

Chapter 5

Inclusion of clump weights along catenary mooring lines of FWTs

5.1 Abstract

In this chapter, the focus is on the dynamics of a FWT with a catenary mooring system when clump weights are attached to the lines. A comparison of three hybrid mooring configurations of a spar-buoy FWT is studied, from both a numerical and an experimental point of view. The accuracy of the calibrated numerical model is demonstrated covering a range of aspects including motions and loads on the mooring lines.

A thorough evaluation of three different mooring systems of a FWT under dynamic only wave conditions is performed to understand the impact of the additional devices. The clump weight is proven to reduce first-order wave loads on the lines, which can improve the fatigue life of the mooring and the consequent positive impact in project.

Most of these new insights into the influence on the dynamic responses of FWTs when clump weights are attached to the catenary mooring lines, findings, descriptions, and conclusions have already been published in Lopez-Olocco et al. [90] and Lopez-Olocco et al. [91].

5.2 Case of study

5.2.1 Description of the FWT

In Chapter 1 the spar-buoy platform concept is pointed out as the other concept leading the offshore market, besides the semi-submersible concept. Therefore, in this chapter, the 5-megawatt reference spar FWT, OC3-Hywind [68, 69], is selected as the case study for this chapter. As illustrated in Fig. 5.1, a conventional catenary mooring system is applied to the spar FWT. The static draft of the FWT is 120 *m* and all the fairleads are 70 *m* below the still water level, the same as specified in the OC3 report [68]. The FWT is moored to the seabed

by three lines, where the projected angle between any neighboring mooring lines is 120° .

The studied water depth (235 m) of this FWT was selected considering the typical range of $200\text{--}300\text{ m}$ among commercial projects, e.g., Hywind Tampen [38]. This depth is different from the one specified in the OC3 report [68], pretending to have a more realistic mooring design. As a consequence, a proper redesign has been carried out.

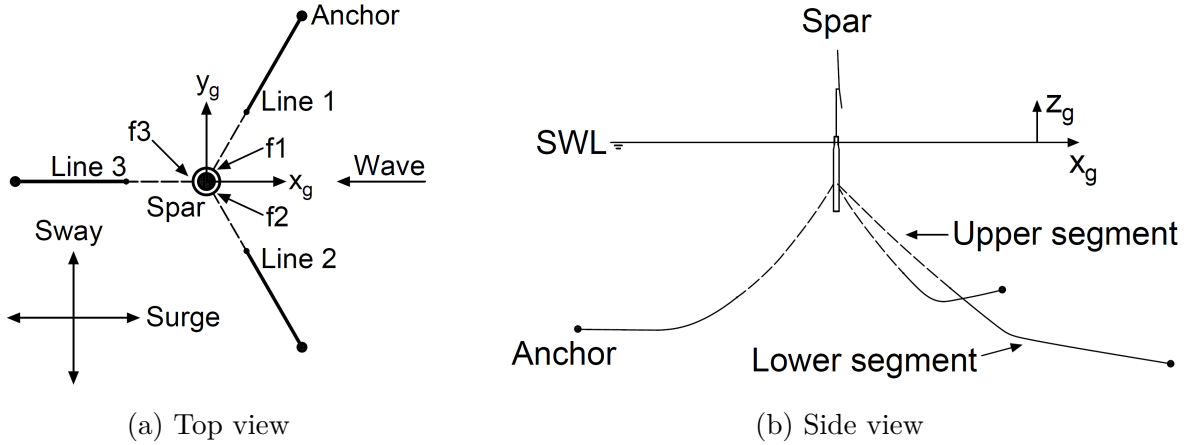


Figure 5.1: Top and side view of the mooring system configuration (dashed line: wire; solid line: chain). The symbols $f1$, $f2$, $f3$, $f4$ denote the fairlead connections.

5.2.2 Environmental conditions

Metocean conditions of the “Norway 5” offshore site [79] are considered for the mooring design and for defining the test matrix. The joint probability distribution of the mean wind speed (U_w), the significant wave height (H_s) and the spectral peak period (T_p) are used to calculate the conditional distributions from which the mean values of H_s and T_p are taken for the operational conditions. For extreme conditions, the 50-year environmental contour is generated based on the joint distribution. The sea state with the highest H_s on the contour line is selected. The environmental conditions are summarized in Table 5.1. Wind speed is included for the sake of completeness, but wind loads are not considered in this chapter.

Table 5.1: Environmental parameters for mooring system design.

Environmental variable	Operational	Extreme
U_w (hub-height) [m/s]	11.40	42.71
H_s [m]	2.57	15.50
T_p [s]	11.12	14.45

5.2.3 Mooring system design

The mooring lines of the spar FWT are redesigned for the selected water depth. A design process similar to the one presented in Liang et al. [83] is followed. A two-segment mooring design is considered in which the upper segment is made of sheathed steel wire rope and the lower segment is made of a R3 studless mooring chain. For simplicity, the delta connection to increase yaw stiffness ([128]) is not considered. The projected angle between any neighboring mooring lines is 120° .

Four design parameters are considered, including the total mooring line length, the length of the wire segment, and the diameters of the wire segment and the chain segment. The design space of the variables is presented in Table 5.2, and the orthogonal sampling method is applied. The design objective is to minimize the material costs in the production and manufacturing of mooring lines. First, static analyzes are performed in MIMOSA [34], a program for moored vessel analysis. Then dynamic analyzes are performed in SIMA [126, 127], a numerical simulation tool for marine operations and floating systems. Details of the objective function, design constraints, analysis procedures, and design check can be found in Liang et al. [83]. The sample of the design space that meets the design constraints with the lowest mooring cost is selected as the final design for the mooring lines of the spar FWT.

Table 5.2: Design variables and design space of the anchor lines

Design variable	Sampling range	Sampling interval
Total mooring line length L_{line} [m]	[660, 680]	5
Wire segment length L_{wire} [m]	[250, 350]	10
Wire segment diameter D_{wire} [mm]	[90, 130]	5
Chain segment length D_{chain} [mm]	[110, 150]	5

As shown in Fig. 5.1, the selected mooring properties are applied to the three mooring lines of the spar FWT. The material properties of the mooring lines are summarized in Table 5.3.

Table 5.3: Properties of the mooring lines adopted in the design.

Moorings property	Lower segment	Upper segment
Material	R3 studless chain	Sheathed steel wire rope
Length [m]	415	250
Diameter [mm]	140	95
Sheath thickness [mm]	-	10
Mass density [kg/m]	392.00	47.39
Submerged weight [N/m]	3535.94	360.42
Extensional stiffness [N]	1.53E+09	8.47E+08
Minimum breaking strength [N]	1.43E+07	9.34E+06

Based on this baseline mooring system, two additional mooring configurations are tested that incorporate the use of a clump weight of 40 kN in full scale. Following a methodology similar

to Chapter 4, the clump weight is placed at two different locations of suspended length, one close to the fairlead and another close to the seabed. Unlike previous works available in the literature (e.g., [13]), the pretensions are maintained to preserve the static draft of the FWT in 120 m:

1. **Config 1:** Close to the fairlead position, at 110 m (see the red dots in Fig. 5.2).
2. **Config 2:** Close to the touchpoint position, at 300 m (see the blue dots in Fig. 5.2).

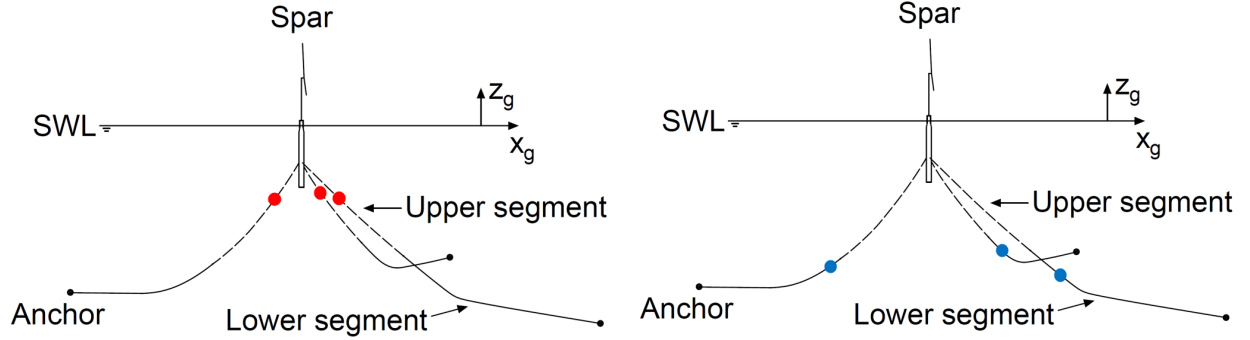


Figure 5.2: Side view of the designed mooring system configurations with clump weights (dashed line: wire; solid line: chain; red colored dot: clump weight Config. 1; blue colored dot: clump weight Config. 2).

5.3 Experimental tests

Model testing stands as a cost-effective and insightful method to predict the behavior of offshore prototypes, especially when building the full-scale version poses risks or is economically unfeasible. It allows for preliminary performance predictions, offers substantial cost savings compared to full-scale tests, and serves as a crucial powerful tool to calibrate numerical models.

In fluid mechanics problems, a correlation can be made from the measurements in model scale to equivalent values for a full-scale prototype if geometric, kinematic, and dynamic similarities are met. In any problem that involves waves and the free surface of a fluid, inertia and gravity forces are predominant [15, 72]. As a result, it is appropriate to preserve (in the model as in the full-sized prototype) the ratio of inertia and gravity forces (Eq. (5.1)). Therefore, the Froude scaling [72] is applied. The similarity laws for different variables used to properly model the equivalent full-sized prototype are listed in Table 5.4.

$$Fr = \sqrt{\frac{\text{inertia forces}}{\text{gravity forces}}} \quad (5.1)$$

Table 5.4: Froude scaling of variables

Variable	Scaling factor
Linear dimension	λ
Fluid or structure velocity	$\lambda^{1/2}$
Fluid or structure acceleration	1
Structure mass ¹	$\lambda^3 \cdot \gamma$
Structure displacement	λ
Time or period	$\lambda^{1/2}$
Force	λ^3
Moment	λ^4

¹ When scaling mass, to take into account the density difference between the sea water (SW, salt water) and the water in the ocean basin (FW, fresh water), the relation $\gamma = \frac{\rho_{sw}}{\rho_{fw}}$ is used.

5.3.1 Experimental set-up

The experimental campaign was carried out in the ocean basin in the *Canal de Ensayos Hidrodinámicos de el Pardo* (INTA-CEHIPAR). The dimensions of the tank are 150 *m* in length, 30 *m* in width, and 5 *m* in depth. The tank is equipped with a towing carriage, in which the data acquisition systems reside. As described in Section 5.2, the water depth of the site is 235 *m*. Therefore, considering the water depth of the tank, a scale ratio λ of 47 is selected. The target model scale properties after applying Froude scaling similarity laws are listed in Table 5.5.

The model was constructed with PVC plastic, and solid lead was used for the ballast. Because this test campaign was conducted under wave-only conditions, the rotor and nacelle were not physically modeled. Instead, an auxiliary aluminum frame was placed on top of the towers (see Fig. 5.3). Equivalent distributed weights were placed on top of the aluminum frames to adjust the inertia of the upper structure. The model FWT and the different components used in its construction are shown in Appendix A in Lopez-Olocco et al. [90]. To avoid water leakage during the experiments, several seals were applied and checked before placing the model in the testing position. Furthermore, during the entire experimental campaign, the model was constantly inspected for water intake to avoid changes in displacement and trim angle.

The model resulted in constructive errors below 5%. A comparison with target values can be found in Table 5.5. The model mass was set to obtain the exact scaled draft. Errors in lengths are normalized with respect to $\sqrt[3]{\nabla}$, with ∇ being the target displacement volume.

Because the mooring lines are too lightweight, submersible load cells could affect the mooring angle due to their elevated weight. Therefore, the lines are sent to the aluminum structure shown in Fig. 5.3 above the water surface, where they were connected to the measurement devices. Pulleys were installed at the fairlead positions for that purpose. A submerged view

Table 5.5: Target and measured mass properties at model scale.

Mass property	Target value	Measured value	Units	Error
Mass	77.403	77.721	<i>kg</i>	0.41 %
Height of COG above keel	0.894	0.891	<i>m</i>	0.67 %
Radius of inertia about x -axis*	1.03	1.04	<i>m</i>	2.94 %
Radius of inertia about y -axis*	1.03	1.04	<i>m</i>	2.95 %
Radius of inertia about z -axis*	0.10	0.94	<i>m</i>	2.02 %

* Measured with reference to center of gravity (*COG*).

of the fairlead connection and the pulleys used is found in Fig. 5.4a. This modification forced us to consider full pretensions instead of just the vertical component in the design process to adjust the mass properties of the model.

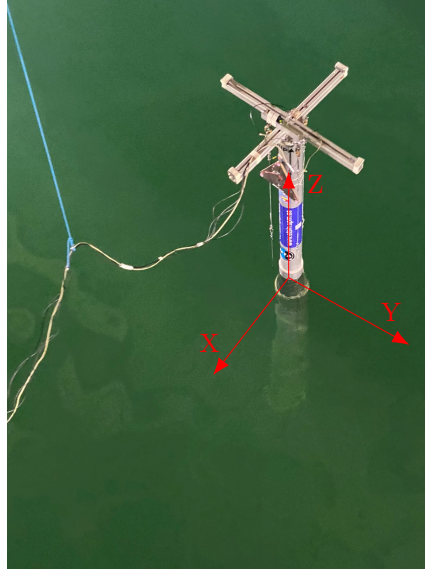


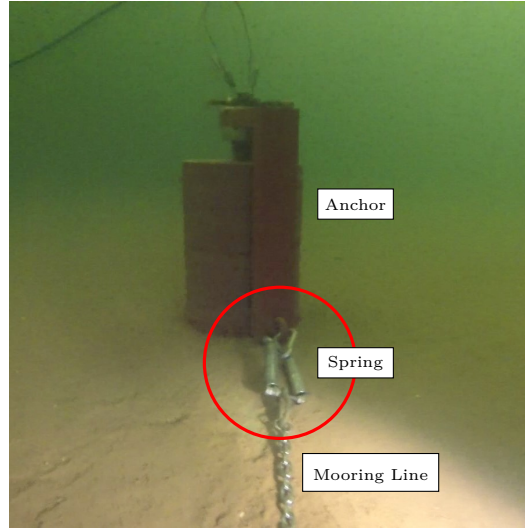
Figure 5.3: Top view of the model with the aluminum structure, including the instrumentation cables.

Special care was taken to reproduce the properties when scaling the mooring lines. The exact length was ensured and the weight per unit length of the available mooring material was chosen to be close to the full-scale ones (see Table 5.3). The connection parts were selected to take this into account and increase the equivalent weight per unit length when needed. The properties of the model scale line are listed in Table 5.6.

When high dynamic conditions are present, stiffness dominates over inertia and overprediction of forces in the model test may be encountered in these situations [4]. The number of snap events may be overpredicted if the mooring material stiffness is not adequately scaled. However, in general, the behavior of mooring lines is captured by incorporating springs into the lines. In order to have line tensions that approximately scale as the other forces involved



(a) Fairlead connection.



(b) Connection between the mooring line and the anchor.

Figure 5.4: Mooring line connections.

in the system, a set of springs was placed at the anchor to properly model the stiffness of the line material. This connection is encircled in red in Fig. 5.4b.

To select the spring, an equivalent linear stiffness of the full-scale mooring line is computed. Since the stiffness of the line should scale with λ^3 when the Froude scaling laws are applied, the linear spring stiffness, K , was selected according to Eq. (5.2)

$$K = \frac{EA}{L}, \quad (5.2)$$

where EA is the axial stiffness of the line and L is the unstretched length of the line at model scale. Results are shown in Table 5.6.

The model is placed 30 *m* away from the wave generator; see Fig. 5.5. In this test set-up, the anchors were placed at the exact scaled positions. Additionally, a diver ensured the correct

Table 5.6: Physical properties of the scaled mooring lines

Component	L [m]	w [Kg/m]	K [N/m]
Chain	8.83	0.160	800
Steel wire	5.32	0.020	

laying of the line at the bottom to prevent the chain from crooking due to the manipulation of the chain during the installation, and conducted minor adjustments to set the pretensions prior to the tests. Table 5.7 shows a comparison between the measured and the target pretensions at the fairlead.

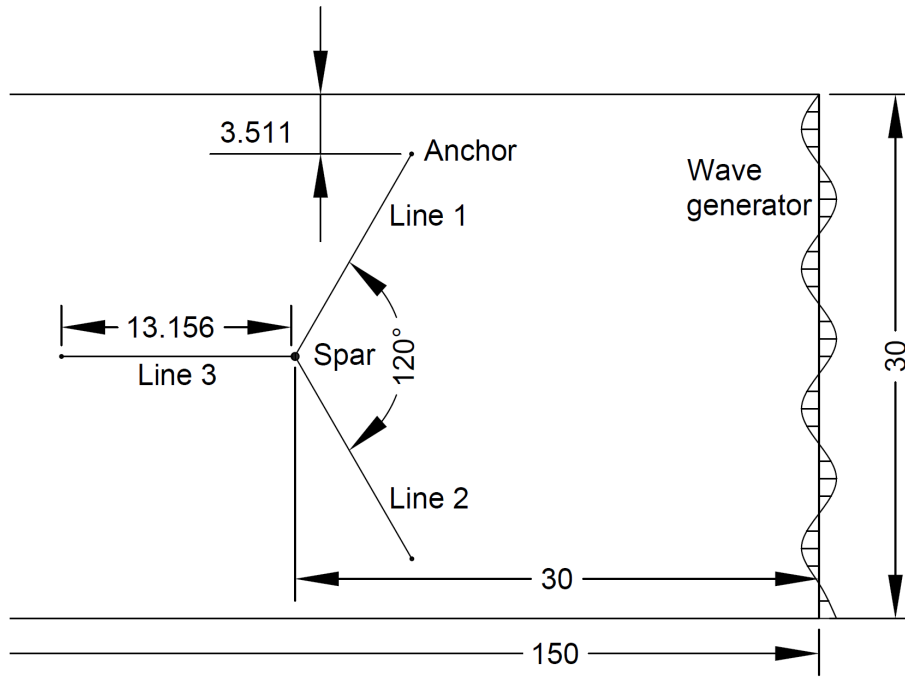


Figure 5.5: Experimental layout of the spar FWT. Dimensions at model scale [m]

5.3.2 Test matrix

In total, 14 tests were carried out for each configuration in this experimental campaign, consisting of six decay tests, two irregular wave cases, one white noise case, and five regular wave cases. For the wave cases, the amplitudes and periods described in Section 5.2.2 were scaled down according to the Froude scaling laws.

Due to the mechanical limitations of the wave generator with the selected scale ratio, the environmental conditions for irregular wave cases described in Section 5.2.2 were modified and listed in Table 5.8a, where the white noise case is also listed. The set of regular wave cases, listed in Table 5.8b covers both operational and extreme conditions.

Table 5.7: Target and measured pretensions for both configurations.

	Pretension	T_{f1}	T_{f2}	T_{f3}	Units
Baseline	Target	6.91	6.91	6.91	N
	Measured	6.24	6.39	5.99	N
Config. 1	Target	6.91	6.91	6.91	N
	Measured	6.18	5.58	5.75	N
Config. 2	Target	6.91	6.91	6.91	N
	Measured	6.16	6.31	5.90	N

Table 5.8: Summary of test cases with irregular and regular waves.

(a) Irregular wave			(b) Regular wave		
	H_s [m]	T_p [s]		H [m]	T [s]
Operational (IRR01)	2.57	11.12	REG01	2.5	5.48
Extreme (IRR02)	12.70	15.45	REG02	2.5	9.60
White noise (WN)	2.00	5-20	REG03	2.5	10.97
			REG04	5.0	8.0
			REG05	10.0	16.0

5.3.3 Instrumentation

All measuring instruments were calibrated prior to testing to ensure the quality and reliability of the data acquisition system. Measurements were recorded with a sampling rate of 100 Hz , which was sufficient considering typical frequencies of the phenomena involved (maximum 1.2 Hz). Fig. 5.6 shows the sensor positions during the experiments.

The 6 degrees of freedom (DOFs) rigid body motions of the model were measured using an optical tracking system, KRYPTON. The system is a camera-based dynamic position measurement of the location of one or more infrared LEDs. The frame equipped with the LEDs was attached to the model on top of the aluminum structure. In Figs. 5.7a–5.7b, the frame and the cameras that point to the model are encircled in red. The measured motions must be further post-processed to obtain the motions of the model’s COG.

The fairlead tensions of the lines were measured with three load cells. Three one-component load cells HBM with a SGfull bridge were used. The measured range of the load cell is 0 to 200 N and the precision is ± 0.081 N based on the residual values of its calibration. The load cell was covered with an insulating material to reduce the drift caused by the environment during the experiments. A detailed view of the sensor can be seen in Fig. 5.8a. A load cell, a turnbuckle for fine adjustment of the target pretension, and a steel wire connected to the catenary line are used. The arrangement can be seen in Fig. 5.8b.

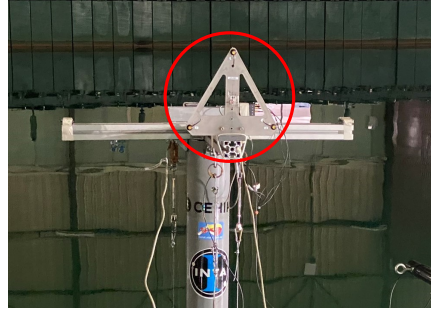
Incoming waves were measured with an ultrasonic wave sensor located in the carriage. The precision of the measuring device is ± 2.027 mm on average. This sensor is shown in Fig. 5.9.



Figure 5.6: The spar model in testing position with the instrumentation circled in red.



(a) Optical tracking camera.



(b) Lead frame.

Figure 5.7: Detailed view of the instruments used for motion measurement during the tests.

5.3.4 Methodology

5.3.4.1 Decay tests

To estimate the natural periods of the spar platform with the mooring system designed, decay tests were performed in the 6 DOFs. The model was manually displaced from equilibrium and then released. The initial and last transient cycles are discarded for each test. Then, the remaining half-cycles are analyzed. In the following, the subscript i refers to the i th-half cycle, starting at time t_i in a local extreme (see Fig. 5.10).

Decay experiments are analyzed by assuming that the measured data of each half cycle can be approximated to the theoretical solution of a damped linear single-DOF system [39]. For example, Eq. (5.3) represents the motion of the uncoupled heave DOF in free vibration.



(a) Detailed view of one of the load cells with the turnbuckle.



(b) Detailed view of the line arrangement.

Figure 5.8: Detailed view of the load used during the tests and the line arrangement.



Figure 5.9: Detailed view of the ultrasonic wave probe.

$$\ddot{z} + 2\mu_{eq,i}\dot{z} + \omega_{3,eq,i}^2 z = 0 \quad (5.3)$$

where z is the displacement in heave DoF (z -axis) and $\mu_{eq,i}$, is the equivalent linear damping coefficient expressed as

$$\mu_{eq,i} = \frac{B_{33,i}}{2 \cdot (M + A_{33,i})} \quad (5.4)$$

and $\omega_{3,eq,i}$ is the equivalent undamped circular natural frequency expressed as

$$\omega_{3,eq,i} = \sqrt{\frac{C_{33}}{M + A_{33,i}}} \quad (5.5)$$

where M , C_{33} , B_{33} , $A_{33,i}$ are the mass, stiffness, linear damping, and added mass in heave,

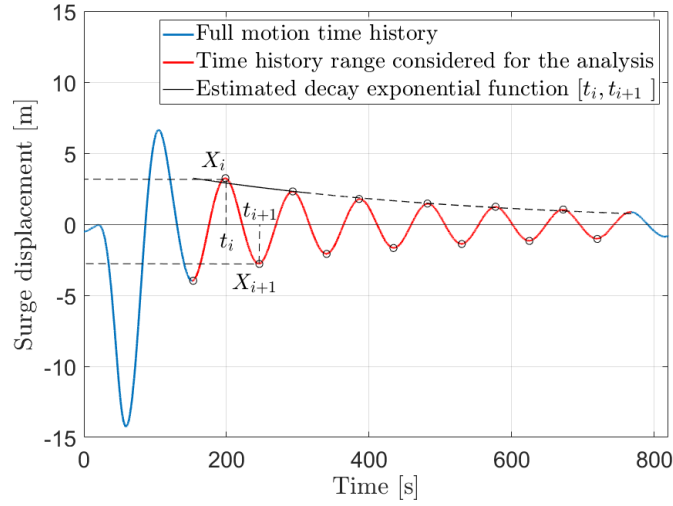


Figure 5.10: Exemplified analysis of a decay time series.

respectively. Assuming that the system is lightly damped, the solution of the motion model of Eq. (5.3) can be approximated by the following analytical solution:

$$z(\tau) = e^{-\mu_{eq,i} \cdot \tau} Z_i \cos(\omega_{3,d,i} \cdot \tau), \quad (5.6)$$

with $\tau = t - t_i$ and $\omega_{3,d,i}$ is the damped circular natural frequency expressed as

$$\omega_{3,d,i} = \sqrt{\omega_{3,eq,i}^2 - \mu_{eq,i}^2} \quad (5.7)$$

This can be determined approximately from the time between consecutive peaks:

$$\omega_{3,d,i} = \frac{\pi}{t_{i+1} - t_i} \quad (5.8)$$

By taking the logarithms of the equation (5.6) for two consecutive peaks in the time interval $[t_i, t_{i+1}]$, the characteristic parameter $\mu_{eq,i}$ is given by:

$$\mu_{eq,i} = \frac{1}{t_{i+1} - t_i} \log \left(\frac{|Z_i|}{|Z_{i+1}|} \right) \quad (5.9)$$

Both are assumed to vary slowly across the decay cycles. Therefore, the mean values of all the analyzed half cycles can be selected as representative values [99].

