that needs to be treated in future analysis.

In earlier work it has now been proved that a quasi-static analysis might underestimate the line tension significantly and, therefore, it can be expected that the results found in this analysis differs from the results found previously, meaning that the design limits might not be satisfied. Potential differences between the two types of models are presented in the coming sections. In case, the solutions does not satisfy the ultimate limit state (ULS) from [5], the layouts will not be varied, but it will be attempted to use line with a larger diameter in order to introduce more strength and stiffness to the systems. The main goal is to find a first guess of four system that can be considered in this project, and which can later be optimized with more advanced methodology. Common for all the system is the use of Viking Braidline Nylon from the manufacturer Bridon. This type of rope might not be the best solution, because of the braided fibres. In later work, a parallel fibre rope should be considered.

After the work in this report was carried out, much focus was put into validation and improvement of the numerical model by use of experimental work. This was not included in this report, meaning that the used models are not as advanced as they will be in later work.

The analysis is performed using the boundary element method (BEM) code NEMOH [1] and the time domain mooring solver OrcaFlex v10.0 [2].

The results of the analysis was presented at a workshop in November 2016 at Aalborg University where all project partners attended. The layouts and results were discussed and the parameters that should be investigated in later work, was identified. This discussion is briefly listed for each of the partners, and the actual optimization and modelling work will be presented in later reports and papers. This upcoming work will provide a more thorough and reliable understanding and description of the moorings.

The report is constructed by four parts, each for one of the partner WECs:

1. Floating Power Plant
2. KNSwing
3. LEANCON
4. Wave Dragon

The reports present only the most relevant results and many similarities in the text and figures can be observed for each WEC. Each part can, therefore, be read separately. In later publications, more comprehensive description of the analysis and hydrodynamic modelling will be presented, and this report should be considered mostly as a result report.

1.1 Difference between QS and Dynamic

The report takes its basis in the results from previous quasi-static analysis, but several studies have now shown that there might be a significant difference between a quasi-static and dynamic model, especially in the extreme state. This is potentially caused by the presence of the dynamic effects from masses, drag etc., while also the dynamic analysis has allowed for inclusion of non-linear effects, and six degrees of freedom (QS only has one).

An import difference between the present analysis and the previous, is the calculation of drift force coefficients. In earlier work, a method was used, which has since proved to provide wrong results. This error has been eliminated, and the drift force calculation highly improved.

Part I

Floating Power Plant

2 | Design Conditions

In this part, the first calculations of a mooring solution for the Floating Power Plant, cf. Fig. 2.1 is summarized. The aim of the analysis is at present not to find the most optimal solution, but continue investigation of the layout found in previous quasi-static analysis cf. [3], and attempt to find a first solutions that satisfies the ULS.

In several papers it has now been shown that a quasi-static analysis is insufficient and tends to underestimate the line tensions and device motion when compared to experimental data. It is, therefore, not expected that the quasi-static and full dynamic analysis will show similar results. In case the line strength and mooring system is found to be insufficient, only the rope diameter is varied.

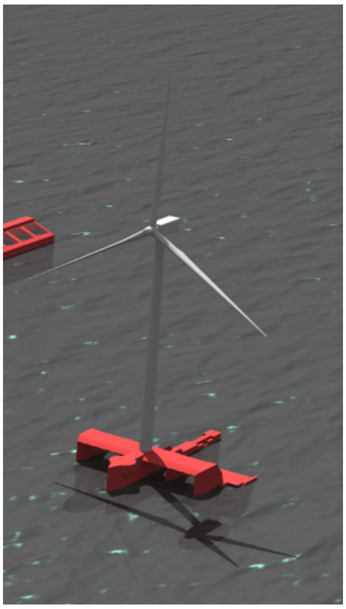

Fig. 2.1. The Floating Power Plant.

The following sections describes the parameters used for the design of the system as defined by the WEC developer. These parameters will be used in the next chapters to investigate the mooring system.

2.1 Structural Description

The investigated geometry resembles the actual geometry of the full-scale Floating Power Plant P60. It is assumed that the power take off (PTO) is disabled during an extreme event, and the floaters are therefore in a fixed position. The storm protection for the device is activated by ballasting the floaters so that the natural frequency is far out of the wave frequency and, hence, the floater will move with the structure. Assuming a fixed position can, therefore, be justified.

The estimation of hydrodynamic properties is based on linear potential theory; hence, only the geometry below the SWL is considered. The BEM code uses a panel mesh, which was constructed and illustrated in Fig. 2.2. This figure also illustrates location of coordinate system. Note that this is located in the water line and at the front of the the structure.

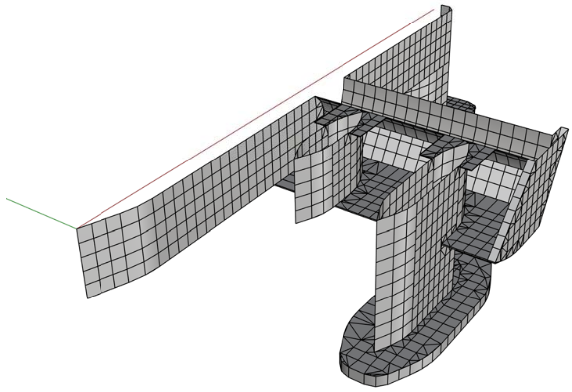

Fig. 2.2. Illustration of the investigated geometry and location of coordinate system.

Structural parameters are listed in Table 2.1. Note that the moment of inertia (MoI) is with respect to the center of gravity and not the origin of the coordinate system. The drag coefficients are used for calculation of current and wind loads using a drag formulation as specified in several design standards. The coefficients are estimated based on a simplified geometry; hence, considering the device to be composed of several rectangles and cylinders.

Name	**Unit**	**Value**		
Structural Mass	[kg]	7,813,125		
Centre of Gravity	[m]	x	y	z
		35.6	0	-5.775
Mass Moment of Inertia	[kg m^2]	x	y	z
wrt CoG	x	$2.06 \cdot 10^9$	0	0
	y	0	$2.37 \cdot 10^9$	0
	z	0	0	$3.56 \cdot 10^9$
Drag Coefficient	[-]			
Above SWL		0.72		
Below SWL		1.35		

Table 2.1. Structural parameters used in the full dynamic analysis

2.2 Environmental Conditions

The mooring system will be designed for deployment at the Belgian coast. For more information on this location, see [4]. A summary of environmental conditions can be found in Table 2.2.

Name	Unit	Value
Water depth	[m]	30
Water level variation	[m]	5.45
Significant wave height	[m]	6.55
Peak wave period	[s]	9.3-13.7
Wind velocity	[m/s]	33
Current velocity	[m/s]	1.3

Table 2.2. Environmental conditions used in the analysis of the Floating Power Plant.

For this initial analysis of the mooring system, the entire range of peak period was not considered, and the average value $T_p = 11.5$ s was used. Similarly, water level variations were not taken into account.

2.3 Design Limits

When designing mooring systems, the stiffness of the system is a vital parameter to consider. It is in many cases preferable to make the system as compliant as possible, thereby introducing lower loads, but also larger displacements. Since the device needs a power cable, it is necessary to define a limit for motions. The heave DOF is not relevant to consider, but the surge is restrained by the layout of the cable. It is assumed that the cable will use a lazy-S shape and with a maximum bending radius of 1.736 m, corresponding to a cable suitable for this device. When calculating the length of the cable, the lowest possible water level is considered. It is additionally assumed that there must be 10% clearance between the cable and the SWL and seabed. This results in a cable length of 77 m. As shown in Fig. 2.3, a minimum and maximum position can be determined, and by assuming that the device is installed in the mean position ± 29 m of excursion can be allowed.

The pitch motion is not significantly affected by the power cable, but since the device is equipped with a wind turbine, large rotation must be avoided. For a device and turbine like this, a limit of ± 10° is defined.

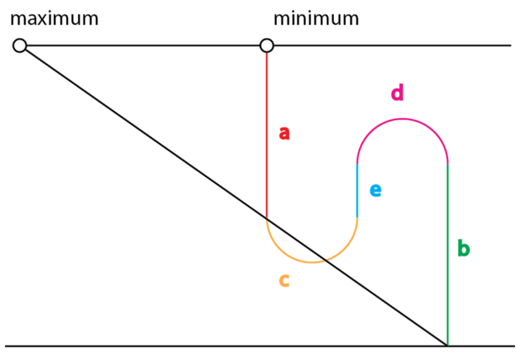

Fig. 2.3. Illustration of the assumed power cable layout used to define excursion limits.

Name	Unit	Value		
		Surge	Heave	Pitch
Displacement	[m]-[deg]	58 (±29)	±10	±10
Velocities	[m/s]-[deg/s]	N/A	N/A	N/A

3 | Mooring Analysis

The following chapter describes the first initial analysis of the mooring of the WEC. The basis and considered layout is resulting from the quasi-static analysis in [3].

3.1 Quasi-static Layout

The layout chosen from the quasi-static layout resembles a taut synthetic turret system with six mooring lines, as illustrated in Fig. 3.1 and with dimensions as listed in Table 3.1.

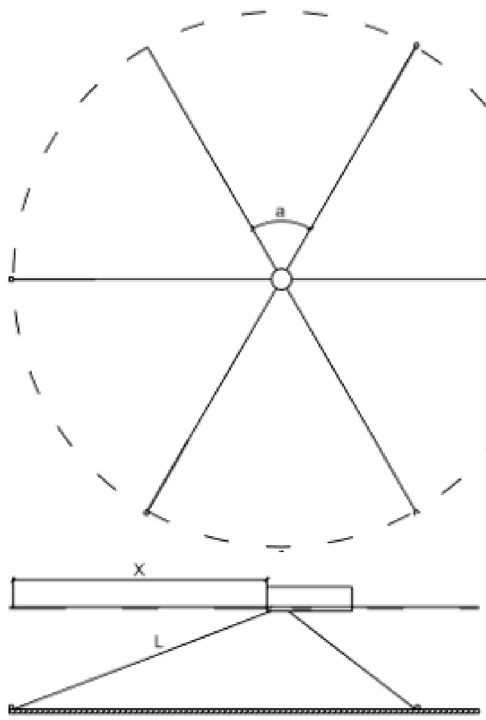

Fig. 3.1. Illustration of mooring system investigated in the quasi-static analysis. Not to scale.

Unstretched length	l	200 m
Seabed footprint (radius)	r	207 m
Line diameter	d	88 mm
Characteristic breaking strength	T_{MBS}	1790 kN
Design breaking strength	$T_{MBS,d}$	1705 kN

Table 3.1. Definition of dimensions for the quasi-static layout.

As seen from the table the footprint is relatively large compared to the size of the device, which might not be considered feasible in a final desing. A scaled 3d model is illustrated in Fig. 3.2

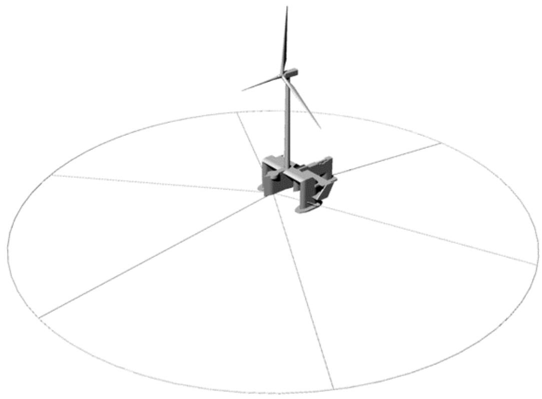

Fig. 3.2. The Floating Power Plant WEC and the investigated mooring system.

The analysis was conducted as a three hour simulation (app. 1000 waves), with the environmental conditions as listed previously. The results are shown in Table 3.2.

Design breaking strength Design tension	$T_{MBS,d}$ T_{design}	1705 kN 2666 kN	$u_T = \frac{T_{MBS,d}}{T_{design}} = 0.6$
Design limit Design excursion	x_{limit} x_{design}	± 29.0 m 48.3 m	$u_x = \frac{x_{limit}}{x_{design}} = 0.6$
Design limit Design excursion	$pitch_{limit}$ $pitch_{design}$	± 10.0° $-19.3°/+14.5°$	$u_p = \frac{pitch_{limit}}{pitch_{design}} = 0.5$

Table 3.2. Results from dynamic analysis of quasi-static layout.

It is clearly seen that the mooring system is insufficient, as the line strength is exceeded, causing failure of lines, and as the excursion and rotation limit is also exceeded.

A solution to this problem is to introduce more strength into the lines, by increasing the line diameter. This will additionally provide stiffness into the system, which potentially can reduce the excursion.

3.2 Dynamic Analysis

Several iterations was done by increasing the line diameter until the best solution was found. With the given linetype and layout, it was not possible to find a solution that satisfied all design requirements. Results can be seen in the following tables.

Unstretched length Seabed footprint (radius)	l r	200 m 207 m
Line diameter Characteristic breaking strength Design breaking strength	d T_{MBS} $T_{MBS,d}$	240 mm 12031 kN 11458 kN

Table 3.3. Definition of dimensions for the quais-static lyout.

Design breaking strength Design tension	$T_{MBS,d}$ T_{design}	11458 kN 4690 kN	$u_T = \frac{T_{MBS,d}}{T_{design}} = 2.4$
Design limit Design excursion	x_{limit} x_{design}	$\pm$ 29.0 m 21.9 m	$u_x = \frac{x_{limit}}{x_{design}} = 1.3$
Design limit Design excursion	$pitch_{limit}$ $pitch_{design}$	$\pm$ 10.0° $-18.4°/+13.6°$	$u_p = \frac{pitch_{limit}}{pitch_{design}} = 0.5$

Table 3.4. Results from dynamic analysis of improved layout.

The table illustrates that with the given layout it is not possible to find a suitable solution. It is possible to ensure sufficient strength in the lines (2.4 times more than required) but it is still not enough to restrain the motions sufficiently. It is, therefore, necessary to investigate the solutions more comprehensively.