Finally, the nondimensional damping ratio, ξ , is defined as a fraction of the critical damping, B_{33}^{crit} , as follows.

$$\xi = \frac{\mu_{eq}}{\omega_{3,eq}} = \frac{B_{eq,33}}{B_{33}^{crit}} \quad (5.10)$$

Three repetitions for each decay test were performed, and different amplitude magnitudes and heading directions were applied to minimize the error in the measurements.

5.3.4.2 Wave tests

Fig. 5.11 shows a snapshot of the model FWT during the experiments; refer to Fig. 5.5 for the layout. The 0° wave heading is pointed in the figure with the light blue arrow. As only one wave heading is considered, the platform motion analysis is focused on surge, heave, and pitch.

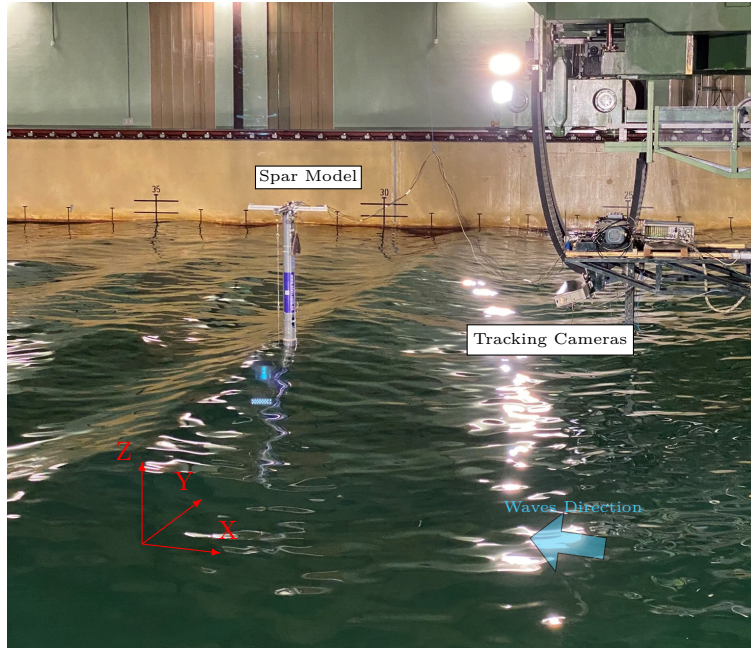
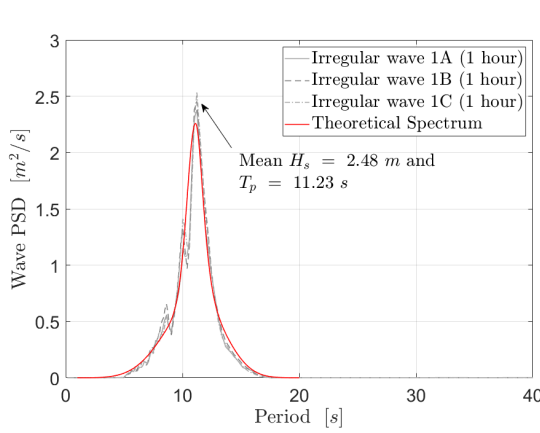


Figure 5.11: Illustration of the model FWT during seakeeping tests.

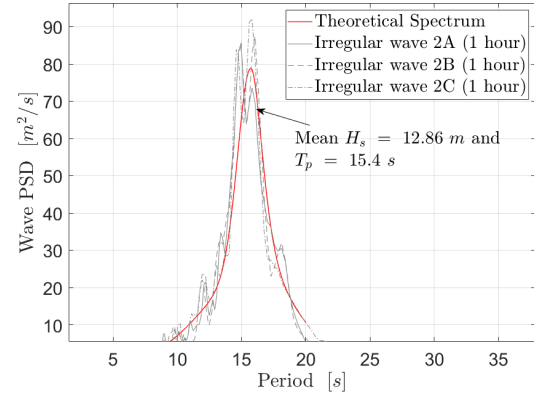
5.3.4.2.1 Wave calibration All wave cases described in Section 5.3.2 were tested for all mooring configurations following the recommendations of the International Towing Tank Conference (ITTC) [60, 61]. A calibration of the waves without the presence of the model was performed to ensure comparable wave loads between the two configurations.

According to ITTC [62], for irregular wave tests, a duration of 20-30 minutes at full scale is generally sufficient to collect statistically representative samples under wave-frequency responses. In this study, to obtain better response statistics with reduced statistical uncertainty [31], a duration of 1 hour with three realizations is considered for each irregular sea state.

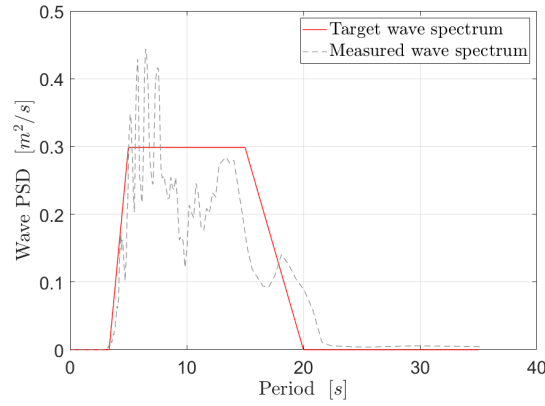
A comparison of the wave power spectrum density (PSD) between the theoretical and experimental results of the two irregular cases, with 3 seeds each, is presented in Figs. 5.12a–5.12b. The calibration of the significant wave height (H_s) and the significant wave period (T_p) of the spectra is within acceptable errors (lower than 5%).



(a) Calibration of wave spectra; wave case IRR01.



(b) Calibration of wave spectra; wave case IRR02.



(c) Calibration of wave spectra; white noise case.

Figure 5.12: Calibration of the wave power spectra.

A white noise spectrum was also calibrated. This case was characterized by a target significant wave height H_s of 2 m and a frequency bandwidth between 0.05 and 0.20 Hz on full scale. Fig. 5.12c shows a comparison of the wave spectra between the theoretical and experimental results.

The same quality criteria were adopted for the regular wave calibration, achieving an error of less than 5% for the wave height and period.

5.3.4.2.2 Response amplitude operators (RAOs) In a linear hydrodynamic model, the response of the model (in motions and tensions) to regular waves is expected to be periodic with the same frequency as the incident wave ω . The forcing input η of a regular wave with amplitude η_0 is expressed as follows:

$$\eta = \eta_0 \cos(\omega t) \quad (5.11)$$

Then, the response output X of a linear system is characterized by the response amplitude

X_0 and the phase ϵ_X as follows:

$$X = X_0 \cos(\omega t + \epsilon_X) \quad (5.12)$$

Both the amplitude of the wave and the amplitude of the response are obtained with the first Fourier harmonic of the corresponding time series. The magnitude of the first-order RAO for a given frequency is calculated according to Eq. (5.13).

$$RAO_X(\omega) = \left| \frac{X_0}{\eta_0} \right| \quad (5.13)$$

The period and height of the calibrated regular waves tested have previously been shown in Table 5.8b. Between 10 and 20 cycles are used to determine the transfer function, following the ITTC recommendations [63].

Alternatively, signals of the calibrated white noise case are utilized to perform a frequency domain analysis of the model responses. Then, the RAO magnitudes can be determined according to Eq. (5.14) [15]. Here, S_{xy} is the cross-spectrum between wave and response function and S_{xx} is the auto-spectrum of the wave.

$$RAO_X = \frac{S_{xy}}{S_{xx}} \quad (5.14)$$

Units of the RAOs are m/m for translational motions, deg/m for rotational motions, kN/m for tensions and forces, and $kN \cdot m/m$ for moments.

5.4 Numerical model calibration

In the numerical model, the spar FWT with the mooring system is modeled in OpenFAST [110] using the physical properties described in Section 5.3.1. A similar methodology of previous works in the literature, e.g. Stewart et al. [130], Browning et al. [9], Cao et al. [12], is adopted to calibrate the numerical model.

The hydrodynamic performance of the platform is simulated by combining the potential flow theory with Morison's equation within the HydroDyn module [70]. First, the hydrodynamic coefficients are calculated in the frequency domain. Subsequently, these coefficients are implemented in the time domain using convolution techniques. For assessing the viscous drag force, drag coefficients are chosen based on Reynolds (Re) and Keulegan-Carpenter (KC) numbers. Fine-tuning of the numerical damping model, based on slender Morison elements, is achieved through iterative adjustments.

The mooring system is modeled with MoorDyn [49] and the unstretched line lengths are slightly adjusted to match the measured pretensions in the experiments in full-scale (see Table 5.9). The inclusion of the clump weight is modeled following the same methodology as in

Section 4.3.2. A previous convergence analysis is performed to determine the right number of elements per line to be used; refer to Fig. 5.13. Table 5.9 shows the comparison, where an error of less than 0.5% is observed in all fairlead connections for all the configurations tested.

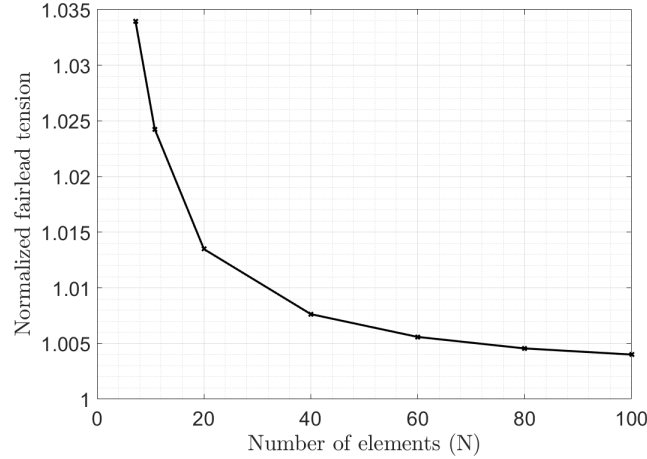


Figure 5.13: Numerical convergence analysis with MoorDyn of equilibrium fairlead pretensions.

Table 5.9: Experimental-numerical comparison of pretension, after line length tuning.

Mooring configuration		T_{f1} [kN]	T_{f2} [kN]	T_{f3} [kN]
Baseline	Model tests	647.85	663.43	621.90
	Numerical model	649.43	664.64	624.16
Config. 1	Model tests	641.63	579.33	596.98
	Numerical model	644.08	576.52	595.18
Config. 2	Model tests	639.55	655.12	612.55
	Numerical model	641.05	657.30	615.05

For all DOFs, numerical decay tests are performed to calibrate the numerical model. This fine-tuning is conducted to tune the linear damping coefficients of the numerical model with regard to the corresponding estimated damping ratios of the experiments. The results of this calibration is shown in Section 5.5.1. After calibration, the relative difference of the damping ratio in all the DOFs of the tuned numerical model is less than 5%, which indicates a good agreement with that of the physical model.

Due to lack of available time in the tank, additional static offset tests to estimate the stiffnesses in the horizontal plane were not carried out. Therefore, force-displacement relationships were not determined and compared. Ideally, these test can enhance the performance of the numerical tool MoorDyn by allowing a fine tuning of the characteristics of the mooring line. This has been left for future work.

5.5 Results

Results are presented in this section focusing on a comparison between the numerical and experimental model FWT. Also, the three configurations are compared to understand the effect of adding clump weights on catenary mooring systems for FWTS.

The estimated natural frequencies and damping ratios of the three configurations are presented in Section 5.5.1. RAOs are presented in Section 5.5.2. Finally, motions and mooring tension analysis for the irregular waves is conducted in Section 5.5.3. In this section, the PSDs and statistical values of motions and tensions are averaged across the three realizations. As only one wave heading is considered (see 5.3.4.2), the platform motion analysis focuses on surge, heave, and pitch DOFs.

5.5.1 Natural frequencies and damping estimation

Following the procedure detailed in Section 5.3.4.1, the natural periods and damping ratios are estimated. The results of the fine-tuning carried out to match the linear damping coefficients of the numerical model with regard to the corresponding estimated damping ratios of the experiments are shown in Table 5.10.

Table 5.10: Estimation of the critical damping ratio ξ (Eq. 5.10) for the experiments and the numerics [%].

Mooring configuration		Surge [%]	Heave [%]	Pitch [%]
Baseline	Model tests	3.87	1.77	1.07
	Numerical model	3.99	1.62	1.10
Config. 1	Model tests	4.90	1.92	1.35
	Numerical model	4.75	1.53	1.13
Config. 2	Model tests	4.42	1.75	1.09
	Numerical model	4.63	1.48	1.12

Fig. 5.14 presents an example of a time series of platform motions for both the experimental decay test and the numerical decay test of the tuned numerical model. Natural periods are estimated from the model tests and compared with those estimated from the numerical decay tests. The comparison is presented in Table 5.11. Overall, a good match of the natural periods obtained from the numerical and experimental methods is found in all the mooring configurations.

The pretensions are maintained in all tested mooring configurations with the addition of the clump weight, therefore, when compared, the geometric stiffness of the lines is different as discussed in Section 4.4.1. The both mooring systems with clump weights are softer than the Baseline configuration, therefore, with a larger natural period in surge. However, the added clump weight closer to the seabed seems to have less influence, with only a 3% difference in the surge natural period.

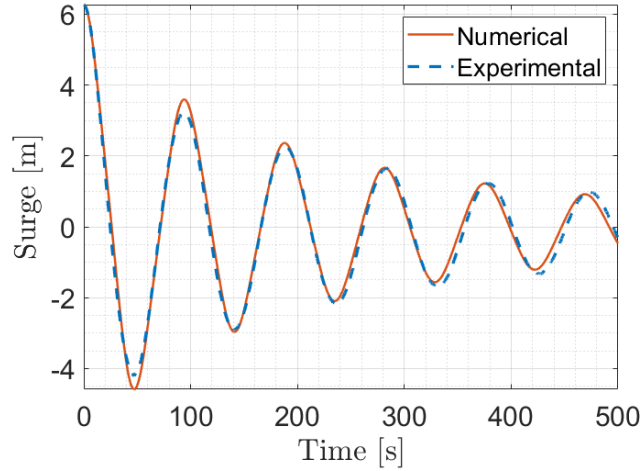


Figure 5.14: Surge platform motions in the experimental and numerical decay tests for the Baseline configuration.

Table 5.11: Natural period estimation for the experiments and the numerics [s].

Mooring configuration		Surge [s]	Heave [s]	Pitch [s]
Baseline	Model tests	89.80	29.80	31.69
	Numerical model	89.90	29.68	32.14
Config. 1	Model tests	97.74	30.07	31.92
	Numerical model	97.35	30.20	31.50
Config. 2	Model tests	92.38	29.52	31.61
	Numerical model	92.44	30.04	31.56

Heave and pitch DOFs do not appear to be influenced by the clump weight because they are barely affected by the catenary mooring.

5.5.2 First-order RAOs from the regular wave and white noise cases

The estimated motion RAOs for the Baseline mooring configuration are shown in Fig. 5.15. A comparison is presented between the white noise and the representative results of the regular waves. Generally, a good match between the two tests is achieved. This is an indication of the system's linear behavior in this frequency range as energy is not transferred between different frequencies in the white noise tests. When the results are compared between the experiments and the numerics, we observe that the differences between them are not substantial in the first-order frequency range.

When the tested configurations are compared, it is observed that the change in geometric stiffness due to the clump weight changes the surge response in the natural frequency, while it does not seem to influence the first-order wave frequency range (see Fig. 5.16a). This

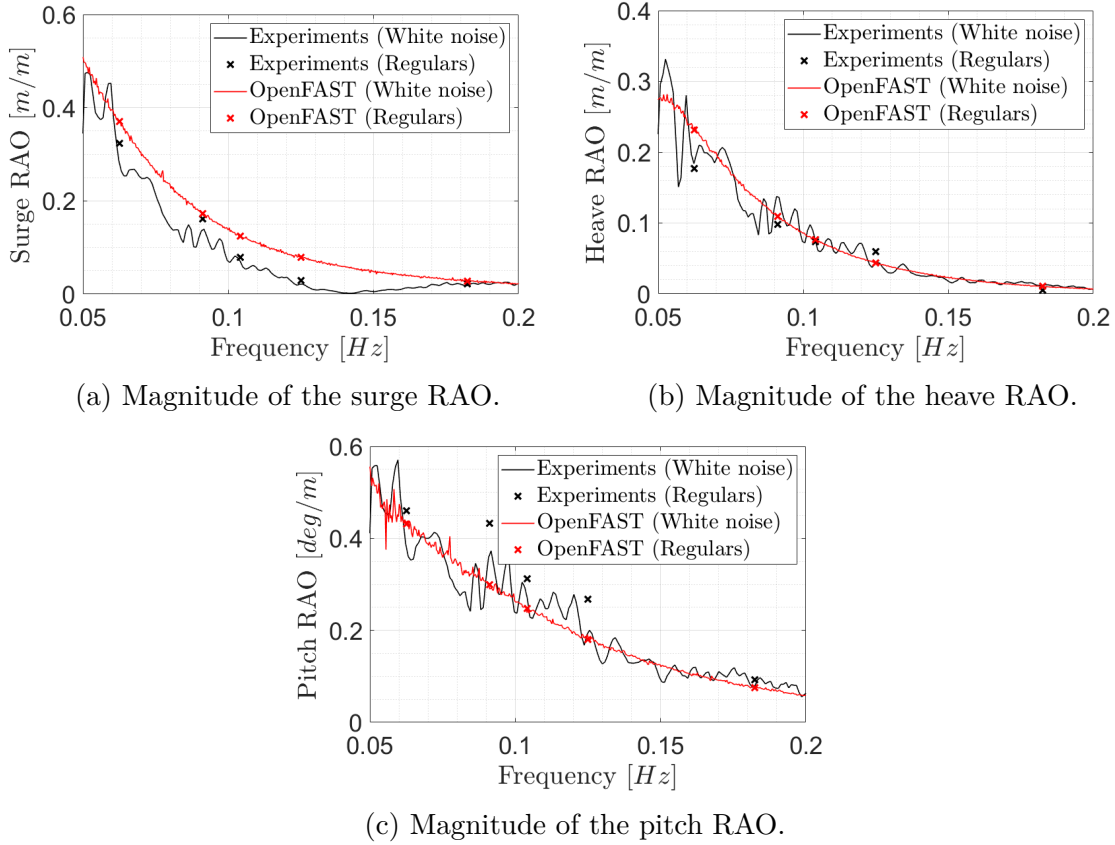


Figure 5.15: Numerical-experimental RAOs magnitudes comparison for the baseline configuration.

can indicate that the system is inertia dominated and therefore the motion dynamics in this frequency range are not affected by the mooring. Heave and pitch do not show a significant change in the motion response as expected (see Figs. 5.16b and 5.16c), only a different magnitude is observed in the natural frequency due to the different damping ratios between configurations. The estimated natural periods of all mooring configurations are observed in all DOFs numerical RAOs.

5.5.3 Response analysis for the irregular wave cases

As discussed in Section 5.3.2, an operational and an extreme sea state have been tested. For FWTS in normal operation, aerodynamic loads have a significant impact on the motion and structural responses, in addition to hydrodynamic loads. As wind loads were not considered during the tests, the studied load cases are representative of scenarios where the spar FWT is parked due to maintenance or faults [67]. In such scenarios, FWTS are usually parked with feathered blades, and wave loads are dominant. The experimental results of the operational condition for the Baseline configuration can be checked in Appendix B and C in Lopez-Olocco et al. [90].

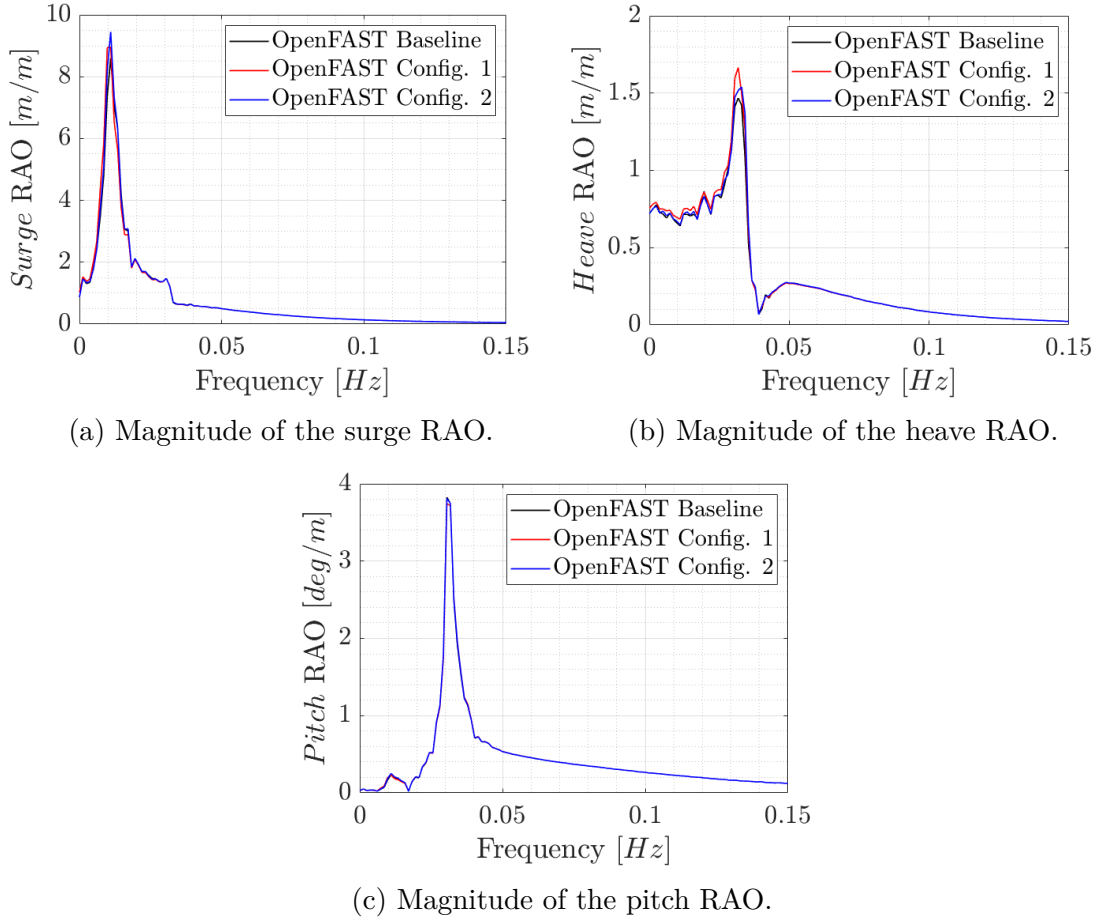


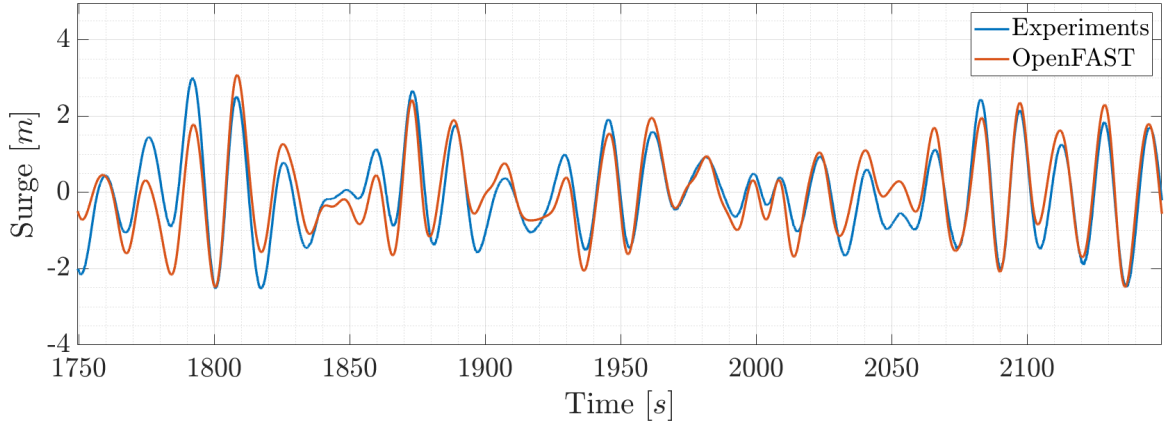
Figure 5.16: Numerical comparison of the magnitude of the surge, heave and pitch RAOs for all the mooring configurations.