3.3 Discussion of Upcoming Analysis

The present analysis showed that it is not possible to design a mooring system with the layout previously found in quasi-static analysis. The main problem arising from too large motions. It is, therefore, needed to investigate more layouts and variation in the layout parameters, and additionally take the cost of the system into consideration. This will, hopefully, allow for the identification of the most suitable and optimized solution. For a turret system with taut synthetic lines several parameters for optimization can be considered:

- Mooring line diameter.
- Foot print radius.
- Number of lines.

The length of the lines are not considered as an optimization parameter, as the vertical pretension of the system must be kept constant in order to ensure the same load on the device. The length will therefore be dependent on the footprint radius, diameter (stiffness) and the number of lines. As seen, there is a total of three parameter to vary, but with a large number of combinations, the process can be time consuming and extensive. In further work, reports and papers, the optimizations of these parameters will be presented.

Part II

KNSwing

4 | The KNSwing WEC

The following chapters summarizes the first calculations of a mooring solution for the KNSwing, cf. Fig. 4.1. The calculation will at present not find the most optimal solution, but continue investigating the layout found in previous quasi-static analysis cf. [3].

In several papers it has now been shown that a quasi-static analysis is insufficient and tends to underestimate the line tensions and device motion when compared to experimental data. It is, therefore, not expected that the quasi-static and full dynamic analysis will show similar results. In case the line strength and mooring system is found to be insufficient, only the rope diameter is varied.

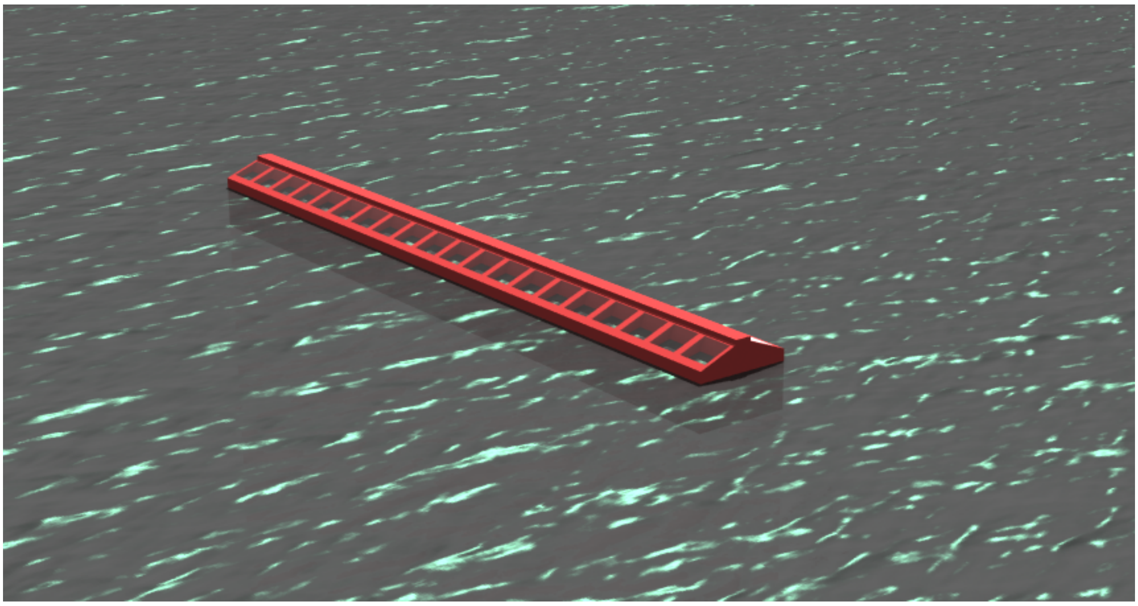

Fig. 4.1. The KNSwing WEC.

The following sections describes the parameters used for the design of the system as defined by the WEC developer. These parameters will be used in the next chapters to investigate the mooring system.

4.1 Structural Description

The investigated geometry resembles the actual geometry of the full-scale KNSwing. The estimation of hydrodynamic properties is based on linear potential theory; hence, only the geometry below the SWL is considered. An illustration of this can be seen in Fig. 4.2, which also illustrates location of coordinate system. Note that this is located in the water line and at the centrelines of the the structure.

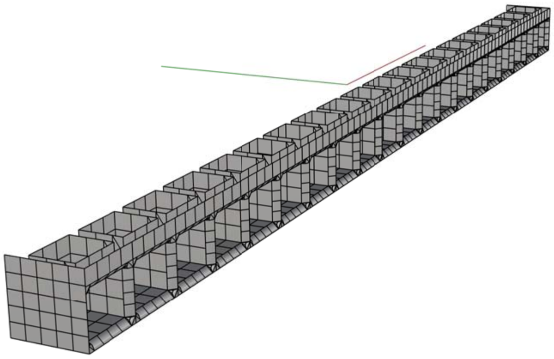

Fig. 4.2. Illustration of the investigated geometry and location of coordinate system.

Structural parameters are listed in Table 4.1. Note that the moment of inertia (MoI) is with respect to the center of gravity and not the origin of the coordinate system. The drag coefficients are used for calculation of current and wind loads using a drag formulation as specified in several design standards. The coefficients are estimated based on simplified geometry; hence, considering the device to be a long rectangle where the flow is restrained from passing the shape over all edges (SWL).

Name	Unit	Value		
Structural Mass	[kg]	44,748,800		
Centre of Gravity	[m]	x	y	z
		0	0	-3.6
Mass Moment of Inertia	[kg m^2]	x	y	z
wrt CoG	x	$2.86 \cdot 10^9$	0	0
	y	0	$2.15 \cdot 10^{11}$	0
	z	0	0	$2.15 \cdot 10^{11}$
Drag Coefficient	[-]			
Above SWL		0.7		
Below SWL		0.7		

Table 4.1. Structural parameters used in the full dynamic analysis

4.2 Environmental Conditions

The mooring system will be designed for deployment at the Danish part of the North Sea. For more information on this location, see [4]. A summary of environmental conditions can be found in Table 4.2.

Name	Unit	Value
Water depth	[m]	40
Water level variation	[m]	2.08
Significant wave height	[m]	9.9
Peak wave period	[s]	11.4-16.8
Wind velocity	[m/s]	39.9
Current velocity	[m/s]	1.0

Table 4.2. Environmental conditions for location at the Danish part of the North Sea.

For this inital analysis of the mooring system, the entire range of peak period was not considered, and the average value $T_p = 14.1$ s was used. Similarly, water level variations were not taken into account.

4.3 Design Limits

When designing mooring systems, the stiffness of the system is a vital parameter to consider. It is in many cases preferable to make the system as compliant as possible, thereby introducing lower loads, but also larger displacements. Since the device needs a power cable and is expected to be deployed in array, it is necessary to define a limit for motions. For the KNSwing the heave and pitch DOF are not relevant and no limits on motions are defined. However, for the surge DOF the power cable is used to define a limit. It is assumed that the cable will use a lazy-S shape and with a maximum bending radius of 1.736 m, corresponding to a cable suitable for this device. When calculating the length of the cable, the lowest possible water level is considered. It is additionally assumed that there must be 10% clearance between the cable and the SWL and seabed. This results in a cable length of 113 m. As shown in Fig. 4.3, a minimum and maximum position can be determined, and by assuming that the device is installed in the mean position ± 44 m of excusion can be allowed.

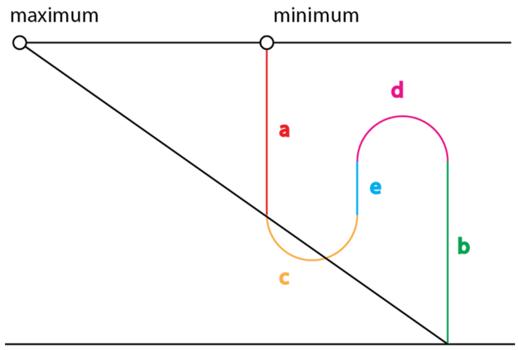

Fig. 4.3. Illustration of the assumed power cable layout used to define excursion limits.

Name	Unit	Value		
		Surge	Heave	Pitch
Displacement	[m]-[deg]	88 (± 44)	N/A	N/A
Velocities	[m/s]-[deg/s]	N/A	N/A	N/A

5 | Mooring Analysis

The following chapter describes the first initial analysis of the mooring of the WEC. The basis is the results from the quasi-static analysis in [3].

5.1 Quasi-static Layout

The layout chosen from the quasi-static layout resembles a taut synthetic system with six mooring lines. The system is illustrated in Fig. 5.1 and dimensions listed in Table 5.1.

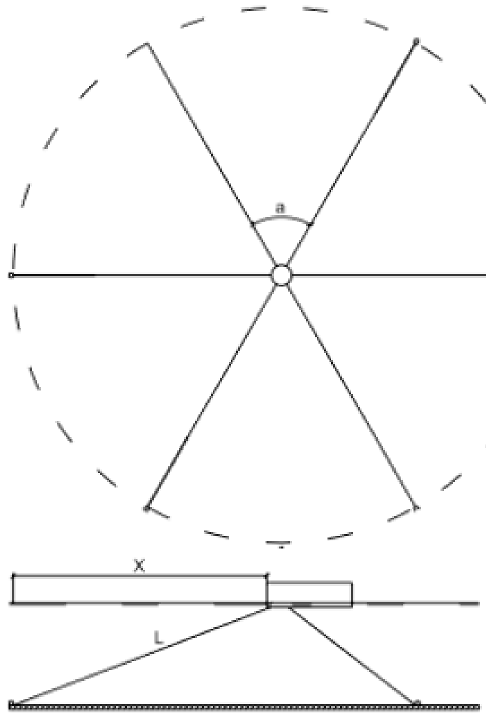

Fig. 5.1. Illustration of mooring system investigated in the quasi-static analysis.

Unstretched length	l	200 m
Seabed footprint (radius)	r	208 m
Line diameter	d	80 mm
Characteristic breaking strength	T_{MBS}	1491 kN
Design breaking strength	$T_{MBS,d}$	1417 kN

Table 5.1. Definition of dimensions for the quais-static lyout.

The system is illustrated in Fig. 5.2

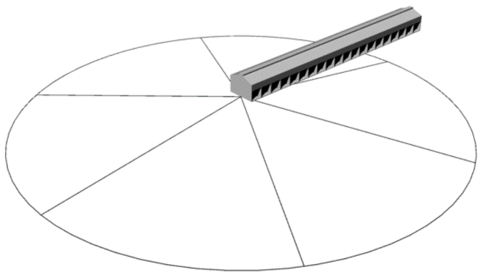

Fig. 5.2. The KNSwing WEC and the investigated mooring system.

Running the simulation provided results as shown in Table 5.2. The results are obtained by running a three hour simulation and finding statistical values for maximum tension and excursion.

Design breaking strength Design tension	$T_{MBS,d}$ T_{design}	1417 kN 1801 kN	$u_T = \frac{T_{MBS,d}}{T_{design}} = 0.8$
Design limit Design excursion	x_{limit} x_{design}	± 44.0 m 42.6 m	$u_x = \frac{x_{limit}}{x_{design}} = 1.0$

Table 5.2. Results from dynamic analysis of quasi-static layout.

It is clearly seen that the mooring system is insufficient, as the line strength is exceeded, causing failure of lines.

A solution to this problem is to introduce more strength into the lines, by increasing the line diameter. This will additionally provide stiffness into the system, which will reduce the excursion.

5.2 Dynamic Analysis

Several iterations was done by increasing the line diameter until a sufficient solution was found. Results can be seen in the following tables.

Unstretched length Seabed footprint (radius)	l r	200 m 208 m
Line diameter Characteristic breaking strength Design breaking strength	d T_{MBS} $T_{MBS,d}$	192 mm 7825 kN 7434 kN

Table 5.3. Definition of dimensions for the first analysis.

Design breaking strength Design tension	$T_{MBS,d}$ T_{design}	7434 kN 2456 kN	$u_T = \frac{T_{MBS,d}}{T_{design}} = 3.0$
Design limit Design excursion	x_{limit} x_{design}	± 44.0 m 19.8 m	$u_x = \frac{x_{limit}}{x_{design}} = 12.2$

Table 5.4. Results from dynamic analysis of improved layout.

The table now illustrates that sufficient strength is available in the lines and the stiffness is high enough to satisfy the excursion limit. As seen, the strength is three times the breaking limit, but this might be desirable since the full range of environmental conditions are not yet investigated, and the ALS (accidental limit state) has not been considered yet. Based on this, the system defined in Table 5.4 is considered a realistic first guess for a mooring system.

5.3 Discussion of Upcoming Analysis

The present analysis showed that it is possible to design a mooring system, which ensures sufficient strength in the lines to withstand the line tension and also ensures enough stiffness to avoid excessive excursion. However, the analysis did not find the most suitable solutions and has not yet investigated the cost of the mooring system. This will be the aim of upcoming work.

The turret system with taut synthetic lines allows for optimization of several parameters, listed as:

- Mooring line diameter.
- Foot print radius.
- Number of lines.

The length of the lines are not considered as an optimization parameter, as the vertical pretension of the system must be kept constant in order to ensure the same load on the device. The length will therefore be dependent on the footprint radius, diameter (stiffness) and the number of lines. As seen, there is a total of three parameter to vary, but with a large number of combinations, the process can be time consuming and extensive. In further work, reports and papers, the optimizations of these parameters will be presented.

Part III

LEANCON

6 | Design Conditions

The following chapters summarizes the first calculations of a mooring solution for the LEANCON Wave Energy device, cf. Fig. 6.1. The investigation is based on the mooring system considered in the earlier quasi-static analysis [3], and hence, is not the layout that will be considered as the final solution. A specific layout (SEBAS) has been proposed for the LEANCON device, but this will not be considered here, as the puporse merely is to find a suitable solution, based on the design previously considered. The SEBAS system will be presented later in this report.