5.5.3.1 Motion responses

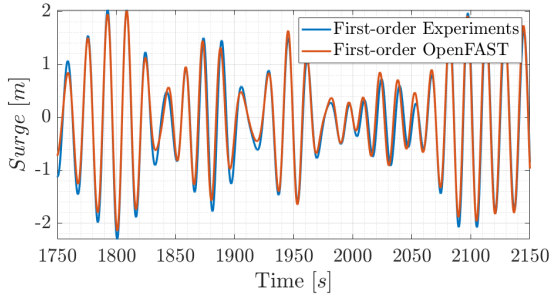
Since the focus of this chapter is on the tested catenary mooring systems, and decay tests have shown that heave and pitch are barely affected by the addition of the clump weight, an example of a comparison of the surge motion time series is shown in Fig. 5.17a. In addition, first-order and second-order wave components are filtered, extracted, and compared. Both components are shown in Fig. 5.17b and Fig. 5.17c, respectively.

A good match between the model tests and the numerical model is achieved in the extreme irregular wave case, indicating that drag coefficients are well selected for the Reynolds and KC numbers of this particular case. First- and second-order wave components are well captured in amplitude, while a phase shift of 90° is observed in the low-frequency response. This can be expected since second-order wave forces have not been modeled for this platform.

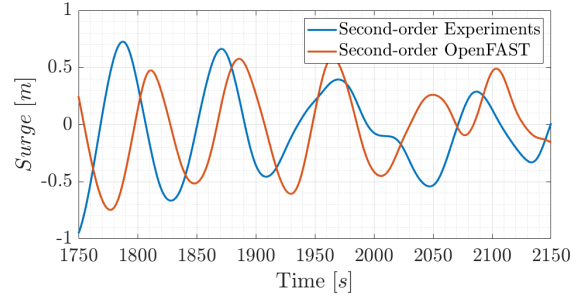
5.5.3.1.1 Spectral analysis As shown in Fig. 5.18, first-order wave frequency response is almost maintained across mooring configurations. This was expected because of the system's



(a) Surge motion time series.



(b) First-order wave component.



(c) Second-order wave component.

Figure 5.17: Numerical-experimental comparison of surge motion for the Baseline mooring configuration in the extreme wave condition, wave seed IRR02B.

linear behavior in this frequency range observed in the comparison of first-order RAOs. In the low-frequency range, the addition of the clump weight appears to increase the response in the natural frequency.

Heave and pitch motion responses do not show considerable differences in all frequency ranges between configurations. As explained above, these DOFs are mainly influenced by the mass properties and primary hydrodynamic forces, and mooring stiffness is less influential.

When the comparison between numerics and the experiments is made, small differences are found, but they are not considerable, the peaks are aligned, and the trend is well captured. The estimated natural periods are observed in all the PSDs.

5.5.3.1.2 Statistics Four statistical values of surge, heave and pitch are presented in Table 5.12 to ease a quantitative comparison between numerics and experiments. Compared to the model tests, the numerical model general trend is to overpredict the maxima and minima statistical values of motion.

It is interesting to notice that comparable mean dynamic offset are observed across configurations. The larger mean offset is observed in Config. 1, with a 56% increase compared to the

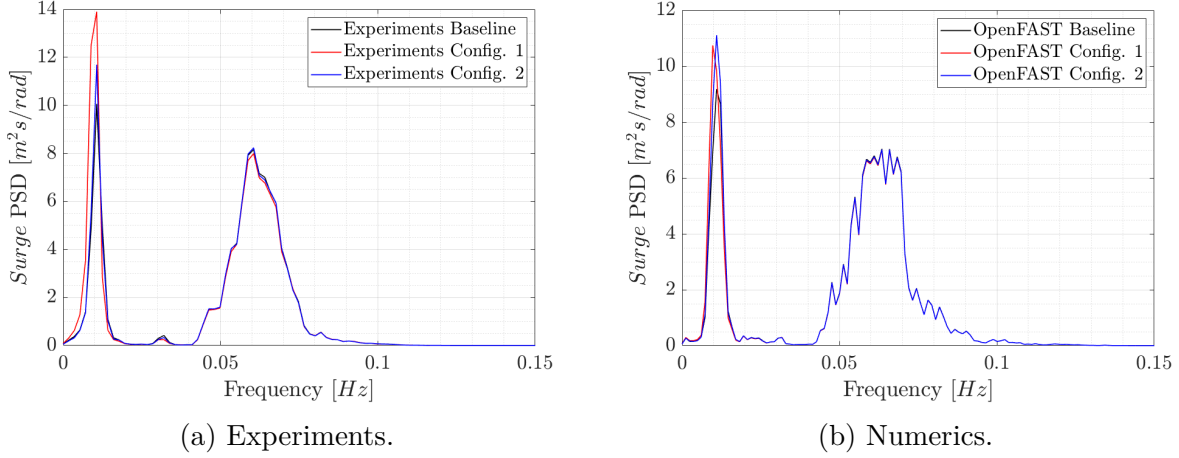


Figure 5.18: Numerical and experimental PSDs of surge motion for all the tested configurations.

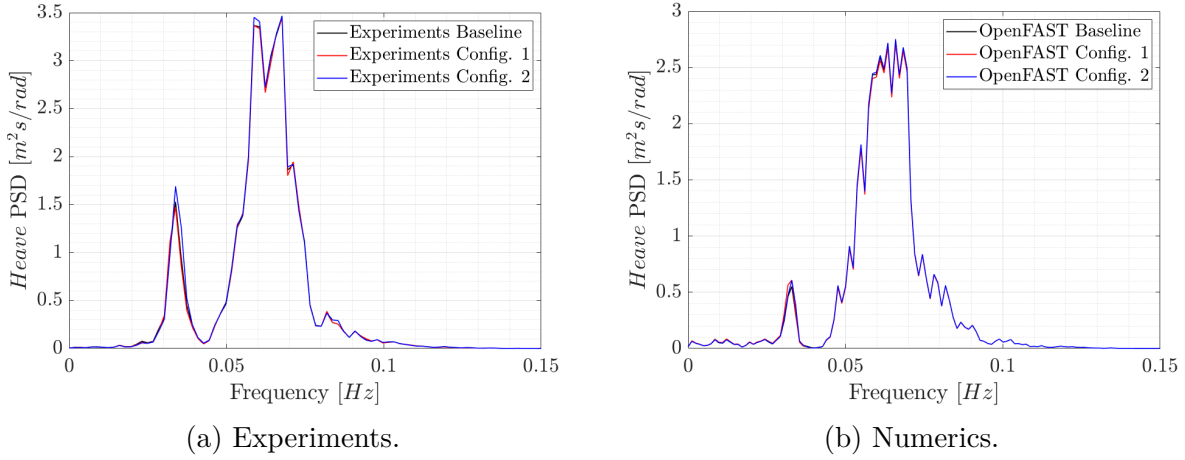


Figure 5.19: Numerical and experimental PSDs of heave motion for all the tested configurations.

Baseline configuration. This is in line with the stiffness reduction in surge with the addition of the clump weight evidenced in previous sections.

Compared to the model tests, this mean dynamic offset is not well captured in the numerical model. This indicates the need of second-order forces modeling to reproduce this mean drift. However, this is not that important in a spar-buoy FWT, since it is well known that they do not show large second-order effects [39].

5.5.3.2 Tension responses

Since the mooring line co-linear with the wave direction is of particular interest in extreme events, a comparison of the fairlead tension T_{f3} time series is shown in Fig. 5.21a. In addition, first-order and second-order wave components are filtered, extracted, and compared. Both

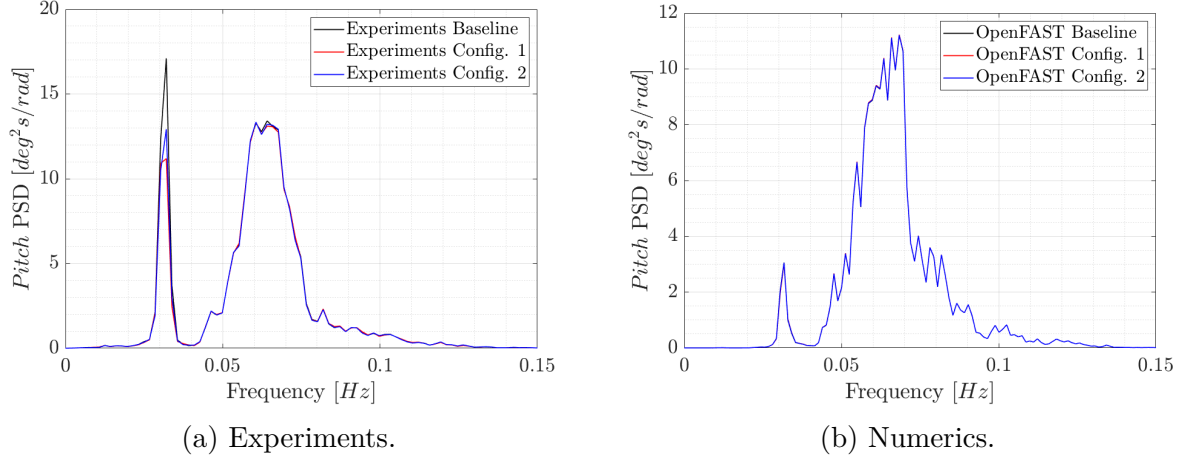


Figure 5.20: Numerical and experimental PSDs of pitch motion for all the tested configurations.

Table 5.12: Motion statistics

		Baseline		Config. 1		Config. 2	
		Exp.	Num.	Exp.	Num.	Exp.	Num.
Surge [m]	max	3.21	3.70	3.63	3.76	3.181	3.69
	min	-4.34	-4.70	-4.61	-4.79	-4.28	-4.77
	mean	-0.16	-0.030	-0.25	-0.04	-0.13	-0.031
	std	1.08	1.125	1.13	1.13	1.09	1.14
Heave [m]	max	2.19	1.80	2.20	1.76	2.22	1.83
	min	-2.28	-2.22	-2.34	-2.24	-2.30	-2.22
	mean	0.039	0.055	0.0083	0.0074	0.023	-0.05
	std	0.67	0.61	0.68	0.60	0.68	0.61
Pitch [deg]	max	4.78	4.71	4.83	4.72	4.80	4.72
	min	-5.46	-4.23	-5.42	-4.22	-5.46	-4.23
	mean	-0.039	-0.068	-0.018	-0.067	-0.029	-0.068
	std	1.53	1.25	1.49	1.25	1.49	1.25

components are shown in Fig. 5.21b and Fig. 5.21c, respectively.

The numerical model was calibrated to match the model test results in the extreme irregular wave case. First-order wave components are not fully captured in amplitude, and a small phase shift is observed. On the contrary, the second-order wave components appear to be reasonably well captured in amplitude, but a phase shift of 180° in the low-frequency response is observed. This can be partially attributed and explained through the following arguments.

1. The energy dissipation due to the friction of the pulley and the line in the fairlead connection (see 5.2). Although it is not large, the numerical model is unable to capture this effect.
2. Different material stiffness between models. In the physical model a spring is selected to reproduce the objective material stiffness of the line in full-scale (see 5.2). In the

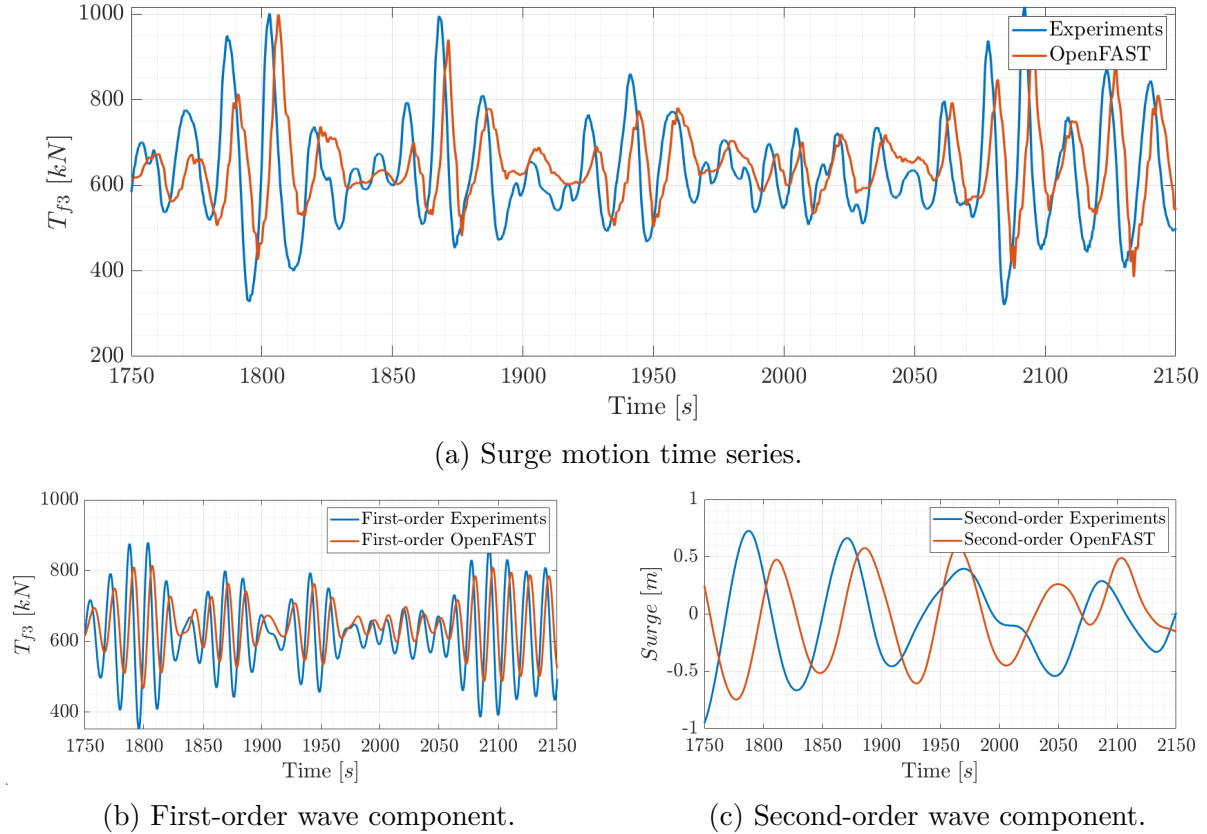


Figure 5.21: Numerical-experimental comparison of the fairlead tension T_{f3} for the Baseline mooring configuration in the extreme wave condition, wave seed IRR02B.

numerical model the objective material stiffness of the line in full-scale is selected. Possibly differences are found because the spring approach may not have been sufficient, plus more fine-tuning on the material stiffness of the line is needed in the numerical model. The future static offsets test might help in this matter.

3. Line-seabed and spring-seabed friction in the physical model that is not correctly modeled in the numerics.

5.5.3.2.1 Spectral analysis For both models, the fairlead tension T_{f1} and T_{f3} (see Fig. 5.1) are selected to be focused on in the analysis; the discussion for T_{f2} is not included due to symmetry. PSDs of fairlead tensions are shown in Figs. 5.22 and 5.23.

T_{f1} shows a larger amount of energy than T_{f3} in the low-frequency range, but in general, tensions are dominated by first-order waves. In both cases, the estimated natural periods of surge and pitch resulting from coupling are demonstrated.

From Fig. 5.22 it is observed that the addition of the clump weight significantly reduces the response in the first-order wave frequency range, while do not change considerably in the natural frequency. This effect seems to be more predominant in Config. 1, when the clump

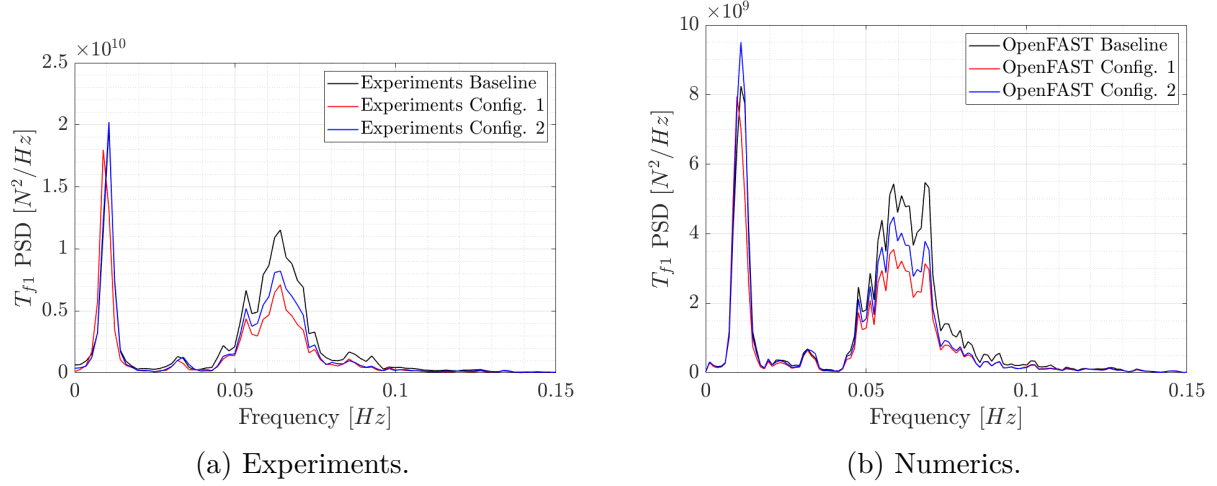


Figure 5.22: Numerical and experimental PSDs of T_{f1} fairlead tension for all the tested configurations.

weight is closer to the fairlead point.

When a comparison between numerics and experiments is made, differences in magnitude are found. The possible reasons for this have already been explained in Section 5.4. However, the peaks are aligned, the trend is well captured, and the estimated natural periods are observed in the PSDs.

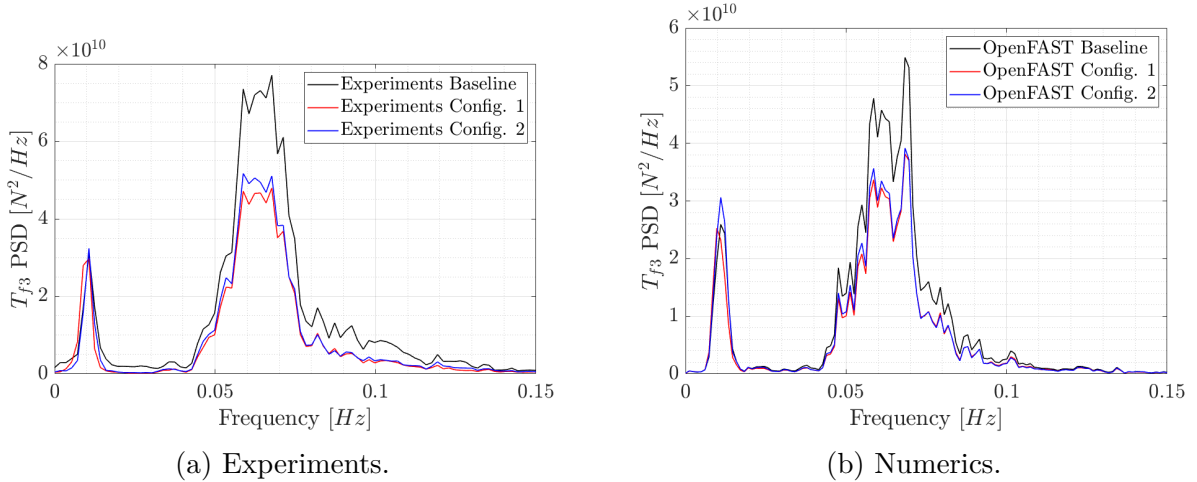


Figure 5.23: Numerical and experimental PSDs of T_{f3} fairlead tension for all the tested configurations.

5.5.3.2.2 Statistics Five statistical values of fairlead tensions are presented in Table 5.13 to allow a quantitative comparison between numerics and experiments. As explained in the previous sections, compared to the model tests, the general trend of the numerical model is to underestimate the statistical values of the maximum and minimum tensions.

In line with the observations of the spectral analysis, a clear reduction in mooring tensions is shown with the addition of the clump weight in the wave frequency range. This reduction is quantified by comparing the standard deviation (STD) values of the fairlead tensions for the baseline configuration and the configurations with clump weights.

The STD values are indicative of the variability and intensity of the loads experienced by the mooring lines. T_{f3} show a notable decrease of around 21% and 19% in Config. 1 and 2, respectively, when compared to the baseline; T_{f2} show a significant decrease of around 18% and 12% in Config. 1 and 2, respectively, when compared to the baseline; and T_{f1} show a decrease of around 21% and 4% in Config. 1 and 2, respectively, compared to baseline. This underscores the effectiveness of clump weights in reducing wave frequency loads, helping to reduce fatigue damage on mooring lines. Although the RMS values remain relatively unchanged across configurations, the key takeaway is the effectiveness of clump weights in mitigating the more damaging wave frequency cyclic loads. Also, in the most favorable case, the maximum tension is reduced in Config. 1 and Config. 2 by around 6%, suggesting that in an ULS design, with the inclusion of a clump weight the mooring line diameter could be reduced due to the reduction of the utilization factor following the procedure detailed in the offshore standard DNV-OS-E301 [30].

It is interesting to note that the RMS in the numerics and experiments is comparable, even when the clump weight is attached, regardless of the position, indicating the overall energy in the tension signal is maintained.

Table 5.13: Fairlead tensions statistics.

		Baseline		Config. 1		Config. 2	
		Exp.	Num.	Exp.	Num.	Exp.	Num.
T_{f1} [kN]	max	861.20	824.30	837.00	798.70	827.80	813.40
	min	443.62	469.07	490.75	496.67	490.50	499.34
	mean	658.56	656.40	643.79	647.31	637.49	647.34
	std	44.84	33.27	36.66	27.90	39.47	30.48
	rms	660.16	657.25	664.86	667.91	648.75	648.06
T_{f2} [kN]	max	786.60	824.00	763.20	798.90	754.20	813.00
	min	466.49	467.50	508.03	495.78	477.11	498.45
	mean	661.72	666.40	575.93	577.31	654.34	657.34
	std	37.25	33.27	29.56	27.90	36.04	30.47
	rms	672.81	667.26	606.61	607.91	665.37	668.06
T_{f3} [kN]	max	1270.60	1166.10	1088.20	1102.60	1143.40	1103.20
	min	125.65	154.98	270.14	248.56	244.68	255.86
	mean	622.05	625.00	599.24	596.11	614.50	615.99
	std	114.92	88.67	89.76	75.78	92.91	78.00
	rms	632.58	631.07	605.71	600.54	631.37	630.68

5.6 Concluding remarks

In this chapter, the model test outcomes and the validation of the corresponding numerical model of a spar FWT with three hybrid catenary mooring configurations are presented. Although further improvement of the numerical model can be achieved, an overall good agreement is found and trends are captured, indicating also that model tests were performed with high quality standards, following the ITTC recommendations and good practices.