An aim of this investigation to go from the result in the QS analysis, with many simplifications, and into a full dynamic analysis, and still have a sufficient mooring system. In several papers it has now been shown that a quasi-static analysis is insufficient and tends to underestimate the line tensions and device motion when compared to experimental data. It is, therefore, not expected that the quasi-static and full dynamic analysis will show similar results. In case the line strength and mooring system is found to be insufficient, only the rope diameter is varied.

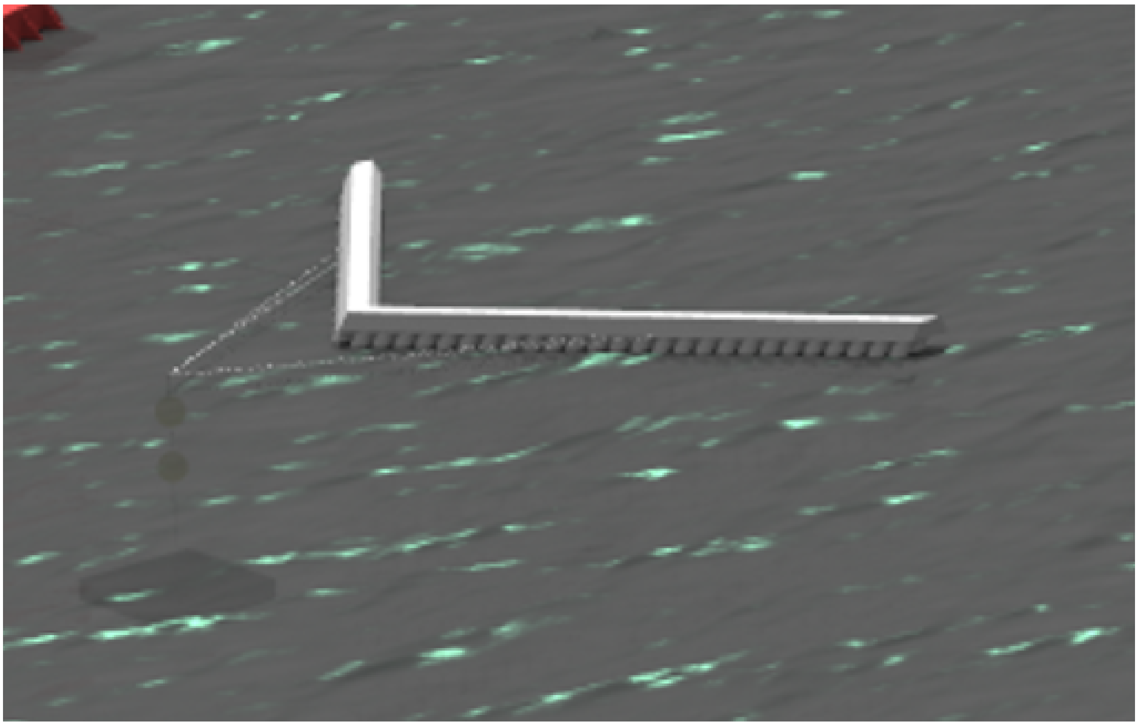

Fig. 6.1. The LEANCON WEC.

The following sections describes the parameters used for the design of the system as defined by the WEC developer. These parameters will be used in the next chapters to investigate the mooring system.

6.1 Structural Description

The investigated geometry resembles the actual geometry of the full-scale LEANCON device for DanWEC. During an extreme event, the system is in a safety mode, where the structure is filled with air, providing large buoyancy and a small draught. The actual volume below the SWL is, therefore, relatively small which is suggested to reduce the wave loads on the structure. The estimation of hydrodynamic properties is based on linear potential theory; hence, only the geometry below the SWL is considered. An illustration of this can be seen in Fig. 6.2, which also illustrates location of coordinate system. Note that this is located in the water line and at the front of the the structure.

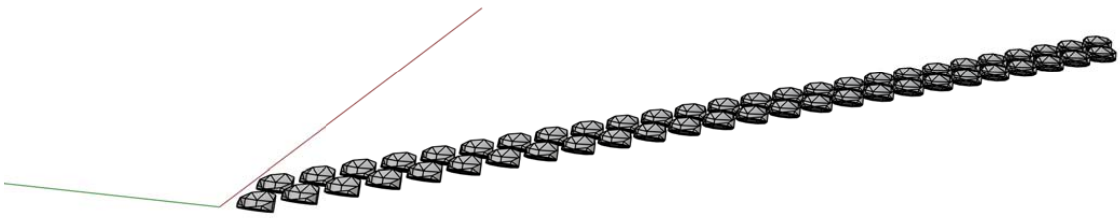

Fig. 6.2. Illustration of the investigated geometry and location of coordinate system.

Structural parameters are listed in Table 6.1. Note that the moment of inertia (MoI) is with respect to the center of gravity and not the origin of the coordinate system. The drag coefficients are used for calculation of current and wind loads using a drag formulation as specified in several design standards. The coefficients are estimated based on simplified geometry; hence, considering the device to be composed of several cylinders.

Name	**Unit**	**Value**		
Structural Mass	[kg]	187,500		
Centre of Gravity	[m]	x	y	z
		27.8	0	2.8
Mass Moment of Inertia	[kg m^2]	x	y	z
wrt CoG	x	$2.29 \cdot 10^8$	0	0
	y	0	$4.19 \cdot 10^7$	0
	z	0	0	$2.70 \cdot 10^8$
Drag Coefficient	[-]			
Above SWL		1.1		
Below SWL		1.1		

Table 6.1. Structural parameters used in the full dynamic analysis

6.2 Environmental Conditions

The mooring system will be designed for deployment at the DanWEC test facility in Hanstholm, Denmark. For more information on this location, see [4]. A summary of environmental conditions can be found in Table 6.2.

Name	Unit	Value
Water depth	[m]	25
Water level variation	[m]	1.67
Significant wave height	[m]	8.28
Peak wave period	[s]	10.47-15.37
Wind velocity	[m/s]	34
Current velocity	[m/s]	1.5

Table 6.2. Environmental conditions at the deployment site at DanWec, Hanstholm.

For this initial analysis of the mooring system, the entire range of peak period was not considered, and the average value $T_p = 12.9$ s was used. Similarly, water level variations were not taken into account.

6.3 Design Limits

When designing mooring systems, the stiffness of the system is a vital parameter to consider. It is in many cases preferable to make the system as compliant as possible, thereby introducing lower loads, but also larger displacements. Since the device needs a power cable it is necessary to define a limit for motions. For the LEANCON WEC the heave and pitch DOF are not relevant and no limits on these motions are defined. The surge motion is defined prior by the developer and is listed in in Table 6.3.

Name	Unit	Value		
		Surge	Heave	Pitch
Displacement	[m]-[deg]	60 ($\pm$30)	N/A	N/A
Velocities	[m/s]-[deg/s]	N/A	N/A	N/A

Table 6.3. Defined restrains on the motion of the WEC.

7 | Mooring Analysis

The following chapter describes the first initial analysis of the mooring of the WEC. The basis is the results from the quasi-static analysis in [3].