The natural surge frequency is DOF mainly sensitive to the addition of the clump weight in the catenary mooring system. Although the pretension is maintained, the geometric stiffness of the line changes and, therefore, the response of the FWT.

Platform motion responses in surge, heave, and pitch are dominated by wave frequency responses and remain similar between configurations. Different low-frequency responses are observed in the surge motion between configurations. In all tested configurations, the highest pitch motions experienced by the platform in the extreme wave scenario remain under the established permissible thresholds outlined for FWT in the available documentation. Then, all three mooring configurations can be suitable for deployment.

Regarding stationkeeping performance in the extreme irregular wave, the inclusion of the clump weight reduces the surge stiffness and therefore increases the mean dynamic offset, especially when the clump weight is closer to the fairlead (Config.1). However, the motion response in the extreme sea state did not appear to be much influenced by the presence of the clump weight, only in the low-frequency range with no clear impact on the response statistics. Regardless of the position in which the clump weight is attached, this additional device on the mooring line does not appear to tackle motion reduction under the conditions of this study. When the intention is to reduce the motions in the horizontal plane in a particular sea state, more mooring configurations with different pretensions and weights should be analyzed. This could be a valuable prospect for future exploration.

On the other hand, as an advantage, the addition of clump weight to the mooring line significantly reduces the dynamic tension on the mooring lines, especially first-order wave frequency loads. This offers a possible solution to reduce fatigue damage, impulsive peak tensions, and lower utilization factors.

The inclusion position of the clump weight has been shown to be important in terms of tensions. Despite the stiffness of the system being reduced in all configurations that include a clump weight, the location closer to the seabed (Config. 2) is less influential. Also, the clump weight location closer to the fairlead (Config. 1) seems to be more effective in terms of mooring tension reduction, although with minimum differences with Config. 2. Therefore, a detailed investigation of additional different positions, quantities, and weights of these devices could be a valuable prospect for future exploration.

Chapter 6

Inclusion of clump weights along shared lines of FWFs

6.1 Abstract

Although shared moorings have been widely analyzed numerically for FWFs as stated in Chapter 2.4, experimental validation has been lacking. In this chapter, model tests of a dual-spar FWF are described. Two mooring arrangements are evaluated: a baseline shared mooring system and an alternative configuration that adds a clump weight at the midpoint of the shared line. For comparison purposes, a single spar platform (already introduced in Chapter 5) is also evaluated to understand the implications of shared mooring systems.

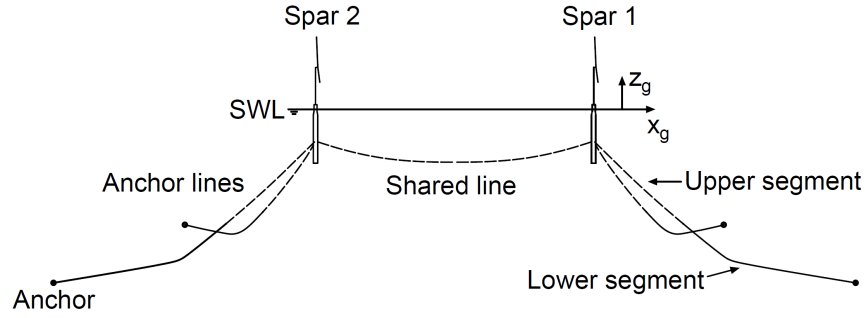
The previous chapters proved, from both a numerical and an experimental point of view, how the addition of a clump weight in catenary mooring systems can reduce wave-frequency loads in the mooring lines. As mentioned in Section 1.2.2.2, snap loads may be a key aspect to consider when designing shared mooring systems for FWFs. One technique that could potentially reduce this adverse effect is incorporating clump weights in the mooring system.

The experiments provide insights into system hydrodynamics and mooring line responses for the three configurations. Most of these new insights into the complex hydrodynamic responses of FWFs with shared moorings, findings, descriptions, and conclusions have been published in Jiang et al. [66], Liang et al. [86] and Lopez-Olocco et al. [90].

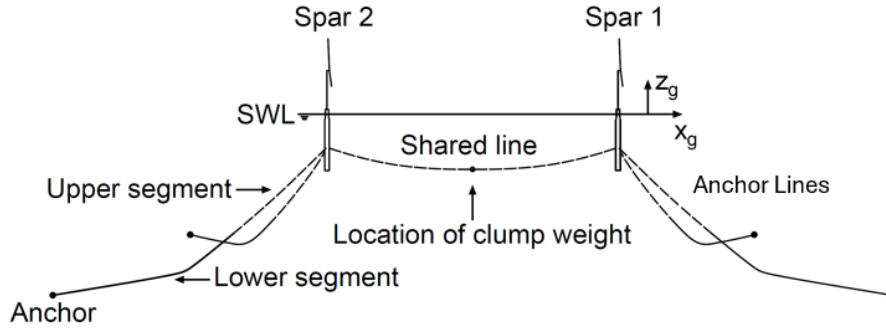
6.2 Description of the FWF

The same spar FWT as in Chapter 5 is selected as the case of study. As illustrated in Fig. 6.1, two shared mooring systems are applied to the dual-spar FWF. For the dual-spar FWF, two FWTs are placed along the defined surge direction, i.e., along the x_g -axis. The initial turbine spacing is 750 m, which is approximately six times the rotor diameter. The turbine spacing of the dual-spar FOWF is limited by physical constraints of the testing facility. In practice,

the turbine spacing of FWTs in an FWF should be determined considering the impacts of aerodynamic interactions [6]. The static drafts of all FWTs are 120 m and all the fairleads are 70 m below the still water level, the same as defined in the OC3 report [68].



(a) Dual-spar FWF, baseline configuration.



(b) Dual-spar FWF, clump configuration.

Figure 6.1: Side view of the Dual-spar FWF with different mooring systems (dashed line: steel wire; solid line: chain).

As shown in Fig. 6.1, each FWT is moored by two single lines (anchor lines) from the fairleads to seabed anchors. For the baseline configuration, two FWTs are connected by a shared line at the fairleads. For the clump configuration, the mooring properties of all mooring lines are the same as those for the baseline configuration, and a clump weight is attached to the middle of the shared line (see Fig. 6.1b).

As can be deduced from Fig. 6.2, the projected angle between two adjacent mooring lines is 120 degrees in the horizontal plane. The radius from the centerline of each FOWT to the corresponding anchors is 623.53 m. The studied water depth and the proper mooring redesign that has been carried out can be referenced in Section 5.2.

6.2.1 Mooring system design

The design adopted for the anchor lines is based on the mooring design of the single FWT and is described in Section 5.2.3. Mooring properties of the selected design are summarized

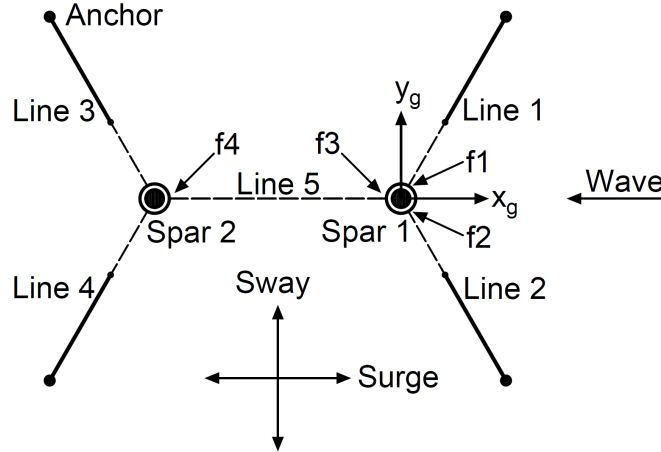


Figure 6.2: Top view of the Dual-spar FWF with different mooring systems (dashed line: wire; solid line: chain). The symbols $f1$, $f2$, $f3$, $f4$ denote the fairlead connections that are measured in the experiments.

in Table 5.3. Since there is no design recommendation for the shared line design [30, 32], the same steel wire properties shown in Table 5.3 are used for the shared line. In addition, the length of the shared line was determined such that the distance between the platforms is equal to the target turbine spacing of approximately six times the rotor diameter in the static condition. When the floating system reaches the static equilibrium, the two FWTs are driven towards each other for a short distance due to the self weight of the shared line, leading to differences in the static pretensions between the single-spar and dual-spar configurations. Mooring properties of the two shared mooring configurations are listed in Table 6.1. As shown, the only difference between the two configurations is the clump weight.

Table 6.1: Mooring properties of the two shared mooring configurations (full scale, refer to Fig. 6.1)

Mooring line	Mooring component	Parameter	Baseline	Clump
Anchor line	Upper segment	Property ¹	Wire	Wire
		Length [m]	250	250
	Lower segment	Property	Chain	Chain
		Length [m]	415	415
Shared line	Segment	Property	Wire	Wire
		Length [m]	739.6	739.6
	Clump weight	Submerged weight [t]	-	15

¹ Mooring properties ‘Chain’ and ‘Wire’ refer to Table 5.3.

6.3 Experimental tests

6.3.1 Experimental set-up

The experimental tests of this campaign were performed at the same facility described in Section 5.3.1. Therefore, the same scaling ratio of $\lambda = 47$ is adopted.

In the dual-spar FWF, two FWTs with the same physical properties described in Section 5.3.1 are used. The mass properties were downscaled with the scaling ratio λ using the Froude scaling similarity laws. The target mass properties and the measured mass properties of the FWT models are listed in Table 6.2. In general, a good agreement is achieved between the target and the measured mass properties.

Table 6.2: Target and measured mass properties of the FOWT models (model scale)

Mass property	Target value	Spar 1		Spar 2	
		Measured value	Relative difference [%]	Measured value	Relative difference [%]
Mass M [kg]	77.403	77.721	0.41	77.213	-0.25
Center of gravity COG [mm] ¹	[0.0, 0.0, 893.62]	[0.002, 0.02, 890.76]	[-, -, -0.32]	[0.073, 0.00, 898.19]	[-, -, 0.51]
Moment of inertia x -axis i_{xx} [mm] ²	1029.5	1044.3	1.44	1044.3	1.44
Moment of inertia y -axis i_{yy} [mm] ²	1029.5	1044.6	1.47	1044.6	1.47
Moment of inertia z -axis i_{zz} [mm] ²	102.6	94.8	-7.60	94.8	-7.60

¹ The height of the COG is measured with regard to the keel.

² Moment of inertia is calculated with regard to the COG.

To scale down the mooring lines and their properties for this configuration, the same procedure described in Section 5.3.1 is followed. The layout of the shared mooring systems is illustrated in Fig. 6.3. The experimental layout of the shared mooring systems is illustrated in Fig. 6.3. As shown, the first FWT model, Spar 1, was placed 30 m away from the wavemaker to ensure the same position as for the single FWT layout (see Fig. 5.5).

For the clump configuration, a flat-cylinder clump weight was attached to the midpoint of the shared line by a diver. The submerged weight of the clump weight is 144.5 g (15 tones at full scale). The measured position of the clump weight on the shared line was 2.6 cm (1.22 m at full scale) from the midpoint towards the Spar 2.

The selected mooring properties in Table 5.3 were scaled down and taken as references in the physical modeling of the mooring lines. The material of the mooring lines and the connecting parts was selected to make the equivalent mass density close to the reference values. To match the material stiffness of the anchor lines and the problems mentioned in Section 5.3.1 associated with that, a set of springs (k_1) was used to connect the single lines and the anchors, as shown in Fig. 6.4. For the shared line, a spring (k_2) was added to the connection between Spar 2 and the shared line to achieve the equivalent material stiffness of the shared line (see Fig. 6.4). The equivalent mooring properties resulting on the model scale are listed in Table 6.3. To verify the precision of the installation, the distance between the models in the baseline configuration was measured several times in the static equilibrium position with a mean value of 16.054 m .

Load cells were used to measure mooring tension. If submersible load cells were installed on the fairleads, they would affect the mooring angles at the fairleads due to the light weight

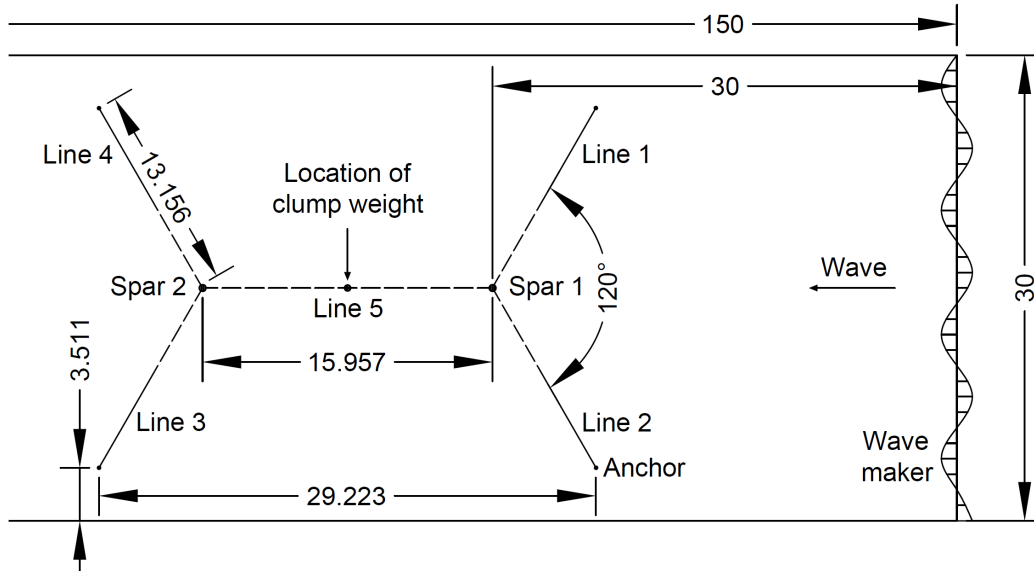


Figure 6.3: Experimental layout of the dual-spar FOWF with shared mooring configurations (dimensions in [m])

Table 6.3: Mooring properties of the mooring lines used in the tests (model-scale)

Mooring properties	Anchor line		Shared line
	Wire	Chain	
Length [m]	5.32	8.83	15.74
Mass density [kg/m]	0.02	0.16	0.02
Equivalent spring ¹ stiffness [N/m]	$k_1 = 800$		$k_2 = 520$

¹ Refer to Fig. 6.4 for the spring positions.

of the mooring lines. Therefore, similarly to what was described in Section 5.3.1, the load cells were installed on the aluminum frames. Fixed pulleys were mounted at the fairlead positions to transfer the mooring lines; see Fig. 6.4. Due to this change, the total mooring tension was considered instead of the vertical mooring tension component when tuning the mass properties of the FOWT models.

The pretension on the mooring lines was measured for each configuration. The measured pretension is presented together with the target pretension in Table 6.4, where T_{f1} and T_{f2} indicate the mooring tension at the fairleads in Line 1 and Line 2; T_{f3} and T_{f4} indicate the mooring tension at the fairleads in Line 5 close to Spar 1 and Spar 2, respectively (see Fig. 6.4 and Fig. 6.2). In general, a good agreement is achieved between the target pretension and the measured pretension. With the attached clump weight, the shared line experiences a change in its shape and an increase in its pretension in static equilibrium, and the two FWTs are drawn closer to each other. As a result, the pretension on the anchor lines also increases.

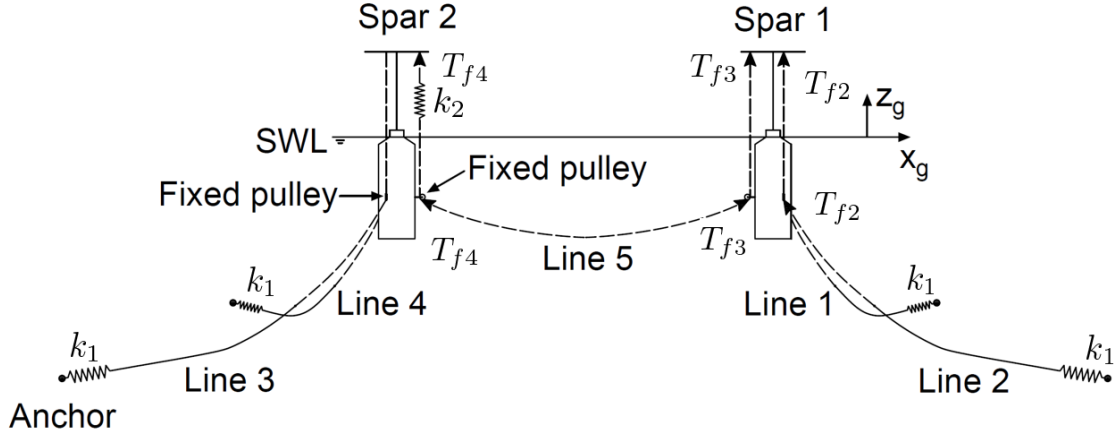


Figure 6.4: Illustration of the experimental layout of the baseline configuration

Table 6.4: Target and measured pretension for the two shared mooring configurations (model-scale)

Variable	Target value	Baseline		Target value	Clump	
		Measured value	Relative difference [%]		Measured value	Relative difference [%]
Pretension T_{f1} [N]	7.62	7.97	4.59	8.73	9.01	3.21
Pretension T_{f2} [N]	7.62	8.04	5.51	8.73	9.07	3.89
Pretension T_{f3} [N]	6.34	6.78	6.94	7.56	7.90	4.50
Pretension T_{f4} [N]	6.34	6.67	5.21	7.56	7.50	0.79

6.3.2 Test matrix

In total, 14 tests including 6 DoF decay tests, irregular and regular waves were performed for each shared mooring configuration. For the wave cases, the same test matrix described in Section 5.3.2 was followed.

6.3.3 Instrumentation

During model tests, variables of interest were measured by sensors in real-time. Measurement devices that were installed and calibrated prior to model tests were already described in Section 5.3.3 for the Spar 1; refer to Figs. 5.6 – 5.9. One identical extra load cell is installed in Spar 2 to measure the fairlead tension of the shared line. The motions of Spar 2 were not measured during the test due to a lack of equipment. Fig. 6.5 shows the instrumentation used at the test position.

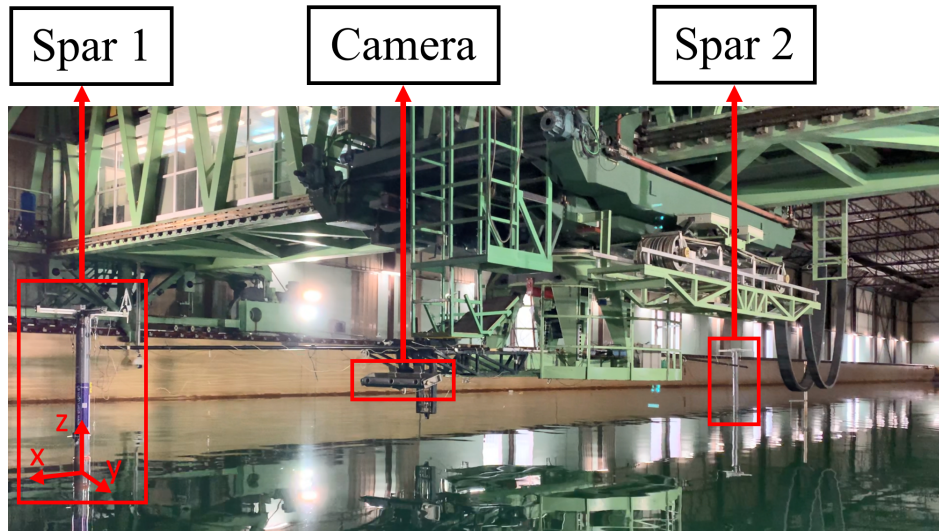


Figure 6.5: Image of the FWT models instrumented in the testing position.

6.3.4 Methodology

6.3.4.1 Decay tests

Taking into account the 6-DOF rigid body motions of each FWT, the dual-spar FWF has twelve natural periods and the corresponding eigenmodes (Liang et al. [83]). These eigenmodes, two FWTs move in the same heading or the opposite directions of a DoF. However, due to the difficulty of applying initial displacements or rotations to both FWTs to excite the eigenmodes, for the dual-spar FWF, in the decay tests an initial displacement or rotation was applied to Spar 1 only. The same experimental procedures as for the Single FWT (see Section 5.3.4.1) are applied to the Dual-spar FWF, as a result, only six eigenmodes were excited during the decay tests and natural periods and damping ratios of the FWT were estimated. In order to calibrate the multibody numerical models, the viscous damping forces estimated from the single spar tests can be applied to each individual FWT of the FWF as a starting point. Then, numerical decay tests can be carried out for the FWF, and the obtained damping ratio and natural periods of the coupled modes will be compared with the experimentally measured ones. An iterative procedure may be needed to adjust the hydrodynamic coefficients of the system components (FWTs and mooring lines) to achieve a good match.

6.3.4.2 Wave tests

To characterize the dynamic behaviors of the FWF, wave-only tests were conducted. All wave cases described in Section 5.3.2 were also tested for the shared mooring configurations following recommendations from the International Towing Tank Conference (ITTC) [60, 61]. The calibration and the estimation of the RAO can be checked in Section 5.3.4.2.

Fig. 6.6 shows a snapshot of the dual-spar model FWF during the experiments; refer to Fig. 6.3 for the layout. The 0° wave heading is pointed in the figure with the light blue arrow.

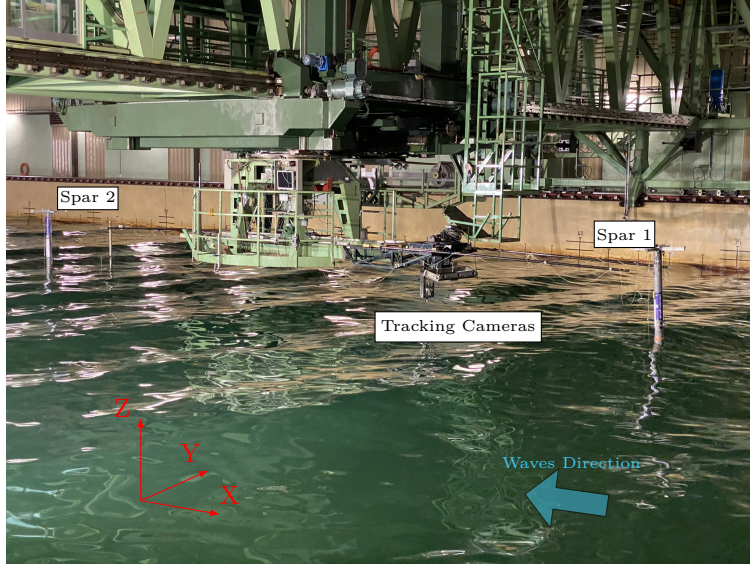


Figure 6.6: Illustration of the Dual-spar FWF during seakeeping tests.

6.4 Results

The results are presented in this section, focusing on a comparison between the shared configurations explained in Section 6.3.1 and the single baseline configuration explained in Section 5.3.1. In the figures, the single spar FWT Baseline configuration is noted as “Single” and the dual-spar FWF configurations are noted as “Dual” and “Dual Clump”.

The estimated natural frequencies and damping ratios of the two configurations are presented in Section 6.4.1. RAOs are presented in Section 6.4.2. Finally, motions and mooring tension analysis for the irregular waves are conducted in Section 6.4.3. As only one wave heading is considered, platform motion analysis focuses on surge, heave, and pitch DOFs.

6.4.1 Natural frequencies and damping estimation

Following the procedure detailed in Section 6.3.4.1, the natural periods and damping ratios are estimated for the tested mooring configurations. As presented in Table 6.5, no significant differences are found between the single and dual configurations for heave, roll, and pitch because these DOFs are hardly affected by the mooring configuration considered.

Note that when a shared mooring is used, the most noticeable differences appear in the DOFs of surge (51%) and sway (7%). This is due to the system reduction in stiffness by changing two anchor lines (one per FWT) to a shared line in the FWF. When the two shared mooring configurations are compared, the natural periods of the clump configuration in the surge, sway, and yaw DOF decrease by 6.11%, 4.68%, and 6.48%, respectively. This observation is expected due to the change in mooring stiffness introduced by the clump weight.

The estimates of the average damping ratios ξ are listed in Table 6.6, which does not show

Table 6.5: Natural period estimation for the tested configurations [s].

	Surge ¹	Sway	Heave	Roll	Pitch	Yaw
Single	93.03	87.92	29.80	31.69	31.71	24.55
Dual	142.88	83.89	30.50	31.56	31.32	23.93
Dual Clump	134.15	79.96	30.55	31.40	31.45	22.38

¹ According to Liang et al. [83], the large natural period in surge DOF obtained from the experimental decay test refers to Mode 1. For other DOFs, it is hard to determine whether Mode 1 or Mode 2 is excited because these two modes have close natural periods and the information of platform motion of Spar 2 is not available.

significant differences between configurations. After adding the clump weight, minor changes in the damping ratios of all DOFs are observed.

 Table 6.6: Estimation of the damping ratio ξ for the tested configurations [%].

	Surge	Sway	Heave	Roll	Pitch	Yaw
Single	3.87	2.91	1.77	1.07	1.27	1.62
Dual	3.56	3.02	1.86	1.08	1.32	1.83
Dual Clump	3.82	3.30	2.02	1.22	1.17	2.04

6.4.2 First-order RAOs from the regular wave and white noise tests

The estimated motion RAOs for both configurations are shown in Fig. 6.7. A comparison is presented between white noise and regular wave results, obtained on the basis of the methods described in Section 5.3.4.2. Generally, a good match between the two tests is achieved for all the mooring configurations. This is an indication of the system's linear behavior in this frequency range, as energy is not transferred between different frequencies in the white noise tests.

Comparing the single- and dual-spar configurations, we observe that the differences between them are not substantial in the first-order frequency range. The reason is that the motion dynamics in this frequency range is barely affected by the mooring used in this study.

As RAOs are just linear operators, whereas the catenary mooring system has nonlinear restoring characteristics, the tension RAOs must be interpreted with caution. To evaluate the impact of the mooring system on tension responses, the tension RAOs have been estimated and are presented in Fig. 6.8.

The results are similar for the anchor lines, but substantial differences can be found for the shared line. A possible explanation is that since additional nonlinearities are present in a

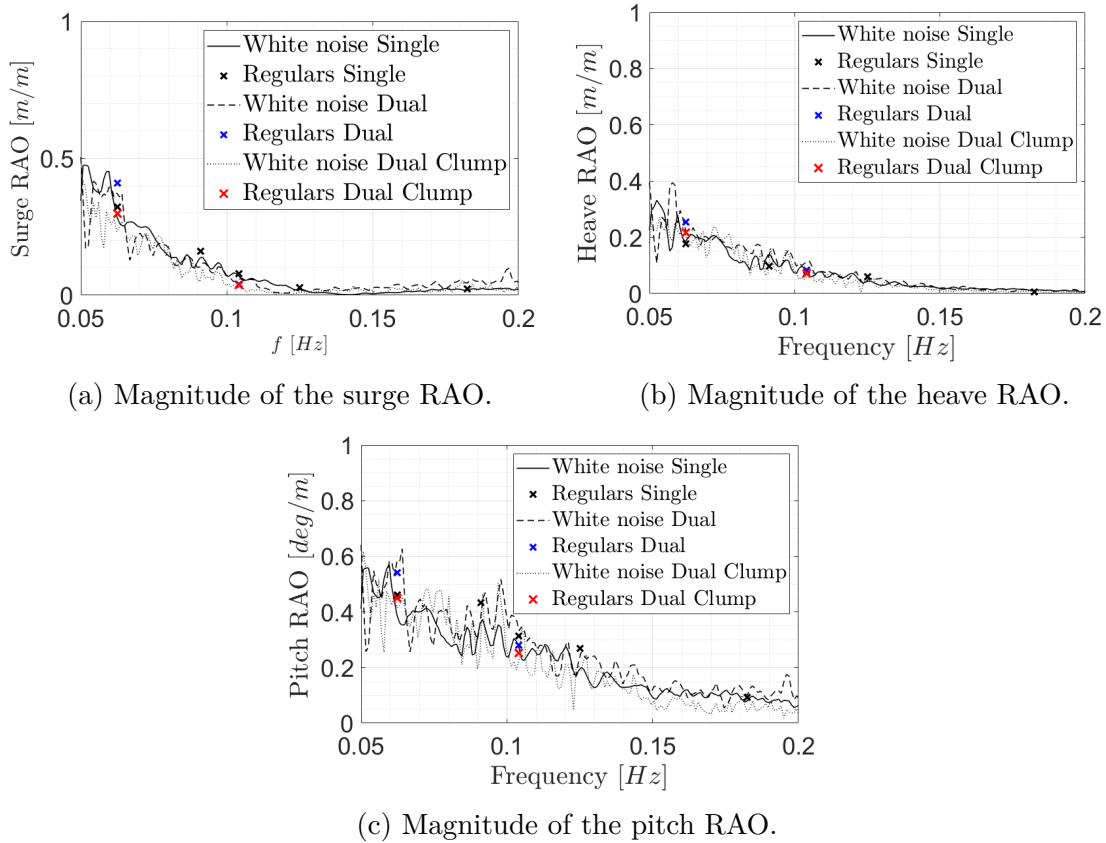


Figure 6.7: Comparison of response amplitude operators for surge, heave and pitch motions, single- and dual-spar configurations.

FWF with shared mooring (primarily due to the shared line), one can expect differences between the transfer function obtained from the white noise tests and from the regular wave tests. When the clump weight is attached to the shared line, a clear reduction of the tension response is achieved, but differences between the white noise tests and regular wave tests are still found. For a deeper investigation on this matter, more repetitions of these tests and other white noise tests with different wave amplitudes and regular waves with different amplitudes and frequencies should be carried out. This has been left for future work.

6.4.3 Response analysis for the irregular wave tests

As discussed in Section 6.3.2, an operational and an extreme sea state have been tested. For FWTs in normal operation, aerodynamic loads have a significant impact on the motion and structural responses in addition to hydrodynamic loads. As wind loads were not considered during the tests, the studied load cases are representative of scenarios where the spar FWTs are parked due to maintenance or faults [67]. Under such scenarios, FWTs are usually parked with feathered blades and wave loads are dominant. To highlight the wave-dominant extreme responses of the FWF, results of the operational condition can be checked in Lopez-Olocco

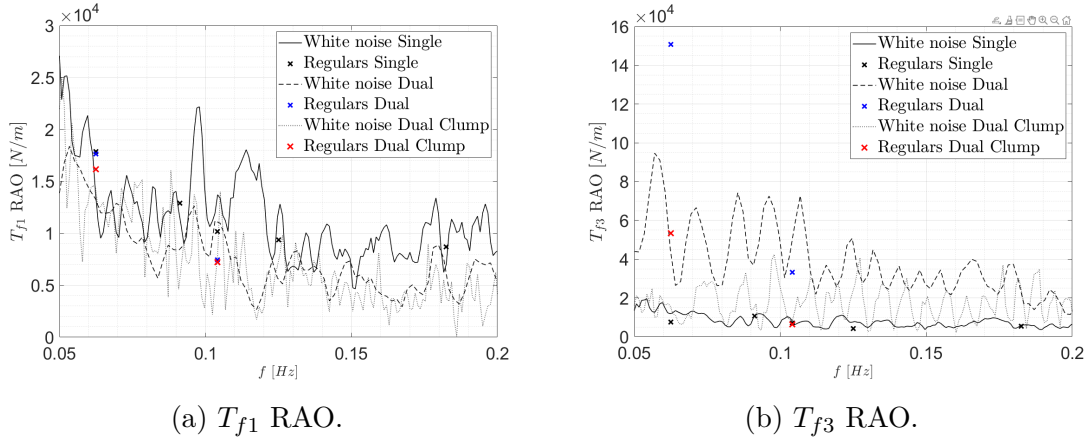


Figure 6.8: Comparison of response amplitude operators for anchor lines (T_{f1}) and shared line (T_{f3}); single- and dual-spar configurations.

et al. [90] and Liang et al. [86].

In order to present the results, first, motions are analyzed, with a focus on surge motion, the crucial one in terms of the inter-array power cable design, and the one that is most affected by the change in the mooring configuration from a single FWT to a dual FWF. The platform-pitch motions are also discussed as the floater's tilt angle relates to serviceability limit state and is determined by tolerance requirements by turbine manufacturers. Mooring tensions are also discussed to close this section.

6.4.3.1 Motion responses

6.4.3.1.1 Spectral analysis The PSDs are averaged across the three realizations of the surge motion in the extreme wave condition and are shown in Fig. 6.9.

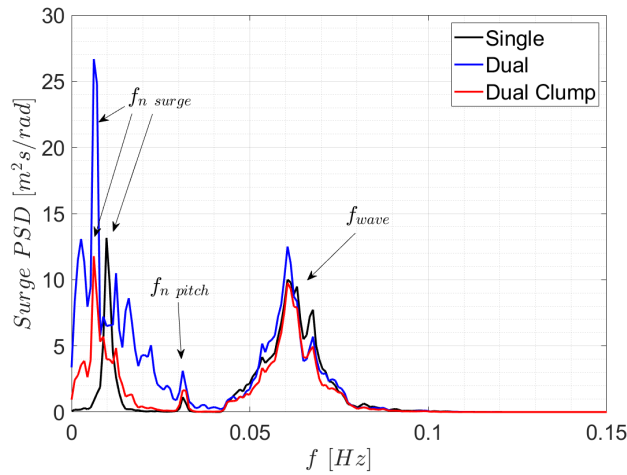


Figure 6.9: Averaged surge spectra for the IRR02 wave case. $H_s = 12.7$ m and $T_p = 15.45$ s

As illustrated in Fig. 6.9, the surge motion PSDs have similar peaks in the first-order wave frequency range (0.05 to 0.2 Hz) for the three configurations despite clear differences in the low-frequency range (0 to 0.05 Hz). In addition, the surge-pitch coupling is evidenced by the peak around 30 s (0.033 Hz), which corresponds to the estimated natural period of pitch (see Table 6.5). This was also observed in Ramachandran et al. [118] and verified in other tests of spar FWTs, e.g., Meng et al. [100], Yang et al. [143].

In the low-frequency range, the surge resonant motions of the three configurations are excited at peaks around 0.01 Hz ; see Table 6.5. Compared with the Single configuration, the Dual configuration displays a larger amount of energy in periods 60 to 120 s (0.02 to 0.0075 Hz). This may be correlated with additional eigenmodes of the FWF due to the complex multibody dynamics present in the configuration, as discussed in Section 6.3.4.1 and in Liang et al. [83].

Although future work is needed for a proper understanding of this particular energy distribution, the significant reduction achieved by the inclusion of the clump weight is clearly observed. The modified mooring stiffness contributes to the variation of peak amplitudes in the low-frequency range as the amplitudes of low-frequency motions are highly dependent on the mooring stiffness [1].

For the pitch DOF, the averaged PSDs are presented in Fig. 6.10a and are similar for all configurations. The differences in the heave motions between the two configurations are not large either (Fig. 6.10b). The reason for this observation is that both the heave and pitch motions are governed by the mass properties and the dominant hydrodynamic stiffness, while the mooring stiffness plays a secondary role.

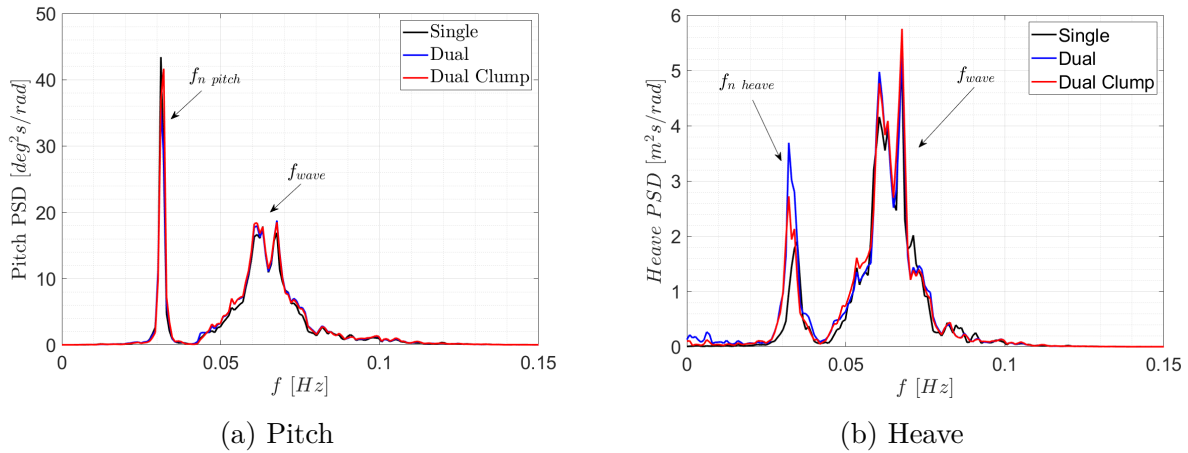


Figure 6.10: Comparison of averaged heave and pitch spectra for the IRR02 wave case. $H_s = 12.7$ m and $T_p = 15.45$ s

Among the investigated DOFs, surge motion is most affected by mooring configurations. Therefore, we should focus on the surge offset when assessing the feasibility of the shared mooring in an FWF.

6.4.3.1.2 Statistics A probability of exceedance (POE) curve measures the number of times a stochastic process exceeds some critical value per unit time. In the extreme sea state, excessive surge or pitch motions of the spar FWT may lead to damage of the inter-array power cables or drivetrain components. According to feedback from industrial partners in various initiatives, the experimentally obtained POEs can also be useful in the verification of numerical models for design and certification purposes. Hence, the POE together with conventional statistics to compare the three configurations is used.

Fig. 6.11 presents the POEs obtained from the time series of the surge and pitch motions for the three realizations. First, it is observed that the shapes of the POEs are consistent across the three realizations. Second, for a given level of POE, e.g., 0.1, the corresponding surge motion (blue curves) of the “Dual” configuration are significantly larger than that (black curves) of the “Single” configuration. However, when the clump weight is added, as expected by the increase in the mooring stiffness, the corresponding surge motion (red curves) of the “Dual Clump” configuration is reduced and remains comparable with the “Single” configuration. This observation is consistent with previous observations for the surge PSDs. Additionally, the differences in the pitch motion POEs between the two configurations are negligible, as expected.

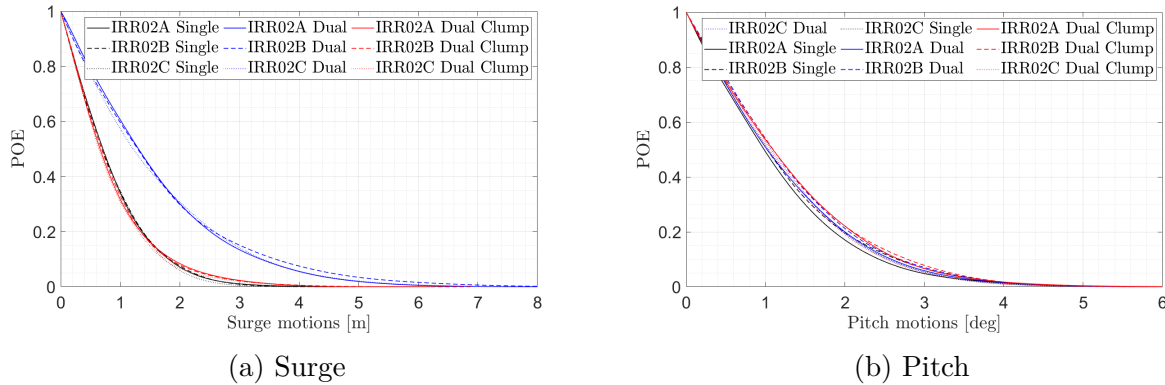


Figure 6.11: POE of surge and pitch for the IRR02 wave case. $H_s = 12.7$ m and $T_p = 15.45$ s.

Eight statistical values of the surge and pitch motions are presented in Fig. 6.12 to facilitate a quantitative comparison of the three configurations. The design standards of FWTs, e.g., DNV-ST-0119 [32], require that the characteristic extreme responses for design are obtained by fitting probability models to the global maxima of each realization, and for a sea state, many realizations should be simulated with different seeds. Due to the limited number of realizations from the experiments, a design check is not performed, but only the representative statistics are compared.

As shown in Fig. 6.12a, the total maxima and minima are mildly above the averaged maxima and minima for the surge motion for both configurations. This indicates a degree of stochastic uncertainty among the three realizations.

Consistent with POEs analysis, there is a larger maximum offset and RMS in surge for the dual-spar configuration than for the single-spar configuration, they are increased by 95% and 36%, respectively. This larger motion observation is aligned with the case of semi-submersible

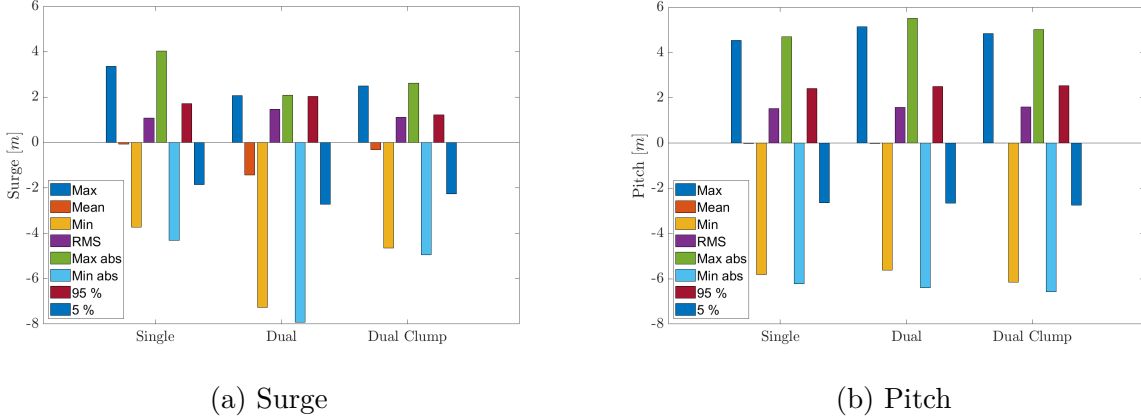


Figure 6.12: Comparison of surge and pitch motion statistics for the IRR02 wave case. $H_s = 12.7 \text{ m}$ and $T_p = 15.45 \text{ s}$. The statistical values are averaged across three realizations except “Max abs” and “Min abs”. “Max abs”: total maximum among three realizations; “Min abs”: total minimum among three realizations; “Max”: maximum; “Min”: minimum; “RMS”: root mean square; “95%”: 95% quantile; “5%”: 5% quantile.

FWF as well (Munir et al. [103]). When the clump weight is attached to the shared line, it is observed how the maximum surge offset is decreased by 36% and the RMS is reduced by 23%, indicating an improved station-keeping performance, comparable to the single-spar configuration.

For the mooring system design of FWF, there are no strict criteria regarding the maximum offset and a rule-of-thumb threshold is 10% of the water depth because of constraints of the inter-array power cables. For the current water depth, the maximum surge offset (approximately 8 m) of the dual-spar FWF without clump weight is still below the threshold of 23.5 m, which can be acceptable considering the design requirements of dynamic cables and farm layout [59].

It is interesting to notice that mean surge of the single spar FWT is substantially smaller than that of Spar 1 of the FWFs, whereas the RMS values are comparable. The larger mean surge of the dual-spar configurations is mainly due to the reduced mooring stiffness in the surge direction, as the shared line’s contribution to the stiffness is relatively small. As a result, the surge mean drift is almost 20 times larger for the “Dual” configuration than for the “Single” configuration. However, when the clump weight is attached to the shared line, the mean drift of the baseline dual-spar configuration experiences a reduction of around 77%, and therefore the improved stiffness of the mooring is shown in the surge direction.

Regarding the platform pitch motion, the two configurations display quite similar statistics, as shown in Fig. 6.12b. This trend is consistent with the POEs presented before. Currently, the maximum allowable pitch angle in the range of $10\text{-}15^\circ$ is common for the non-operational load cases [113], e.g., DLCs 6.1 and 6.2 in the IEC standard [58]. This design criterion is also fulfilled for all configurations in the extreme wave case.

6.4.3.2 Tension responses of the anchor lines

For the three configurations, the fairlead tension T_{f1} (see Fig. 5.1 and 6.2) of a selected anchor line (Line 1) is focused in the analysis. As Line 1 and Line 2 are symmetrical, the discussion for Line 2 is not included here. The results and discussions on differences in tension responses are found in Appendix C of Lopez-Olocco et al. [90].

6.4.3.2.1 Spectral analysis The averaged PSD across the three realizations of the anchor line tensions for the extreme wave case is shown in Fig. 6.13.

It is observed that the response in the first-order wave frequency range is more similar than the response in the low-frequency range for all configurations. This is in line with the observations in Section 6.4.3.1.1 regarding the surge motion PSDs. In the low-frequency range, the estimated natural surge periods and the surge-pitch coupling are also observed.

When the clump weight is attached to the line, the considerable amount of energy between 60-120 s (0.02 to 0.0075 Hz) observed in the “Dual” configuration is drastically reduced. This was also observed in Section 6.4.3.1.1 due to the correlation between dynamic line tension and surge motions. Moreover, the addition of the clump weight in the shared slightly decreases the tension response of the anchor line within the first-order wave frequency range. Aligned with Chapter 5, this highlights the advantage of clump weights in reducing wave frequency loads, helping to reduce fatigue damage to catenary mooring lines.

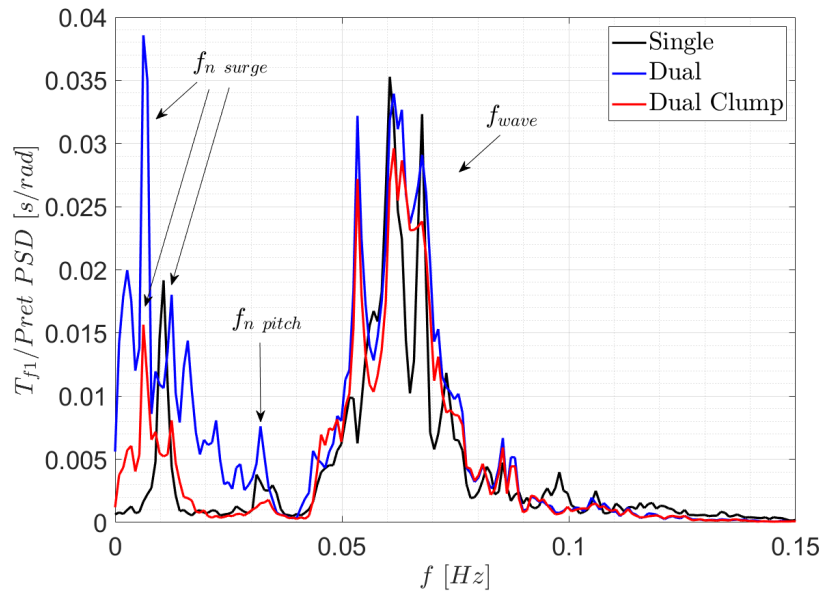


Figure 6.13: Comparison of the anchor line tension PSDs for the IRR02 wave case. $H_s = 12.7$ m and $T_p = 15.45$ s.

6.4.3.2.2 Statistics Fig. 6.14 shows the POE curves of the time series of the fairlead tension, T_{f1} . In order to account for the different pretensions in the single- and dual-spar

configurations, the statistics are normalized with the pretension. Similar to POEs of the motions 6.4.3.1.2, these POEs can also be used in verification of numerical analysis results of mooring lines. As expected, the normalized T_{f1} fairlead tension POEs show relatively small variability across the three realizations for all configurations. This observation is similar to that of the surge or pitch motion.