7.1 Quasi-static Layout

The layout chosen from the quasi-static layout resembles a single anchor leg mooring (SALM) system with one submerged buoy, a chain tether and a synthetic hawser. The system is illustrated in Fig. 7.1 and dimensions listen in Table 7.1.

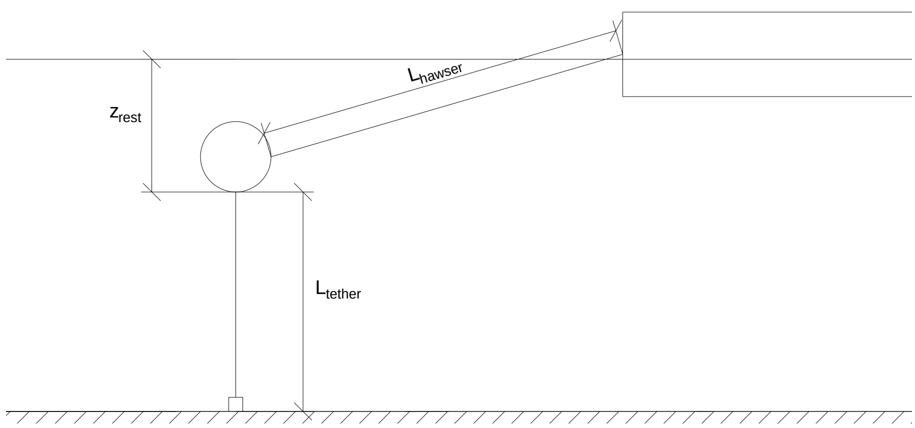

Fig. 7.1. Illustration of mooring system investigated in the quasi-static analysis.

Hawser length	l	60 m
Line diameter	d	192 mm
Characteristic breaking strength	T_{MBS}	7806 kN
Design breaking strength	$T_{MBS,d}$	7434 kN
Tether length	l	16 m
Line diameter	d	120 mm
Characteristic breaking strength	T_{MBS}	13539 kN
Design breaking strength	$T_{MBS,d}$	12894 kN

Table 7.1. Definition of dimensions for the quasi-static layout.

The system is illustrated in Fig. 7.2

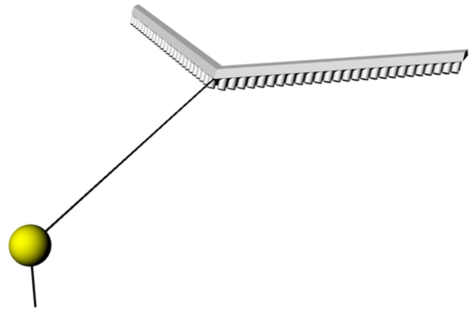

Fig. 7.2. The LEANCON WEC and the investigated mooring system.

Running the simulation provided results as shown in Table 7.2. The results are obtained by running a three hour simulation and finding statistical values for maximum tension and excursion.

Hawser Design breaking strength Design tension	$T_{MBS,d}$ T_{design}	7434 kN 7396 kN	$u_T = \frac{T_{MBS,d}}{T_{design}} = 1.0$
Tether Design breaking strength Design tension	$T_{MBS,d}$ T_{design}	12894 kN 8060 kN	$u_T = \frac{T_{MBS,d}}{T_{design}} = 1.6$
Design limit Design excursion	x_{limit} x_{design}	± 30.0 m 24.0 m	$u_x = \frac{x_{limit}}{x_{design}} = 1.3$

Table 7.2. Results from dynamic analysis of quasi-static layout.

It is seen that the mooring system is sufficient, considering both the line tension and WEC excursion. Therefore, no further actions are done by now. It is worth to notice that the tension in the hawser is close to the strength, while the strength in the tether is 1.6 times larger than the tension. Preferable, this can be optimized, either by adjusting the line dimensions or by changing the buoy volume.

7.2 Discussion of Upcoming Analysis

The present analysis showed that a SALM type system could be designed for the LEANCON device, without further analysis either than considering the quasi-static layout. However, another mooring layout has been proposed for the LEANCON device, illustrated in Fig. 7.3. The system has been denoted as the SEBAS system (Slacked Elastic Buoyancy Anchoring System). This system is still a SALM type system, but consists of two submerged buoys, a deformable tether (steel rods connected by universal joints) and four nylon lines. Further analysis should focus on this design, and allows for optimization of several parameters:

- Mooring line diameter.
- Buoy 1 volume.
- Buoy 2 volume.
- Mooring line length.

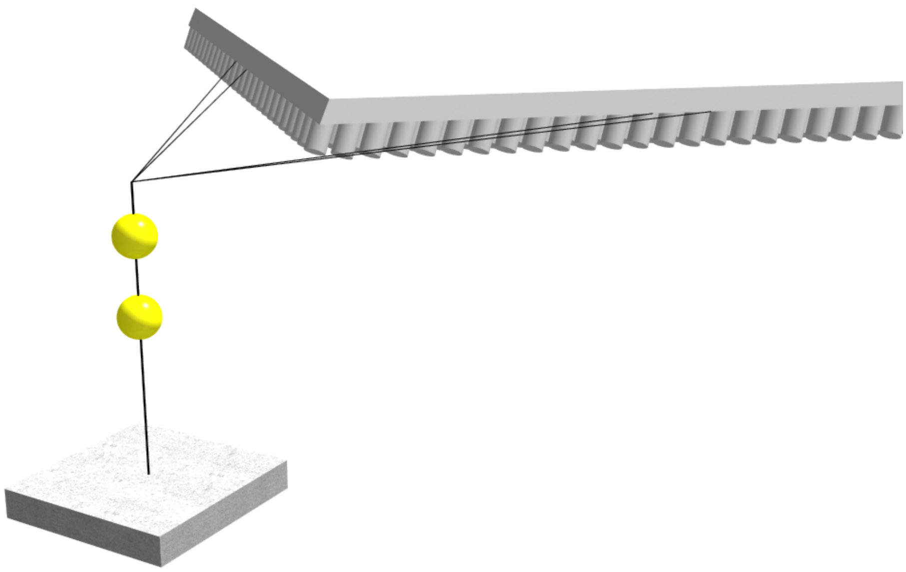

Fig. 7.3. Illustration of mooring system suggested for the LEANCON WEC.

As seen, there is a total of four parameter to vary, but with a large number of combinations, the process can be time consuming and extensive. In further work, reports and papers, the optimizations of these parameters will be presented.

Part IV

Wave Dragon

8 | Design Conditions

The following chapters summarizes the first calculations of a mooring solution for the Wave Dragon Wave Energy device, cf. Fig. 8.1. The analysis tends not to find the most optimal solution, but continues investigation of the layout found in previous quasi-static analysis cf. [3].

In several papers it has now been shown that a quasi-static analysis is insufficient and tends to underestimate the line tensions and device motion when compared to experimental data. It is, therefore, not expected that the quasi-static and full dynamic analysis will show similar results. In case the line strength and mooring system is found to be insufficient, only the rope diameter is varied. This analysis is done in order to highlight what parameters that need further investigation, and if a solution can be found based on the suggested layout.