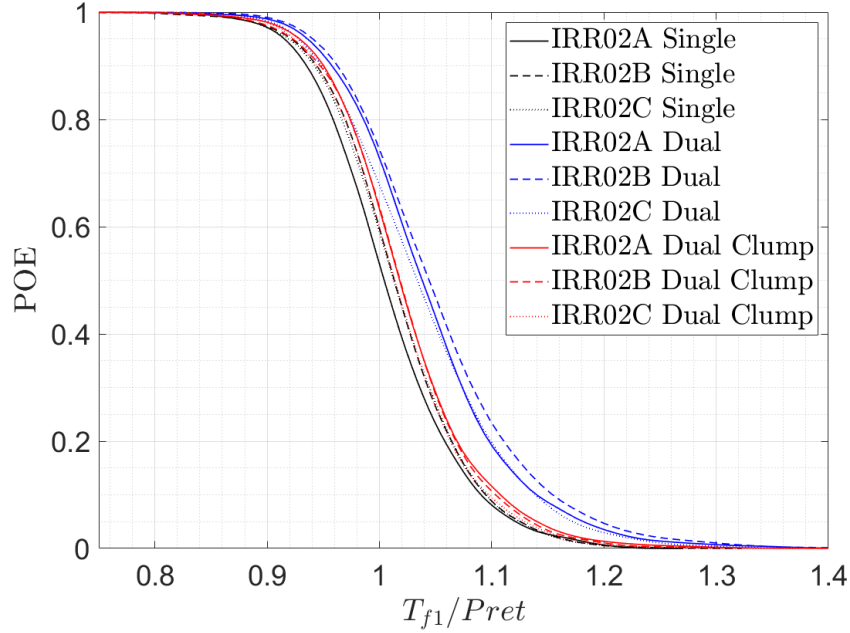


Figure 6.14: Comparison of the anchor line tension POEs for the IRR02 wave case. $H_s = 12.7 \text{ m}$ and $T_p = 15.45 \text{ s}$.

Generally, tension POEs have similar trends in all configurations. For a given POE level, a moderately higher tension is observed for the “Dual” configuration than for the “Single”. When the clump weight is attached in the “Dual Clump” configuration, mooring tension is reduced and remains relatively close to the “Single”. This observation is expected and in line with the spectral analysis of the previous section.

As mentioned in Section 6.4.3.1.2, statistical quantities, e.g. the quantiles 5% and 95%, mean and root mean square value, can be used to verify numerical models. Therefore, these values for the fairlead tensions in the anchor lines are presented in Fig. 6.15.

It is interesting to note that the mean value of the fairlead tension is close to the pretension in all configurations, indicating that the mean drift in surge for the dual-spar FWFs does not significantly impact the mean tension. This can be attributed to the reduced mooring stiffness in the FWF as previously discussed. Among other quantities, the RMS, and the 5% and 95% quantiles are slightly larger for the dual-spar configurations than for the single-spar configuration. This trend is consistent with the POEs shown in Fig. 6.14. Similar to the observation for the motions, the total maxima and minima of the three realizations are of the same order as the average maxima and minima.

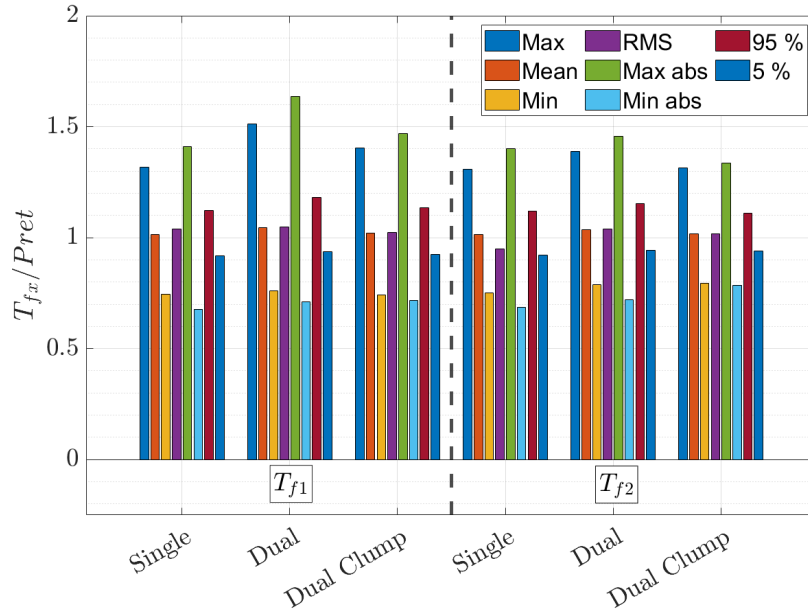


Figure 6.15: Anchor lines tension statistics (normalized with the pretension) for the IRR02 wave case. $H_s = 12.7 \text{ m}$ and $T_p = 15.45 \text{ s}$.

6.4.3.3 Tension responses of the shared line

Because the dynamics of the shared line is different from that of the anchor lines, the fairlead tensions in the shared line are analyzed separately in this section. This difference was shown when analyzing tension RAOs in Section 6.4.2 and can be clearly appreciated by observing the time series for the extreme wave condition for the anchor lines (T_{f1}) and shared line for the single- and dual-spar configurations (T_{f3}), as presented in Figs. 6.16 and 6.17.

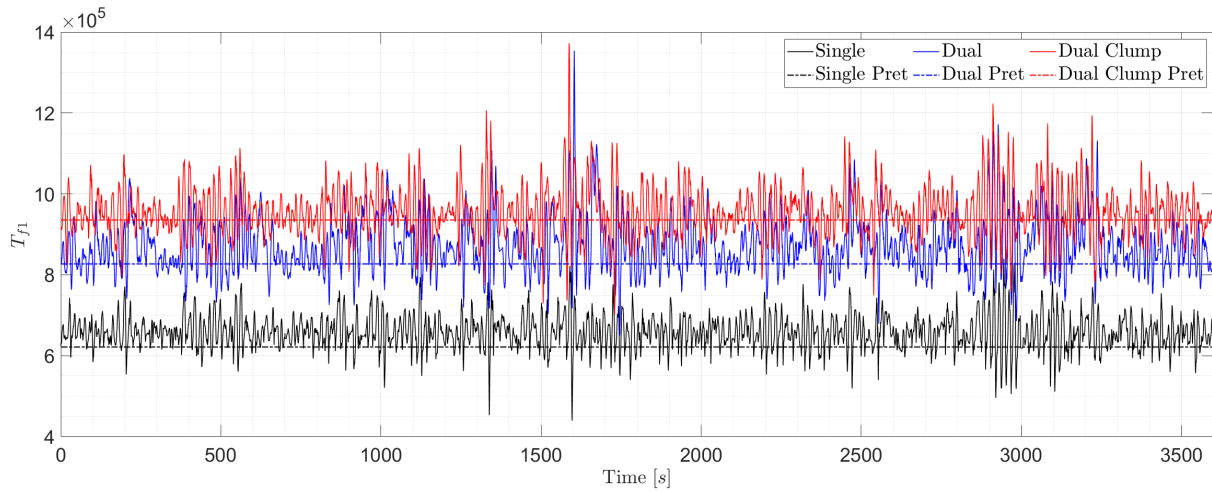


Figure 6.16: Comparison of the anchor line tension $[N]$ in all configurations for extreme case IRR02B.

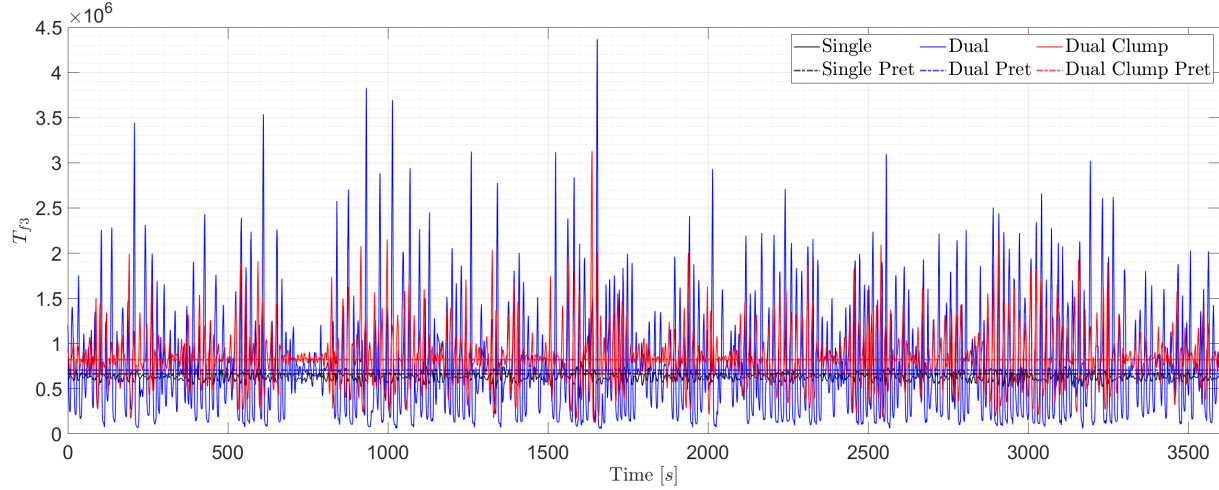


Figure 6.17: Comparison of the shared line tension $[N]$ in all configurations for extreme case IRR02B.

In the following sections, shared line tensions of Spar 1 and Spar 2 (T_{f3} and T_{f4}) are analyzed and compared between the two dual-spar configurations: “Dual” and “Dual Clump” configurations.

6.4.3.3.1 Spectral analysis The averaged PSDs of the three realizations for the shared line tension T_{f3} and T_{f4} time series are presented in Fig. 6.18. As expected, no considerable differences between both fairleads located at the two spars is appreciated. Remarkably, unlike the PSDs of the anchor line tension (see Section 6.4.3.1.1), the PSD of the shared line tension displays mostly peaks in the first-order wave frequency range. For the shared line, the advantage of reducing first-order wave frequency loads with the addition of the clump weight described in Section 6.4.3.2.1 is even more drastic, as shown in the figure.

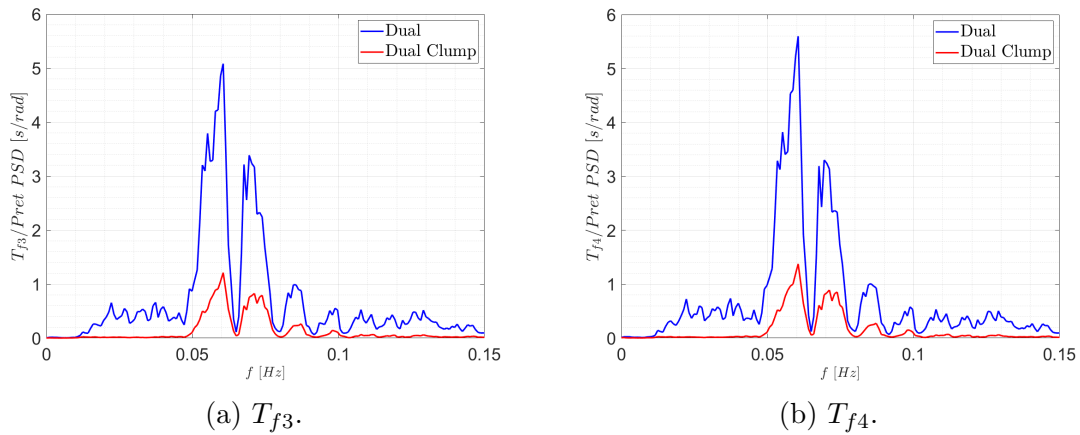


Figure 6.18: Shared line fairlead tension T_{f3} PSD for the extreme IRR02 wave case. $H_s = 12.7$ m and $T_p = 15.45$ s.

6.4.3.3.2 Slack and Snap events analysis As highlighted in Chapter 1, when analyzing the dynamic mooring tensions, an important factor to consider are snap events. According to Hsu et al. [54], a snap event can be described as a sudden and violent increase in tension that appears after a slack in the line. They proposed the following snap criteria based on the DNV-RP-H103 guideline [29]:

$$T_{slack} \leq 0.1 \cdot T_{mean} \quad ; \quad T_{snap} \geq 1.9 \cdot T_{mean} \quad (6.1)$$

where T_{slack} is the local tension minima, T_{snap} is the local tension maxima and T_{mean} is the mean dynamic tension.

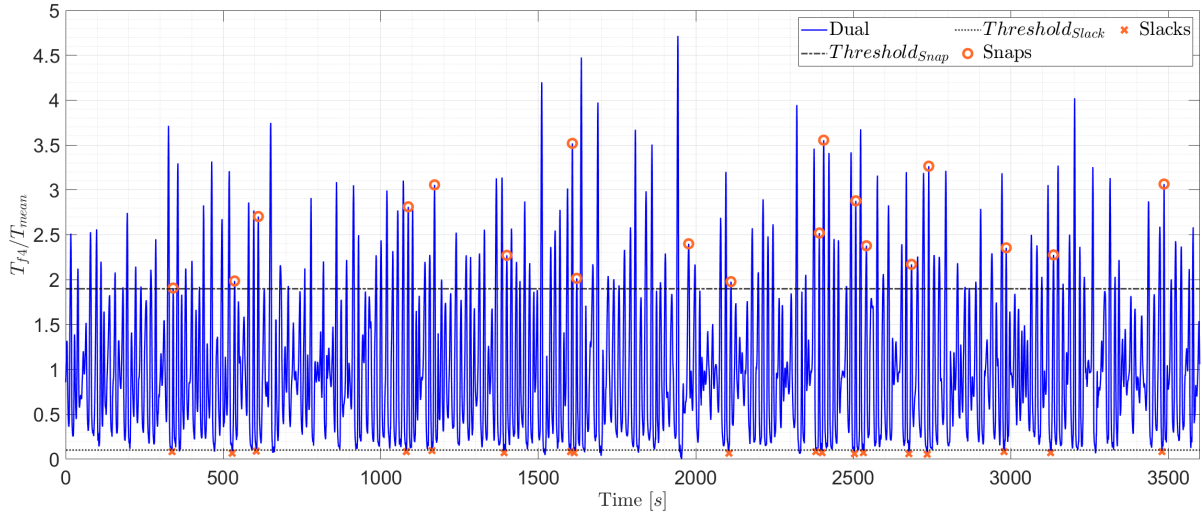
For the anchor lines in all configurations, the thresholds are far from the maximum ranges of the tension time series and therefore no slack/snap events are identified. In contrast, for the shared line, a number of snap/slack events can be identified. In Fig. 6.19 the snap and slack events of the fairlead tension T_{f4} and their thresholds (dashed lines) are marked following the above criteria for both shared configurations.

This extreme dynamics for shared lines in terms of snap and slack events can also be observed in the time series presented by Gomes et al. [44], who devised a shared mooring system for a set of five wave energy converters. As the present dual-spar FWF has one shared line, there is a significant reduction in the mooring stiffness in surge compared to the single-spar FWT. Also, the motions of Spar 1 and Spar 2 are most probably not in phase in irregular waves, and the relative distance between them varies. These factors contribute to the observed snap/slack events. Oscillations in the shared line tension due to these events can be critical to the mooring design.

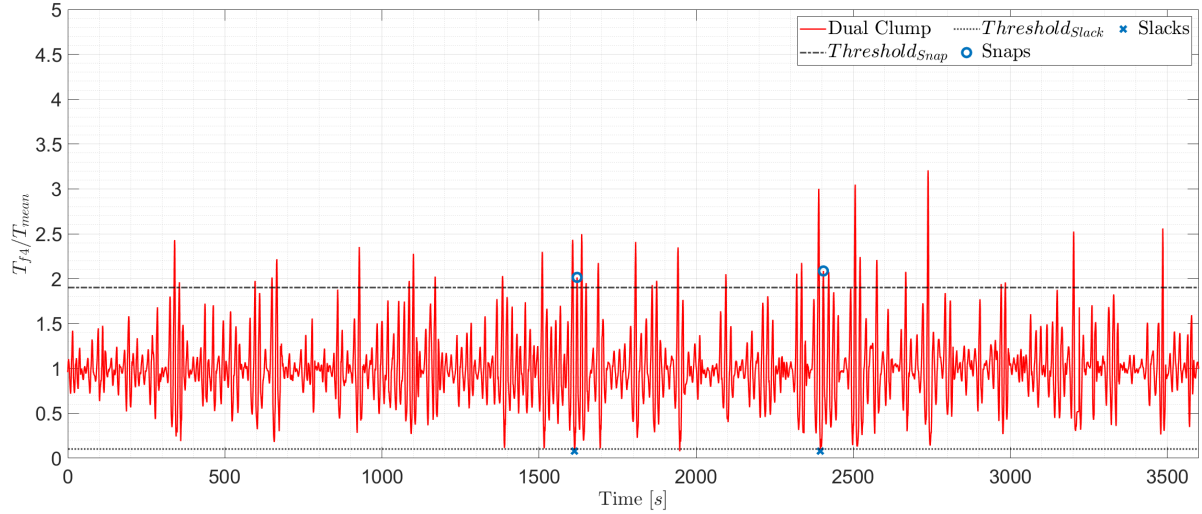
It can be concluded from the figures that the number of snap events observed in the shared line decreases significantly when the clump weight is added. The average number of snap events identified in T_{f4} is 18.33 for “Dual” configuration and, when the clump weight is added, 1.33. It is concluded then that the addition of a clump weight to the shared line may diminish the impact of snap loads and, therefore, reduce the safety margin preserved for the snap loads and lead to a more cost-effective design of shared lines of FWFS. However, as high peak tensions and dynamic tensions are associated with snap events, a proper design of the shared line with a higher steel grade or an increased steel wire diameter should be carried out.

6.4.3.3.3 Statistics Fig. 6.20 shows POEs of the times series of the shared line tension T_{f3} in the extreme irregular wave case. The grey zone refers to the region where the line tension is within the thresholds of the slack/snap criteria; refer to Eq. (6.1). Regarding the snap events, it can be seen that the shared line tension T_{f3} for the “Dual” configuration exceeds the snap threshold during 15% of the time, while when the clump weight is included, the snap threshold is exceeded only 5% of the time. Regarding slack events, the occurrence rate is much lower for the “Dual Clump” configuration.

POEs of the T_{f3} peak tensions (maxima and minima) are presented in Fig. 6.21. It is remarkable that approximately 30% of the peaks are above the snap-event threshold and 5% are below the slack-event threshold for the “Dual” configuration. When the clump weight is



(a) “Dual” configuration.



(b) “Dual Clump” configuration.

Figure 6.19: Identified snap load events in the time series of mooring tension T_{f4} , case IRR02A.

attached, a reduction of 20% of the peaks above the snap-event threshold is achieved, while the peaks below the slack-event threshold are almost nonexistent for this fairlead.

POEs of the T_{f4} peak tensions (maxima and minima) are presented in Fig. 6.22. Some small differences with T_{f3} are encountered in the peaks, and therefore more slack/snap events occur during the time series as discussed in the previous section. These differences appear to be caused by motions of the springs used to scale the stiffness of the shared line during the experiments (see Fig. 6.4).

Then, it can be concluded that the frequent occurrence of snap events can be addressed with the addition of the clump weight in the shared line. This can prevent premature failure of the

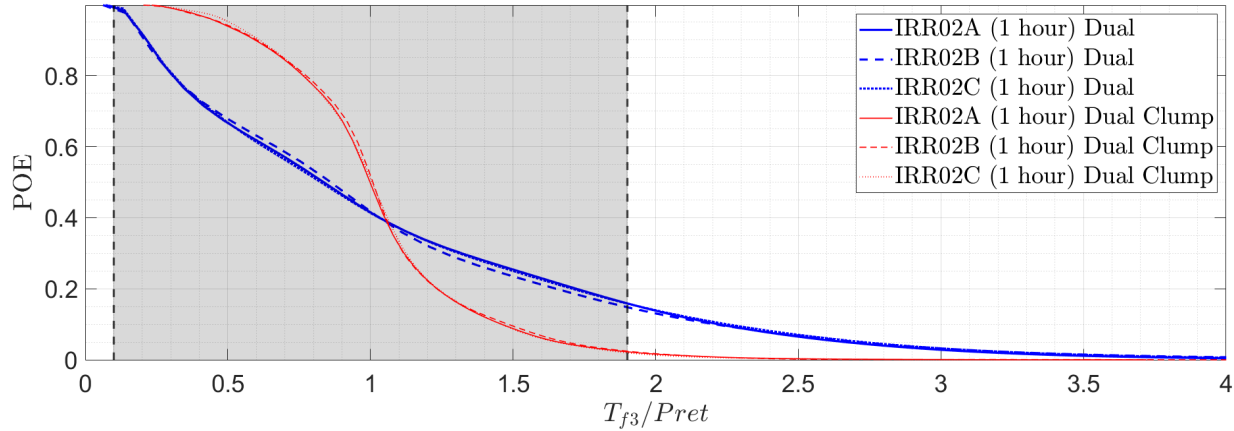


Figure 6.20: POE of the time history of the shared line fairlead tensions T_{f3} for the extreme IRR02 wave case. $H_s = 12.7$ m and $T_p = 15.45$ s.

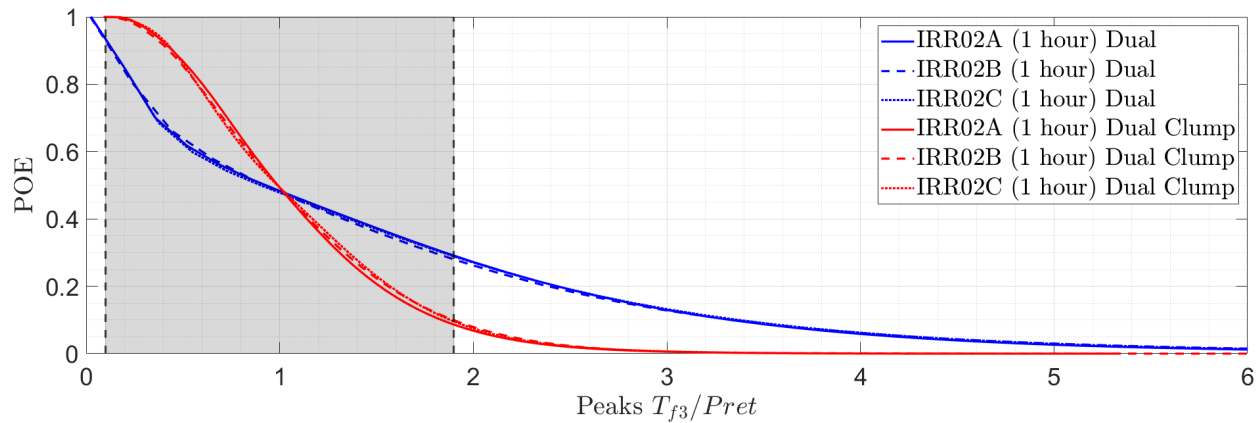


Figure 6.21: POE of the peaks of the time history of the shared line fairlead tensions T_{f3} for the extreme IRR02 wave case. $H_s = 12.7$ m and $T_p = 15.45$ s.

shared line due to fatigue or mooring breakage, as analyzed in the previous sections.

Statistics of the shared line tensions are presented in Fig. 6.23. As shown, with the clump weight addition, all the statistics are significantly changed. For example, the normalized value of the maximum tension exceeds five for the “Dual” configuration and it gets reduced to 3.5 (30%) for the “Dual Clump” configuration. Although peak tensions and dynamic tensions are reduced with this additional mooring component, still a proper design of the shared line with higher steel grade and increased wire diameter should be carried out.

Compared with the anchor line (see Fig. 6.15), the shared line displays a higher level of dynamic tension, and the difference between the maximum tension and the 95% quantile grows larger.

6.4.3.3.4 Analysis of Extreme Mooring Tension The extreme mooring tension is an important metric for mooring design based on ULS assessment of FWT structures according

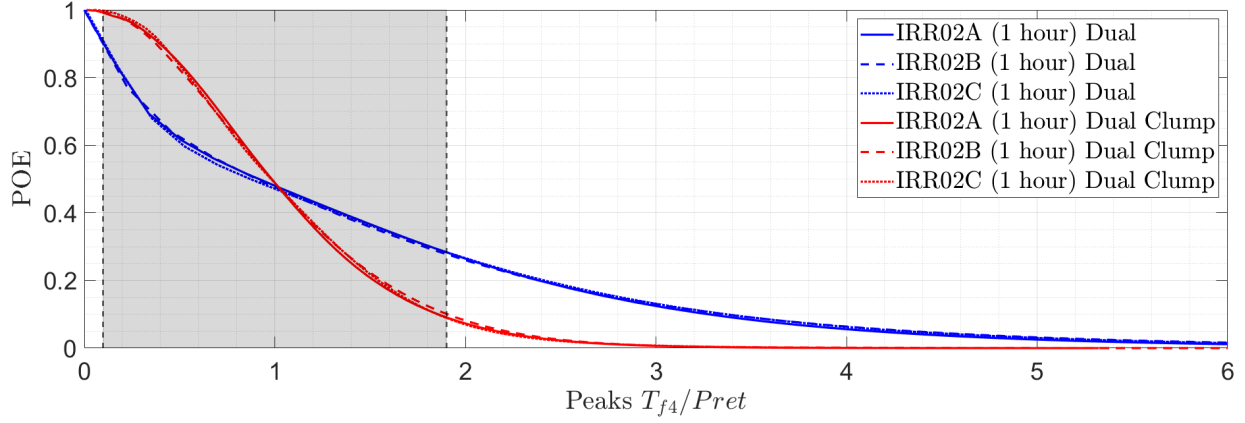


Figure 6.22: POE of the peaks of the time history of the shared line fairlead tensions T_{f4} for the extreme IRR02 wave case. $H_s = 12.7 \text{ m}$ and $T_p = 15.45 \text{ s}$.

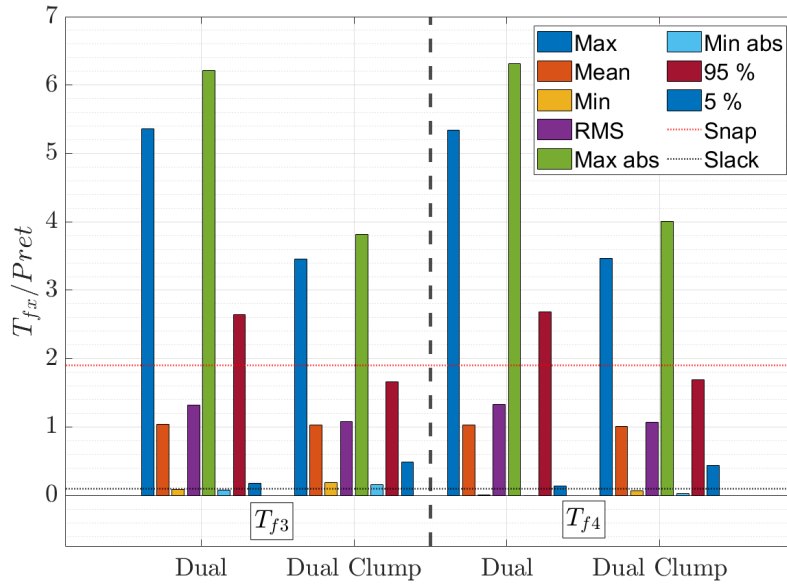


Figure 6.23: shared line fairlead tension statistics (normalized with the pretension) for the extreme sea state. IRR02 wave case. $H_s = 12.7 \text{ m}$ and $T_p = 15.45 \text{ s}$

to existing design guidelines [1, 30, 31]. An analysis of extreme mooring tension is performed based on the measured mooring tension. First, local tension maxima are identified according to the definition in the design standard DNV-OS-E301 [30] from the mooring tension time series and then fitted to a three-parameter (3-P) Weibull distribution:

$$F(T_{max}) = 1 - e^{-\left(\frac{T_{max}-\gamma}{\alpha}\right)^\beta} \quad (6.2)$$

where α , β , and γ are the scale, shape and position parameters, respectively. Quantile-Quantile plots (QQ-plots) are generated and presented for the fitted distributions as an example in

Fig. 6.24. For extreme value predictions, capturing the tail of the distribution function, i.e. the largest values, is of primary importance (Razola et al. [120]). As observed in the Q-Q plots, The 3-P Weibull distribution closely corresponds to the data, particularly in the upper tail, with relatively small discrepancies across the full range of tension values. This is an indication that could perform well for extreme value prediction. Therefore, the most probable maxima extreme (MPME) of mooring tension calculated based on the fitted distribution can be used as a statistical reference value [30, 94]:

$$T_{MPME} = \gamma + \alpha \left[-\ln \left(\frac{1}{N} \right) \right]^{\frac{1}{\beta}} \quad (6.3)$$

where N is the number of local tension maxima. For each case in the extreme condition, T_{MPME} is calculated for the mooring tension variables measured during the tests.

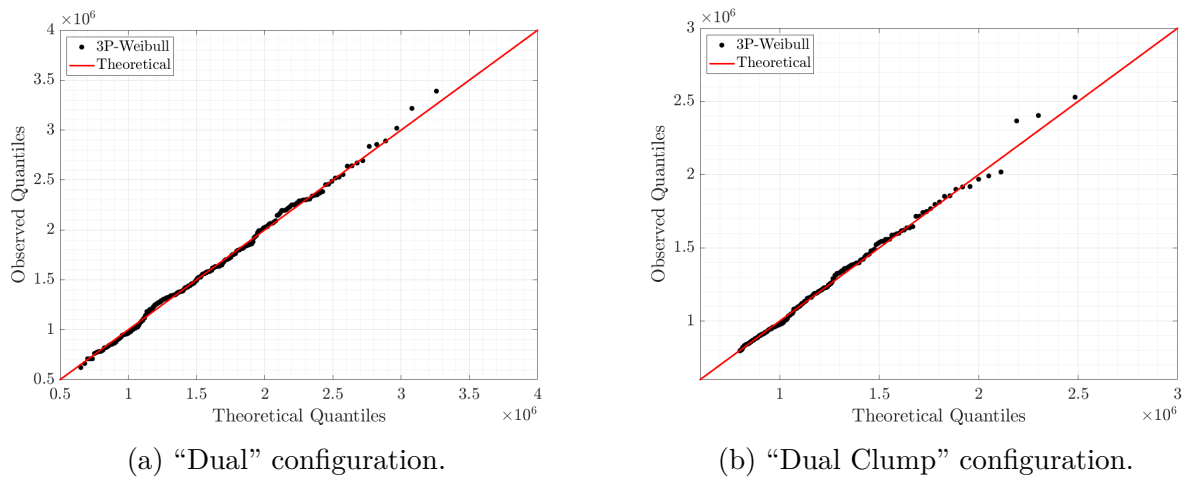


Figure 6.24: Quantile-Quantile (Q-Q) plots for the 3-P Weibull fitted distribution in mooring tension T_{f4} , extreme condition, IRR02A wave case. $H_s = 12.7$ m and $T_p = 15.45$ s.

As an example, Fig. 6.25 shows the probability of exceedance (POE) of local maxima in the fairlead tensions T_{f3} and T_{f4} in the (1-hr seed) extreme condition, Case IRR02A. The calculated T_{MPME} is also plotted in the figure. For the fairlead tensions in the shared line, the addition of the clump weight reduces the peak events in the time history and results in a considerable reduction in the POE for a given level of tension threshold; see Fig. 6.25. In addition, it is clearly observed that T_{MPME} is considerably reduced from “Dual” to “Dual Clump” configuration.

The average T_{MPME} of the three cases is presented in Table 6.7. As shown for both fairleads, by adding clump weight the extreme mooring tension in the shared line T_{f3} and T_{f4} decreases by 27% and 30%, respectively. Since the mooring properties of the shared line are the same for both shared mooring configurations, adding a clump weight can reduce the extreme mooring tension in the shared line and lead to a lower utilization factor, which means there is a possibility of cost reduction through a redesign of the shared line.

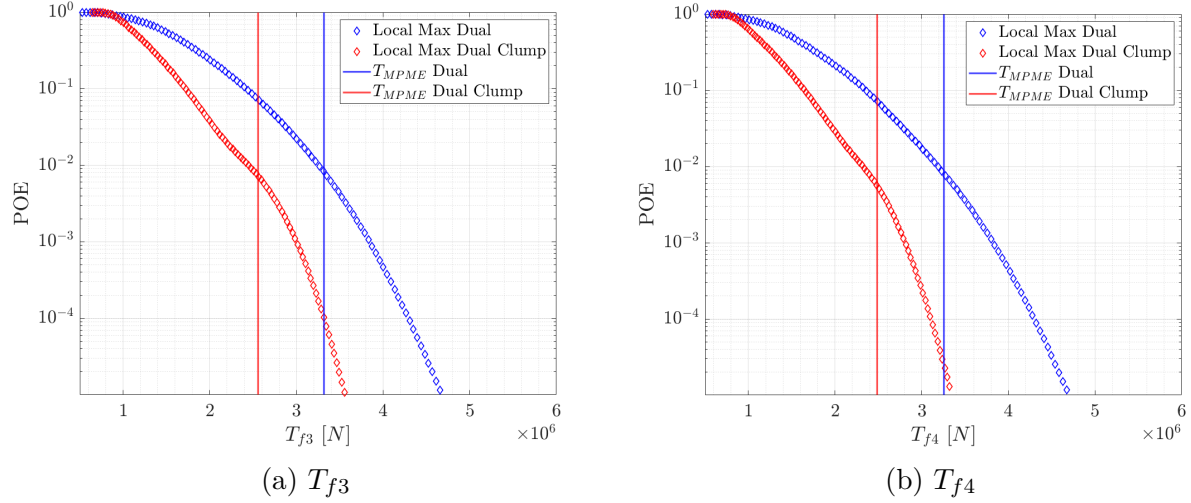


Figure 6.25: Comparison of estimated MPME of mooring tension in the two mooring configurations, extreme condition, IRR02A wave case. $H_s = 12.7$ m and $T_p = 15.45$ s.

Table 6.7: T_{MPME} for the two shared mooring configurations (averaged over three cases).

Configuration	T_{f3} [N]	T_{f4} [N]
Dual	3.48e6	3.40e6
Dual Clump	2.55e6	2.38e6

6.5 Concluding remarks

In this chapter, an experimental study was carried out that compared three mooring configurations for a floating wind turbine (FWT) and two floating wind farms (FWFs). The experiments included decay tests, irregular wave tests, white noise tests, and regular wave tests. The results from the tests include natural periods, damping ratios, response amplitude operators (RAOs) of motion and tension, motion and tension spectra, and statistical analysis of motions and tensions. The configurations analyzed in this chapter are a single-spar floating wind turbine with a catenary mooring system, a dual-spar floating wind farm with a shared mooring line, and a dual-spar floating wind farm with a shared mooring line incorporating a clump weight at its midpoint.

The shared mooring system can offer a potential cost-effective solution by reducing the number of anchors and mooring lines needed for multiple turbines. However, the complex multibody dynamics involved in shared mooring is yet to be fully understood. This study revealed the following implications when moving from a single moored FWT to a FWF with shared mooring.

- The surge natural period for the dual-spar configuration is increased by almost a 51% with respect of the single-spar configuration due to the reduced mooring stiffness with the shared line; while natural periods in heave and pitch show minimal changes between

the configurations, as these DOFs are hardly affected by the catenary mooring system.

- Larger surge motions and surge mean drift are observed for the dual-spar configuration compared to the single-spar configuration, attributed to the reduced mooring stiffness due to the shared line. As expected, heave and pitch motions are similar across the configurations, meeting the design criteria of a maximum surge offset of 10% of the water depth and a maximum pitch angle of 15° s.
- Anchor line tensions were similar between configurations, with no slack/snap events, while the shared line exhibited significant dominant dynamic tensions in the first-order wave frequency range and several slack/snap events.

When the clump weight is added in the shared line, considerable effects in the hydrodynamic response of the FWF are observed. This chapter aimed to provide comprehensive insight into the coupled dynamic performance of the shared configurations when the device is attached, hence, the key findings are as follows.

- The addition of a clump weight to the shared line reduced the surge natural period by 6.11%.
- Reduced low-frequency surge motions and dynamic tensions in both the anchor and shared lines are observed, leading to fewer slack/snap events and lower extreme tensions. The shared line extreme mooring tension decreased by up to 30%, and the number of snap events significantly reduced with the clump weight inclusion.
- However, the pretension in the anchor lines and the shared line are increased due to the clump weight. Potential need for redesigning the anchor lines if the original design does not have sufficient safety margins to accommodate the increased pretension.

The experimental results demonstrated the benefits and drawbacks of shared mooring systems for floating wind farms. Although shared moorings offer potential cost savings and reduced infrastructure, they also introduce challenges such as increased surge motions and susceptibility to slack/snap events. The inclusion of a clump weight mitigated some of these issues by reducing dynamic tensions, snap events, and large dynamic offsets, indicating its potential as an effective enhancement for shared mooring systems. Future research should explore combined environmental loading conditions (wind, waves, and currents) and further optimize shared mooring designs to improve their performance and reliability.

Chapter 7

Conclusions and future work

7.1 Conclusions

In this Ph.D. thesis, a comprehensive study of the dynamics of clump weights and their impact on the performance of floating wind turbines (FWTs) and floating wind farms (FWFs) is carried out. By integrating empirical analytical models, numerical simulations, and experimental validations, the problem is addressed across four different “zoom levels”, from the isolated clump weight itself to the complete FWF. This multi-scale approach ensures the findings are robust and applicable at various levels of complexity, providing a detailed understanding of the physical phenomena involved.

An extensive review of the state of the art regarding mooring systems for FWTs and FWFs is carried out at the beginning of this work. In this literature review, several research gaps, such as the need for numerical simulations of bluff bodies in a viscous fluid with transient impulsive starts, the need for numerical simulations of dynamic mooring line simulation codes that include additional devices in the line, the need for numerical simulations of floating wind turbines with additional devices in catenary mooring lines, the need of hydrodynamic experimental model test of shared mooring wind farms to validate numerical tools are identified, among others.

To address the research gaps found in the literature, in this work, an important number of numerical simulations have been performed. The strong level of experimental validation of these numerical simulations that have been carried out in this work should be underlined. The main achievements and contributions of this research are summarized as follows.

- Numerical simulations with the open-source CFD tool OpenFOAM were carried out to study the flow around an impulsively started scaled clump weight. The performance of the overset technique is evaluated and different turbulence modeling approaches are compared. The results were successfully validated with experiments in the CEHINAV towing tank proving the ability of this dynamic mesh technique in capturing the complex transient flow phenomena involved in impulsive starts. In addition, the results were also compared with a quasi-static empirical method to estimate the accuracy of the

hydrodynamics coefficients used to model the clump weights in dynamic mooring lines simulation codes.

- The additional devices like clump weights have been implemented in the OPASS code [2], a finite element numerical tool of dynamic mooring lines. Afterwards, the numerical results were successfully validated with experimental forced oscillations test of an isolated submerged chain that included clump weights at two different positions. In addition, the results were verified with another validated open-source computational tool that is widely used in the offshore industry, MoorDyn [49].
- Three mooring system configurations for a spar FWT that included clump weights were proposed, in which again, two different positions were chosen for the study. A set of numerical simulations with the open-source tool OpenFAST were carried out using MoorDyn as the dynamic mooring line code. The results were then validated with hydrodynamic model tests of the scaled FWT with a complete catenary mooring system.
- For the first time in the literature, hydrodynamic model test were carried out for a dual-spar FWF with a shared mooring to study the complex multibody dynamics present in this type of mooring arrangement. Two mooring arrangements to explore the contribution of the clump weight in a shared line were evaluated: a baseline shared mooring system and an alternative configuration that added a clump weight at the midpoint of the shared line.

Throughout this document, the inclusion of clump weights has been shown to have significant effects on the dynamics of the mooring lines and the overall performance of FWTs and FWFs. To summarize the key findings and real technical conclusions of this Ph.D. thesis, the following bullet points are included.

- At the smallest scale of the “zoom levels”, the hydrodynamic forces of the clump weight were analyzed with OpenFOAM using the overset moving mesh technique. Despite the computational challenges, the CFD tool proved to be effective in simulating the complex flow dynamics associated with impulsive starts of this bluff body. The sudden disruptions of boundary layers seen in unsteady transient flows at high Reynolds numbers were reasonably well captured showing good agreement with the experimental measurements. The quasi-static empirical model provided a reasonable approximation of the hydrodynamic forces, especially under steady-state conditions, although it was less accurate during the transient phases of impulsive starts and stops, where fluid inertia played a significant role. The use of hydrodynamic coefficients to model viscous drag and added mass may not be sufficient for this cases and might be benefit from further improvement. However, in practical engineering applications this mid-fidelity solution can be reasonably accepted.
- At the second scale of the “zoom levels”, the clump weight implementation in the OPASS dynamic mooring line code captured remarkably well the dynamic effects when compared with the experiments. In catenary lines, the viscous drag contribution of the clump weights to the line dynamics seems to be negligible, compared with the mass and inertia loads, being the primary contributions. When clump weights are included in

catenary mooring lines, the geometric stiffness increases if pretension is not maintained, enhancing energy dissipation particularly when placed further from the fairlead. This can potentially reduce surge motion but with the counterpart of increasing tension. In the other way around, when the pretension is maintained, the tensions are reduced because of the additional weight but with the counterpart of potentially increase surge motions. In addition, the different modeling approach adopted in the MoorDyn code also showed similar results for all the tested cases, proving to be an effective tool to be used in coupled simulation codes of FWT like OpenFAST when these additional devices are attached.

- At the third scale of the “zoom levels”, for the complete mooring system of a floating wind turbines, the inclusion of clump weights in the catenary lines modifies dynamic responses in extreme environmental conditions. A clear reduction in first-order wave mooring tensions is evident, which can potentially lower fatigue damage. While the motions with hydrostatic restoring remained practically unchanged with the clump weight inclusion, the motions in the horizontal plane were slightly augmented, specially in the low-frequency range, and can be attributed to the change in the mooring stiffness. Although no additional static tests were performed to estimate the stiffness changes in the system due to the inclusion of these additional devices, from the findings of the isolated mooring line it can be concluded that similar conclusions apply.
- At the fourth and last scale of the “zoom levels”, when moving from individual moored FWTs to a number of FWTs with a shared mooring system at a farm level, increased motions are observed in the horizontal plane due to the drastic reduction in the mooring stiffness. This phenomenon has the unwanted consequence of an increase in the mooring tensions, especially in the shared line produced by the coupled dynamics and relative motions of the platforms, together with the evidence of slack/snap events in the shared line. Inclusion of clump weights in the shared line has proven to be an effective solution to mitigate these effects. These devices that are included in the shared line reduce the motions in surge to significantly lower the impulsive tensions, improving overall performance and almost eliminating snap loads.

In summary, this work provides a thorough investigation into the use of clump weights in floating wind energy systems. The multi-scale approach, combining numerical, experimental, and empirical analytical methods, has led to significant advancements in understanding the dynamics, benefits, and counterparts of clump weights addition in the mooring lines. The practical implications for the offshore wind industry are significant. These new insights into clump weight dynamics can guide the design of more efficient mooring systems, reducing costs and improving performance. The enhanced validated numerical models can be used for better planning and operation of FWTs and FWFs, ensuring more accurate predictions and safer designs.

7.2 Future research lines

Despite the comprehensive approach with the different “zoom levels”, several aspects have not yet been exhausted, and further research in the future would be beneficial to better understand the influence of clump weights. In the following, each of these technical points and the possible future research lines are described separately.

- The numerical simulations to predict the hydrodynamics of a clump weight with an impulsive start are far from being exhausted. More computational fluid dynamics (CFD) studies with OpenFOAM, focusing on improving the results and comparison with the experiments can be carried out. Also, including a motion law with real clump weight motions when they are added to the line, are required for more precise modeling and proper force predictions in real industry applications. In addition, more experimental work to help enhance the theoretical model to improve the prediction of hydrodynamic forces of the clump weight is something worth investigating.
- The new capabilities included in the OPASS code can benefit from the extensive study of the hydrodynamics of the clump weight itself. Instead of modeling and simplifying the hydrodynamic forces of the clump weight, directly using the hydrodynamic forces from OpenFOAM in the code can potentially improve the mooring line dynamics. Further research on this matter can be addressed and validated with the same force oscillation experiments. Additionally, the capabilities of the OPASS code can be further extended by including bodies of any shape in the line with the proper forces modeling for each case.
- Although an extensive numerical and experimental study was performed for a FWT with different mooring systems that included clump weights, the conclusions of this Ph.D thesis can benefit from more analysis in the future. The experimental work can be further extended, especially to include static offsets test to fully understand how the stiffness of the catenary mooring system is changed due to the clump weight. More clump weight positions along the line and properties of the clump weight itself (like mass, volume and shape) can be explored. Lastly, fatigue calculations with the validated numerical model should also be performed in the future to fully understand the long-term impacts on mooring systems when clump weights are added.
- Experimental works for FWFs are required in the offshore industry, especially for the novel concept of shared mooring systems. To the author’s knowledge at the moment of the experiments carried out in part of this Ph.D. none model test were performed. However, further investigation and work is needed. Testing more wave headings, including wind in the experiments, perform static offsets test to fully understand the impact of the inclusion of the clump weight in the stiffness of the system and in the low-frequency response, more decay test and more sea states with different amplitudes and periods, are aspects worth of a detailed future study. In addition, extending the numerical simulations with OpenFAST of the single platform to the farm level using FAST.farm that can be validated with the carried out experiments will provide more insights into the complex multibody dynamics and the impact of the clump weight

addition in the shared line.

In general, the whole research of this Ph.D. thesis can benefit from an exhaustive cost analysis. Now that the technical benefits in terms of mooring tensions and overall performance of the FWT or FWF are determined, understanding how the inclusion of the clump weight in the mooring line impacts the overall cost of an offshore wind project is something worth investigating in detail.

Potential CAPEX reductions can be achieved by reducing the diameter of the mooring line thanks to the inclusion of a properly designed clump weight or a set of them. However, when additional devices are attached to the line, the connection parts and risk of line breaking increase, and with them the subsea inspections and maintenance. These OPEX costs can play an important role in the overall cost of an offshore wind project. Quantifying this cost balance between CAPEX and OPEX can be the next step of this research.

Bibliography

- [1] ABS. Guidance notes on global performance analysis for floating offshore wind turbines. *The American Bureau of Shipping, Houston (TX), USA*, 2020.
- [2] José Azcona, Xabier Munduate, Leo González, and Tor A Nygaard. Experimental validation of a dynamic mooring lines code with tension and motion measurements of a submerged chain. *Ocean Engineering*, 129:415–427, 2017.
- [3] José Azcona Armendáriz. *Computational and Experimental Modelling of Mooring Lines Dynamics for Offshore Floating Wind Turbines*. PhD thesis, Universidad Politécnica de Madrid, 2016.
- [4] Carlos Barrera, Raúl Guanche, and Iñigo J Losada. Experimental modelling of mooring systems for floating marine energy concepts. *Marine Structures*, 63:153–180, 2019.
- [5] Carlos Barrera, Raúl Guanche, Álvaro Rodríguez, José A Armesto, and Iñigo J Losada. On the importance of mooring system parametrisation for accurate floating structure designs. *Marine Structures*, 72:102765, 2020.
- [6] Rebecca Jane Barthelmie and LE Jensen. Evaluation of wind farm efficiency and wind turbine wakes at the nysted offshore wind farm. *Wind Energy*, 13(6):573–586, 2010.
- [7] Lars Bergdahl, Johannes Palm, Claes Eskilsson, and Jan Lindahl. Dynamically scaled model experiment of a mooring cable. *Journal of Marine Science and Engineering*, 4(1):5, 2016.
- [8] Roger Bouard and Madeleine Coutanceau. The early stage of development of the wake behind an impulsively started cylinder for $40 < \text{Re} < 104$. *Journal of Fluid Mechanics*, 101(3):583–607, 1980.
- [9] JR Browning, J Jonkman, A Robertson, and AJ Goupee. Calibration and validation of a spar-type floating offshore wind turbine model using the fast dynamic simulation tool. In *Journal of physics: conference series*, volume 555, page 012015. IOP Publishing, 2014.
- [10] Niccolo Bruschi, Giulio Ferri, Enzo Marino, and Claudio Borri. Influence of clumps-weighted moorings on a spar buoy offshore wind turbine. *Energies*, 13(23):6407, 2020.
- [11] Miguel Cabrerizo-Morales, Rafael Molina-Sanchez, and Luis Pérez-Rojas. Small-scale study of mooring line tension thresholds based on impulsive load analysis during big floating structure operation and commissioning. *Water*, 13(8):1056, 2021.