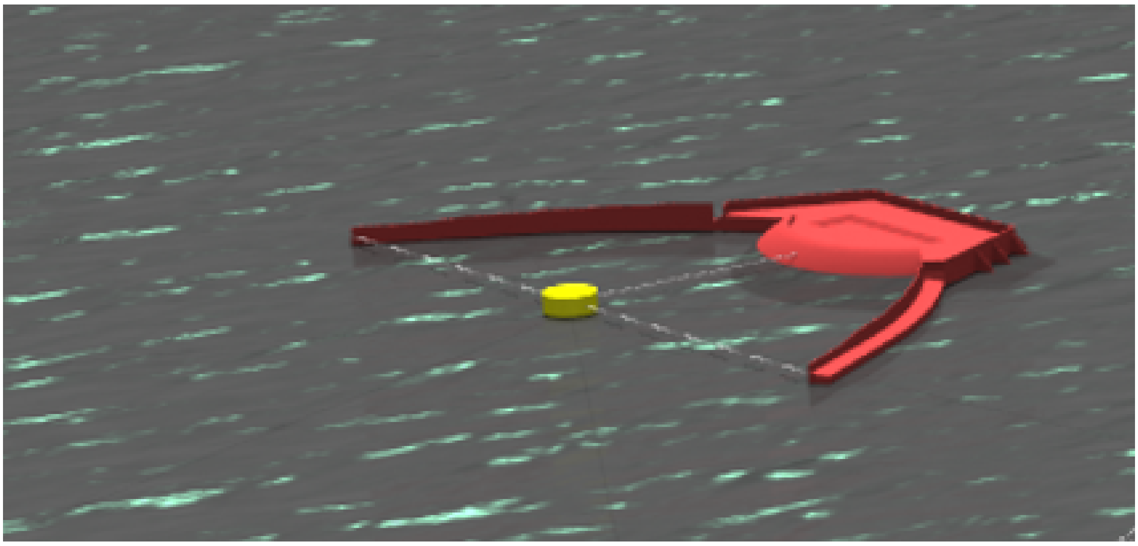

Fig. 8.1. The Wave Dragon WEC. Note that this illustration is in operational condition. In survival mode, the structure is submerged, cf. Fig. 8.2

The following sections describes the parameters used for the design of the system as defined by the WEC developer. These parameters will be used in the next chapters to investigate the mooring system.

8.1 Structural Description

The investigated geometry resembles the actual geometry of the full-scale Wave Dragon device for DanWEC. The estimation of hydrodynamic properties is based on linear potential theory; hence, only the geometry below the SWL is considered. An illustration of this can be seen in Fig. 8.2, which also illustrates location of coordinate system. Note that this is located in the water line and at the x-coordinate for the CoG of the the structure.

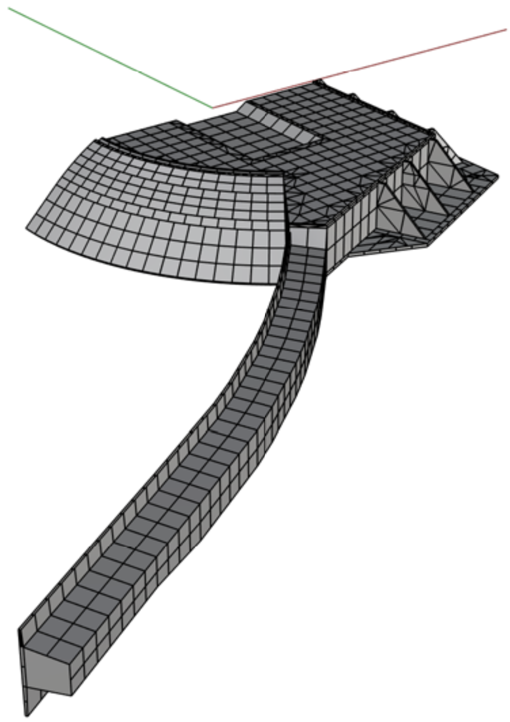

Fig. 8.2. Illustration of the investigated geometry and location of coordinate system.

Structural parameters are listed in Table 8.1. Note that the moment of inertia (MoI) is with respect to the center of gravity and not the origin of the coordinate system. The drag coefficients are used for calculation of current and wind loads using a drag formulation as specified in several design standards. The coefficients are estimated based on simplified geometry.

Name	**Unit**	**Value**		
Structural Mass	[kg]	7,000,000		
Centre of Gravity	[m]	x	y	z
		0	0	-3.38
Mass Moment of Inertia	[kg m^2]	x	y	z
wrt CoG	x	$9.17 \cdot 10^9$	0	0
	y	0	$2.15 \cdot 10^9$	0
	z	0	0	$1.12 \cdot 10^{10}$
Drag Coefficient	[-]			
Above SWL		1.2		
Below SWL		1.5		

Table 8.1. Structural parameters used in the full dynamic analysis

8.2 Environmental Conditions

The mooring system will be designed for deployment at the DanWEC test facility in Hanstholm, Denmark. For more information on this location, see [4]. A summary of environmental conditions can be found in Table 6.2.

Name	Unit	Value
Water depth	[m]	25
Water level variation	[m]	1.67
Significant wave height	[m]	8.28
Peak wave period	[s]	10.47-15.37
Wind velocity	[m/s]	34
Current velocity	[m/s]	1.5

For this initial analysis of the mooring system, the entire range of peak period was not considered, and the average value $T_p = 12.9$ s was used. Similarly, water level variations were not taken into account.

8.3 Design Limits

When designing mooring systems, the stiffness of the system is a vital parameter to consider. It is in many cases preferable to make the system as compliant as possible, thereby introducing lower loads, but also larger displacements. Since the device needs a power cable the motion need to be restrained in order to avoid damage on the cable. For the Wave Dragon the heave and pitch DOF is not relevant and no limits on these are defined. However, for the surge DOF the power cable is used to define a limit. It is assumed that the cable will use a lazy-S shape and with a maximum bending radius of 1.736 m, corresponding to a cable suitable for this device. When calculating the length of the cable, the lowest possible water level is considered. It is additionally assumed that there must be 10% clearance between the cable and the SWL and seabed. This results in a cable length of 64 m. As shown in Fig. 8.3, a minimum and maximum position can be determined, and by assuming that the device is installed in the mean position ± 27 m of excursion can be allowed.

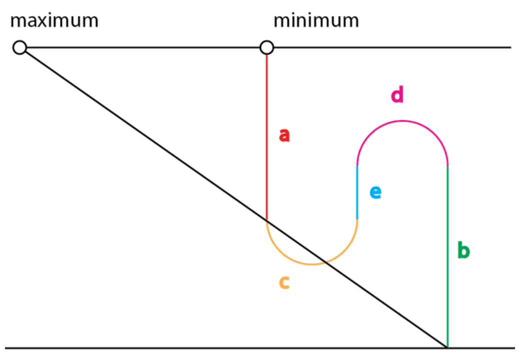

Fig. 8.3. Illustration of the assumed power cable layout used to define excursion limits.

Name	Unit	Value		
		Surge	Heave	Pitch
Displacement	[m]-[deg]	54 (±27)	N/A	N/A
Velocities	[m/s]-[deg/s]	N/A	N/A	N/A

9 | Mooring Analysis

The following chapter describes the first initial analysis of the mooring of the WEC. The basis is the results from the quasi-static analysis in [3].

9.1 Quasi-static Layout

The layout chosen from the quasi-static layout resembles a single point mooring (SPM) system with one surface buoy, a nylon hawser and six synthetic mooring lines. The system is illustrated in Fig. 9.1 and dimensions listen in Table 9.1.

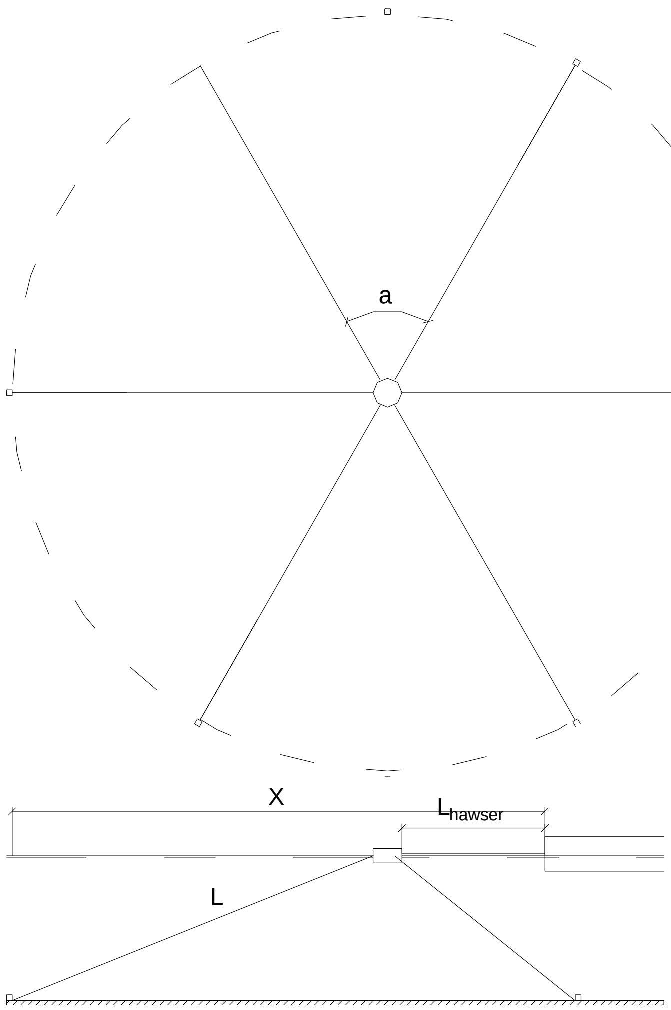

Fig. 9.1. Illustration of mooring system investigated in the quasi-static analysis.

Seabed footprint radius	r	203 m
Hawser length	l	40 m
Line diameter	d	192 mm
Characteristic breaking strength	T_{MBS}	7806 kN
Design breaking strength	$T_{MBS,d}$	7434 kN
Mooring line length	l	200 m
Line diameter	d	128 mm
Characteristic breaking strength	T_{MBS}	3562 kN
Design breaking strength	$T_{MBS,d}$	3392 kN

Table 9.1. Definition of dimensions for the quasi-static layout.

The system is illustrated in Fig. 9.2

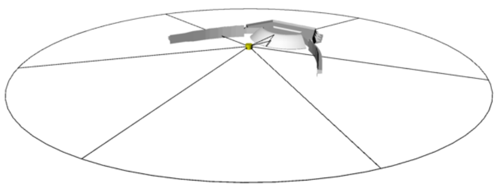

Fig. 9.2. The Wave Dragon WEC and the investigated mooring system.

Running the simulation provided results as shown in Table 9.2. The results are obtained by running a three hour simulation and finding statistical values for maximum tension and excursion.

Hawser Design breaking strength Design tension	 $T_{MBS,d}$ T_{design}	 7434 kN 7311 kN	$u_T = \frac{T_{MBS,d}}{T_{design}} = 1.0$
Mooring line Design breaking strength Design tension	 $T_{MBS,d}$ T_{design}	 3392 kN 4939 kN	$u_T = \frac{T_{MBS,d}}{T_{design}} = 0.7$
Design limit Design excursion	x_{limit} x_{design}	± 27.0 m 59.0 m	$u_x = \frac{x_{limit}}{x_{design}} = 0.5$

Table 9.2. Results from dynamic analysis of quasi-static layout.

It is seen that the mooring system is insufficient, considering both the line tension and WEC excursion.

A solution to this problem is to introduce more strength into the lines, by increasing the line diameter. This will additionally provide stiffness into the system, which will reduce the excursion. This, however, might increase the tension in the hawser.

9.2 Dynamic Analysis

Several iterations was done by increasing the line diameter until a sufficient solution was found. Results can be seen in the following tables.

Seabed footprint radius	r	203 m
Hawser length	l	40 m
Line diameter	d	240 mm
Characteristic breaking strength	T_{MBS}	12032 kN
Design breaking strength	$T_{MBS,d}$	11459 kN
Mooring line length	l	200 m
Line diameter	d	240 mm
Characteristic breaking strength	T_{MBS}	12032 kN
Design breaking strength	$T_{MBS,d}$	11459 kN

Table 9.3. Definition of dimensions for the first analysis.

Hawser			
Design breaking strength	$T_{MBS,d}$	11459 kN	$u_T = \frac{T_{MBS,d}}{T_{design}} = 1.2$
Design tension	T_{design}	9838 kN	
Mooring line			
Design breaking strength	$T_{MBS,d}$	11459 kN	$u_T = \frac{T_{MBS,d}}{T_{design}} = 1.6$
Design tension	T_{design}	7227 kN	
Design limit	x_{limit}	± 27.0 m	$u_x = \frac{x_{limit}}{x_{design}} = 0.7$
Design excursion	x_{design}	41 m	

Table 9.4. Results from dynamic analysis of quasi-static layout.

It is seen from the table that it was not possible to find a solution that fulfilled the motion design requirement, as these are very strict. In the present layout, the strength in all lines are heavily over dimensioned, but was increased in order to give stiffness to the system. The buoy was not varied in the analysis.

9.3 Discussion of Upcoming Analysis

The present analysis showed that it is not feasible to design a mooring system with the layout previously found in quasi-static analysis. The main problem arising is the large motions. It is, therefore, needed to investigate more layouts and variation in the layout parameters, and additionally take the cost of the system into consideration. This will, hopefully, allow for the identification of the most suitable and optimized solution. For a SPM system with taut synthetic lines several parameters for optimization can be considered:

- Mooring line diameter.
- Seabed Footprint
- Hawser diameter
- Buoy
- Number of lines

As seen, there is a total of five parameter to vary, but with a large number of combinations, the process can be time consuming and extensive. In further work, reports and papers, the optimizations of these parameters will be presented.

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