- [12] Qun Cao, Erin E Bachynski-Polić, Zhen Gao, Longfei Xiao, Zhengshun Cheng, and Mingyue Liu. Analysis of a hybrid mooring system concept for a semi-submersible wind turbine in intermediate water depth under operational, extreme, and yaw error conditions. In *International Conference on Offshore Mechanics and Arctic Engineering*, volume 85932, page V008T09A017. American Society of Mechanical Engineers, 2022.
- [13] Qun Cao, Zhengshun Cheng, Longfei Xiao, and Mingyue Liu. Dynamic analysis of three alternative mooring systems for a semi-submersible wind turbine in intermediate water depth. *Journal of Offshore Mechanics and Arctic Engineering*, pages 1–23, 2023.
- [14] Subrata Chakrabarti. *Handbook of Offshore Engineering (2-volume set)*. Elsevier, 2005.
- [15] Subrata Kumar Chakrabarti. *Offshore structure modeling*, volume 9. world scientific, 1994.
- [16] Dominic DJ Chandar. On overset interpolation strategies and conservation on unstructured grids in openfoam. *Computer Physics Communications*, 239:72–83, 2019.
- [17] Chien-Cheng Chang and Ruey-Ling Chern. A numerical study of flow around an impulsively started circular cylinder by a deterministic vortex method. *Journal of Fluid Mechanics*, 233:243–263, 1991.
- [18] Haifei Chen, Tanausú Almeida Medina, and Jose Luis Cercos-Pita. Cfd simulation of multiple moored floating structures using openfoam: An open-access mooring restraints library. *Ocean Engineering*, 303:117697, 2024.
- [19] Hao Chen, Ling Qian, Zhihua Ma, Wei Bai, Ye Li, Derek Causon, and Clive Mingham. Application of an overset mesh based numerical wave tank for modelling realistic free-surface hydrodynamic problems. *Ocean Engineering*, 176:97–117, 2019.
- [20] Lin Chen and Biswajit Basu. Development of an open-source simulation tool for mooring systems. In *Proceedings of the 2018 Civil Engineering Research in Ireland conference*, pages 823–828, 2018.
- [21] M Cheng, YT Chew, and SC Luo. A hybrid vortex method for flows over a bluff body. *International journal for numerical methods in fluids*, 24(3):253–274, 1997.
- [22] Rahul Chitteth Ramachandran, Cian Desmond, Frances Judge, Jorrit-Jan Serraris, and Jimmy Murphy. Floating wind turbines: marine operations challenges and opportunities. *Wind Energy Science*, 7(2):903–924, 2022.
- [23] European Commission. An eu strategy to harness the potential of offshore renewable energy for a climate neutral future. *European Commission: Brussels, Belgium*, 2020.
- [24] Patrick Connolly and Matthew Hall. Comparison of pilot-scale floating offshore wind farms with shared moorings. *Ocean Engineering*, 171:172–180, 2019.
- [25] Madeleine Coutanceau and Roger Bouard. Experimental determination of the main features of the viscous flow in the wake of a circular cylinder in uniform translation. part 1. steady flow. *Journal of Fluid Mechanics*, 79(2):231–256, 1977.

-
- [26] Madeleine Coutanceau and Roger Bouard. Experimental determination of the main features of the viscous flow in the wake of a circular cylinder in uniform translation. part 2. unsteady flow. *Journal of Fluid Mechanics*, 79(2):257–272, 1977.
- [27] L Crudu, DC Obreja, and O Marcu. Moored offshore structures-evaluation of forces in elastic mooring lines. In *IOP Conference Series: Materials Science and Engineering*, volume 147, page 012096. IOP Publishing, 2016.
- [28] Arturo De la Escalera and Jose María Armingol. Automatic chessboard detection for intrinsic and extrinsic camera parameter calibration. *Sensors*, 10(3):2027–2044, 2010.
- [29] DNV. DNV-RP-H103: modelling and analysis of marine operations. *Det Norske Veritas, Høvik, Norway*, 2011.
- [30] DNV. Offshore standard DNV-OS-E301, Position mooring. Høvik, Norway, 2015.
- [31] DNV. Recommended Practice DNV-RP-0286, Coupled Analysis of Floating Wind Turbines. Høvik, Norway, 2019.
- [32] DNV. DNV-ST-0119 Floating wind turbine structures. Oslo, Norway, 2021.
- [33] Bureau Veritas DNV. Nr 493 r02 e. *Classification of Mooring Systems for Permanent Offshore Units*, 583, 2002.
- [34] DNV GL. MIMOSA-User’s Documentation Programme Version 5.7. Høvik, Norway, 2003.
- [35] Fei Duan, Zhiqiang Hu, and JM Niedzwecki. Model test investigation of a spar floating wind turbine. *Marine Structures*, 49:76–96, 2016.
- [36] Alexandre Dupuis, Philippe Chatelain, and Petros Koumoutsakos. An immersed boundary–lattice-boltzmann method for the simulation of the flow past an impulsively started cylinder. *Journal of Computational Physics*, 227(9):4486–4498, 2008.
- [37] Emma C Edwards, Anna Holcombe, Scott Brown, Edward Ransley, Martyn Hann, and Deborah Greaves. Evolution of floating offshore wind platforms: A review of at-sea devices. *Renewable and Sustainable Energy Reviews*, 183:113416, 2023.
- [38] Equinor. Hywind Tampen: The World’s First Renewable Power for Offshore Oil and Gas. <https://www.equinor.com/energy/hywind-tampen>, 2019. [Online; accessed 12-October-2022].
- [39] Odd Faltinsen. *Sea loads on ships and offshore structures*, volume 1. Cambridge university press, 1993.
- [40] Oscar Festa, Susan Gourvenec, and Adam Sobey. Comparative analysis of load reduction device stiffness curves for floating offshore wind moorings. *Ocean Engineering*, 298: 117266, 2024.
- [41] Joshua S Furtado, Hugh HT Liu, Gilbert Lai, Herve Lacheray, and Jason Desouza-Coelho. Comparative analysis of optitrack motion capture systems. In *Advances in Motion Sensing and Control for Robotic Applications: Selected Papers from the Symposium on*

- Mechatronics, Robotics, and Control (SMRC'18)-CSME International Congress 2018, May 27-30, 2018 Toronto, Canada*, pages 15–31. Springer, 2019.
- [42] Xifeng Gao, Xiaoyong Liu, Xutian Xue, and Nian-Zhong Chen. Fracture mechanics-based mooring system fatigue analysis for a spar-based floating offshore wind turbine. *Ocean Engineering*, 223:108618, 2021.
 - [43] Marek Goldschmidt and Michael Muskulus. Coupled mooring systems for floating wind farms. *Energy Procedia*, 80:255–262, 2015.
 - [44] Rui PF Gomes, Luís MC Gato, João CC Henriques, Juan CC Portillo, Ben D Howey, Keri M Collins, Martyn R Hann, and Deborah M Greaves. Compact floating wave energy converters arrays: Mooring loads and survivability through scale physical modelling. *Applied Energy*, 280:115982, 2020.
 - [45] Andrew J. Goupee, Bonjun J. Koo, Richard W. Kimball, Kostas F. Lambrakos, and Habib J. Dagher. Experimental Comparison of Three Floating Wind Turbine Concepts. *Journal of Offshore Mechanics and Arctic Engineering*, 136(2), 03 2014. ISSN 0892-7219. 020906.
 - [46] José E Gutiérrez-Romero, Julio García-Espinosa, Borja Serván-Camas, and Blas Zamora-Parra. Non-linear dynamic analysis of the response of moored floating structures. *Marine Structures*, 49:116–137, 2016.
 - [47] Matthew Hall. Moordyn v2: New capabilities in mooring system components and load cases. In *International Conference on Offshore Mechanics and Arctic Engineering*, volume 84416, page V009T09A078. American Society of Mechanical Engineers, 2020.
 - [48] Matthew Hall and Patrick Connolly. Coupled dynamics modelling of a floating wind farm with shared mooring lines. In *International Conference on Offshore Mechanics and Arctic Engineering*, volume 51319, page V010T09A087. American Society of Mechanical Engineers, 2018.
 - [49] Matthew Hall and Andrew Goupee. Validation of a lumped-mass mooring line model with deepcwind semisubmersible model test data. *Ocean Engineering*, 104:590–603, 2015.
 - [50] Yuda Apri Hermawan and Yoshitaka Furukawa. Coupled three-dimensional dynamics model of multi-component mooring line for motion analysis of floating offshore structure. *Ocean Engineering*, 200:106928, 2020.
 - [51] Tobias Holzmann. Mathematics, numerics, derivations and OpenFOAM®. *Loeben, Germany: Holzmann CFD*, 2016.
 - [52] Wei-ting Hsu, Krish P Thiagarajan, Matthew Hall, Michael MacNicoll, and Richard Akers. Snap loads on mooring lines of a floating offshore wind turbine structure. In *ASME 2014 33rd International Conference on Ocean, Offshore and Arctic Engineering*. American Society of Mechanical Engineers Digital Collection, 2014.
 - [53] Wei-ting Hsu, Krish P Thiagarajan, Michael MacNicoll, and Richard Akers. Prediction of extreme tensions in mooring lines of a floating offshore wind turbine in a 100-year

- storm. In *International Conference on Offshore Mechanics and Arctic Engineering*, volume 56574, page V009T09A050. American Society of Mechanical Engineers, 2015.
- [54] Wei-ting Hsu, Krish P Thiagarajan, and Lance Manuel. Extreme mooring tensions due to snap loads on a floating offshore wind turbine system. *Marine Structures*, 55:182–199, 2017.
- [55] Wen-Yang Hsu, Tzu-Ching Chuang, Ray-Yeng Yang, Wei-Ting Hsu, and Krish P Thiagarajan. An experimental study of mooring line damping and snap load in shallow water. *Journal of Offshore Mechanics and Arctic Engineering*, 141(5), 2019.
- [56] E Huse. Influence of mooring line damping upon rig motions. In *Offshore Technology Conference*. OnePetro, 1986.
- [57] IEA. World energy outlook 2022. IEA Paris, France, 2022.
- [58] IEC. 61400-3-1. wind energy generation systems part 3-1: Design requirements for fixed offshore wind turbines. *IEC 61400-3-Ed. 1.0*, 2019.
- [59] M Ikhennicheu, M Lynch, S Doole, F Borisade, D Matha, J.L. Dominguez, R.D. Vicente, H Tim, L Ramirez, S Potestio, C Molins, and P Trubat. *Review of the state of the art of mooring and anchoring designs, technical challenges and identification of relevant DLCs*. Corewind, 2021.
- [60] ITTC. Recommended procedures and guidelines: Seakeeping experiments, 2017.
- [61] ITTC. Recommended procedures and guidelines: Model tests for offshore wind turbines, 2017.
- [62] ITTC. Recommended procedures and guidelines: Floating offshore platform experiments, 2017.
- [63] ITTC. Recommended procedures and guidelines: Analysis procedure for model tests in regular waves, 2017.
- [64] Ha-Kun Jang, Sewan Park, Moo-Hyun Kim, Kyong-Hwan Kim, and Keyyong Hong. Effects of heave plates on the global performance of a multi-unit floating offshore wind turbine. *Renewable energy*, 134:526–537, 2019.
- [65] Chunyan Ji and Zhiming Yuan. Experimental study of a hybrid mooring system. *Journal of Marine Science and Technology*, 20(2):213–225, 2015.
- [66] Z Jiang, G Liang, T Lopez-Olocco, A Medina-Manuel, LA Saavedra-Ynocente, and A Souto-Iglesias. Model test of a dual-spar floating wind farm in regular waves. In *Advances in the Analysis and Design of Marine Structures*, pages 171–177. CRC Press, 2023.
- [67] Zhiyu Jiang, Madjid Karimirad, and Torgeir Moan. Response analysis of parked spar-type wind turbine considering blade-pitch mechanism fault. *International Journal of Offshore and Polar Engineering*, 23(02), 2013.

- [68] Jason Jonkman. Definition of the Floating System for Phase IV of OC3. Technical Report NREL/TP-500-47535, National Renewable Energy Lab.(NREL), Golden, CO (United States), 2010.
- [69] Jason Jonkman, Sandy Butterfield, Walter Musial, and George Scott. Definition of a 5-MW reference wind turbine for offshore system development. Technical Report NREL/TP-500-38060, National Renewable Energy Lab.(NREL), Golden, CO (United States), 2009.
- [70] Jason M Jonkman, AN Robertson, and Greg J Hayman. Hydrodyn user’s guide and theory manual. *National Renewable Energy Laboratory*, 2014.
- [71] Jason Mark Jonkman. *Dynamics modeling and loads analysis of an offshore floating wind turbine*. University of Colorado at Boulder, 2007.
- [72] Johan MJ Journée and WW Massie. *Offshore hydromechanics*, volume 1. Delft University of Technology Delft, 2001.
- [73] Mun Seung Jung and Oh Joon Kwon. A parallel unstructured overset mesh technique for unsteady flow simulations. In *Computational Fluid Dynamics 2006: Proceedings of the Fourth International Conference on Computational Fluid Dynamics, ICCFD, Ghent, Belgium, 10-14 July 2006*, pages 317–322. Springer, 2009.
- [74] Eirini Katsidoniotaki and Malin Göteman. Numerical modeling of extreme wave interaction with point-absorber using openfoam. *Ocean Engineering*, 245:110268, 2022.
- [75] Neil Kitney and David T Brown. Experimental investigation of mooring line loading using large and small-scale models. *J. Offshore Mech. Arct. Eng.*, 123(1):1–9, 2001.
- [76] Bonjun J Koo, Andrew J Goupee, Richard W Kimball, and Kostas F Lambrakos. Model tests for a floating wind turbine on three different floaters. *Journal of Offshore Mechanics and Arctic Engineering*, 136(2), 2014.
- [77] Petros Koumoutsakos and A Leonard. High-resolution simulations of the flow around an impulsively started cylinder using vortex methods. *Journal of Fluid Mechanics*, 296: 1–38, 1995.
- [78] Sébastien Lemaire, Guilherme Vaz, Menno Deij van Rijswijk, and Stephen R Turnock. Influence of interpolation scheme on the accuracy of overset method for computing rudder-propeller interaction. *Journal of Verification, Validation and Uncertainty Quantification*, 8(1):011002, 2023.
- [79] Lin Li, Zhen Gao, and Torgeir Moan. Joint distribution of environmental condition at five European offshore sites for design of combined wind and wave energy devices. *Journal of Offshore Mechanics and Arctic Engineering*, 137(3), 2015.
- [80] Yanbing Li, Richard Shock, Raoyang Zhang, and Hudong Chen. Numerical study of flow past an impulsively started cylinder by the lattice-boltzmann method. *Journal of Fluid Mechanics*, 519:273–300, 2004.
- [81] Yilun Li, Shuangxi Guo, Weimin Chen, Dingbang Yan, and Jixiang Song. Analysis on

- restoring stiffness and its hysteresis behavior of slender catenary mooring-line. *Ocean Engineering*, 209:107521, 2020.
- [82] Guodong Liang, Karl Merz, and Zhiyu Jiang. Modeling of a shared mooring system for a dual-spar configuration. In *International Conference on Offshore Mechanics and Arctic Engineering*, volume 9: Ocean Renewable Energy. American Society of Mechanical Engineers, 2020.
 - [83] Guodong Liang, Zhiyu Jiang, and Karl Merz. Mooring analysis of a dual-spar floating wind farm with a shared line. *Journal of Offshore Mechanics and Arctic Engineering*, 143(6):062003, 2021.
 - [84] Guodong Liang, Zhiyu Jiang, and Karl Merz. Influence of aerodynamic loads on a dual-spar floating offshore wind farm with a shared line in parked conditions. In *International Conference on Offshore Mechanics and Arctic Engineering*. American Society of Mechanical Engineers, 2022.
 - [85] Guodong Liang, Zhiyu Jiang, and Karl Merz. Dynamic analysis of a dual-spar floating offshore wind farm with shared moorings in extreme environmental conditions. *Marine Structures*, 90:103441, 2023.
 - [86] Guodong Liang, Tomas Lopez-Olocco, Antonio Medina-Manuel, Leandro Antonio Saavedra-Ynocente, Antonio Souto-Iglesias, and Zhiyu Jiang. Experimental investigation of two shared mooring configurations for a dual-spar floating offshore wind farm in irregular waves. *Marine Structures*, 95:103579, 2024. ISSN 0951-8339. doi: <https://doi.org/10.1016/j.marstruc.2024.103579>. URL <https://www.sciencedirect.com/science/article/pii/S0951833924000078>.
 - [87] Guodong Liang, Finn-Christian Wickmann Hanssen, Karl Otto Merz, and Zhiyu Jiang. Numerical analysis of a tethered-buoy mooring system for a prototype floating wind farm. *Wind Energy*, 2024.
 - [88] Zhenqing Liu, Yuangang Tu, Wei Wang, and Guowei Qian. Numerical analysis of a catenary mooring system attached by clump masses for improving the wave-resistance ability of a spar buoy-type floating offshore wind turbine. *Applied Sciences*, 9(6):1075, 2019.
 - [89] Tomas Lopez-Olocco, Leo M González-Gutiérrez, Javier Calderon-Sanchez, Adolfo Marón Loureiro, Leandro Saavedra Ynocente, Ana Bezunartea Barrio, and Nicolás Vivar Valdés. Experimental and numerical study of the influence of clumped weights on a scaled mooring line. *Journal of Marine Science and Engineering*, 10(5):676, 2022.
 - [90] Tomas Lopez-Olocco, Guodong Liang, Antonio Medina-Manuel, Leandro Saavedra Ynocente, Zhiyu Jiang, and Antonio Souto-Iglesias. Experimental comparison of a dual-spar floating wind farm with shared mooring against a single floating wind turbine under wave conditions. *Engineering Structures*, 292:116475, 2023.
 - [91] Tomas Lopez-Olocco, Leo M. González Gutiérrez, and Krish Thiagarajan. Validation of a mooring system with clump weights for a spar floating wind turbine model using

- openfast. in *43th International Conference on Ocean, Offshore & Arctic Engineering*, singapore expo, singapore. Submitted for publication, 2024.
- [92] Ericka Lozon and Matthew Hall. Coupled loads analysis of a novel shared-mooring floating wind farm. *Applied Energy*, 332:120513, 2023.
 - [93] Ericka Lozon, Matthew Hall, Paul McEvoy, Seojin Kim, and Bradley Ling. Design and analysis of a floating-wind shallow-water mooring system featuring polymer springs. In *International Conference on Offshore Mechanics and Arctic Engineering*, volume 86618, page V001T01A012. American Society of Mechanical Engineers, 2022.
 - [94] Yan Jenny Lu, Youl-Nan Chen, Pao-Lin Tan, and Yong Bai. Prediction of most probable extreme values for jackup dynamic analysis. *Marine Structures*, 15(1):15–34, 2002.
 - [95] Y Luo. Optimum design of clump weights for offshore mooring systems. In *The Second International Offshore and Polar Engineering Conference*. OnePetro, 1992.
 - [96] James F Manwell, Jon G McGowan, and Anthony L Rogers. *Wind energy explained: theory, design and application*. John Wiley & Sons, 2010.
 - [97] TFI Marine. Close-up view of seasprings in a mooring line, 2022. <https://www.openaccessgovernment.org/article/sustainable-marine-technologies-and-innovation-tfi-seasprings/172130/> [Accessed: June 5th 2024].
 - [98] Marco Masciola, Amy Robertson, Jason Jonkman, Alexander Coulling, Andrew Goupee, et al. Assessment of the importance of mooring dynamics on the global response of the deepcwind floating semisubmersible offshore wind turbine. In *The Twenty-third International Offshore and Polar Engineering Conference*. International Society of Offshore and Polar Engineers, 2013.
 - [99] Antonio Medina-Manuel, Elkin Botia-Vera, Simone Saettone, Javier Calderon-Sanchez, Gabriele Bulian, and Antonio Souto-Iglesias. Hydrodynamic coefficients from forced and decay heave motion tests of a scaled model of a column of a floating wind turbine equipped with a heave plate. *Ocean Engineering*, 252:110985, 2022. ISSN 0029-8018.
 - [100] Long Meng, Yan-ping He, Yong-sheng Zhao, Jie Yang, He Yang, Zhao-long Han, Long Yu, Wen-gang Mao, and Wei-kang Du. Dynamic response of 6mw spar type floating offshore wind turbine by experiment and numerical analyses. *China Ocean Engineering*, 34(5):608–620, 2020.
 - [101] Florian R Menter. Improved two-equation k-omega turbulence models for aerodynamic flows. Technical report, 1992.
 - [102] JR Morison, JW Johnson, and SA Schaaf. The force exerted by surface waves on piles. *Journal of Petroleum Technology*, 2(05):149–154, 1950.
 - [103] Hammad Munir, Chern Fong Lee, and Muk Chen Ong. Global analysis of floating offshore wind turbines with shared mooring system. In *IOP Conference Series: Materials Science and Engineering*, volume 1201, page 012024. IOP Publishing, 2021.

- [104] Walter Musial, Paul Spitsen, Patrick Duffy, Philipp Beiter, Matt Shields, Daniel Mulas Hernando, Rob Hammond, Melinda Marquis, Jennifer King, and Sriharan Sathish. Offshore wind market report: 2023 edition. Technical report, National Renewable Energy Laboratory (NREL), Golden, CO (United States), 2023.
- [105] Abhinav Muta and Prabhu Ramachandran. Efficient and accurate adaptive resolution for weakly-compressible sph. *Computer Methods in Applied Mechanics and Engineering*, 395:115019, 2022.
- [106] Anders Myhr, Karl Jacob Maus, and Tor Anders Nygaard. Experimental and computational comparisons of the OC3-HYWIND and Tension-Leg-Buoy (TLB) floating wind turbine conceptual designs. In *The Twenty-first International Offshore and Polar Engineering Conference*. OnePetro, 2011.
- [107] Anders Myhr, Catho Bjerkseter, Anders Ågotnes, and Tor A Nygaard. Levelised cost of energy for offshore floating wind turbines in a life cycle perspective. *Renewable energy*, 66:714–728, 2014.
- [108] Toshio Nakajima, Seizo Matora, and Masataka Fujino. On the dynamic analysis of multi-component mooring lines. In *Offshore Technology Conference*. OnePetro, 1982.
- [109] Finn Gunnar Nielsen, Tor David Hanson, and Bjørn Skaare. Integrated dynamic analysis of floating offshore wind turbines. In *International conference on offshore mechanics and arctic engineering*, volume 47462, pages 671–679, 2006.
- [110] National Renewable Energy Laboratory (NREL). Openfast online documentation, 2023. URL <https://openfast.readthedocs.io/en/main/>.
- [111] Manual OrcaFlex. Version 9.8 b. *Orcina Ltd*, 2014.
- [112] Kirk T Patton. An experimental determination of hydrodynamic masses and mechanical impedances. Technical report, NAVY UNDERWATER SOUND LAB NEW LONDON CT, 1965.
- [113] Brandon T Pereyra, Zhiyu Jiang, Zhen Gao, Morten T Andersen, and Henrik Stiesdal. Parametric study of a counter weight suspension system for the tetraspar floating wind turbine. In *International Conference on Offshore Mechanics and Arctic Engineering*, volume 51975, page V001T01A003. American Society of Mechanical Engineers, 2018.
- [114] Romain Pinguet, Sam Kanner, Michel Benoit, and Bernard Molin. Validation of open-source overset mesh method using free-decay tests of floating offshore wind turbine. In *ISOPE International Ocean and Polar Engineering Conference*, pages ISOPE–I. ISOPE, 2020.
- [115] P Ploumhans and GS1807293 Winckelmans. Vortex methods for high-resolution simulations of viscous flow past bluff bodies of general geometry. *Journal of Computational Physics*, 165(2):354–406, 2000.
- [116] Dongsheng Qiao and Jinping Ou. Mooring line damping estimation for a floating wind turbine. *The Scientific World Journal*, 2014, 2014.

- [117] Dongsheng Qiao, Jun Yan, Haizhi Liang, Dezhi Ning, Binbin Li, and Jinping Ou. Analysis on snap load characteristics of mooring line in slack-taut process. *Ocean Engineering*, 196:106807, 2020.
- [118] GKV Ramachandran, Amy Robertson, JM Jonkman, and Marco D Masciola. Investigation of response amplitude operators for floating offshore wind turbines. In *The Twenty-third International Offshore and Polar Engineering Conference*. OnePetro, 2013.
- [119] L. Ramírez, D. Fraile, and G. Brindley. Offshore wind in europe – key trends and statistics 2020, 2020. URL <https://windeurope.org/intelligence-platform/product/offshore-wind-in-europe-key-trends-and-statistics-2020/>.
- [120] Mikael Razola, Katrin Olausson, Karl Garne, and Anders Rosén. On high-speed craft acceleration statistics. *Ocean Engineering*, 114:115–133, 2016.
- [121] Amy Robertson, Jason Jonkman, Marco Masciola, H Song, Andrew Goupee, Alexander Coulling, and C Luan. Definition of the semisubmersible floating system for phase ii of oc4. Technical report, National Renewable Energy Lab.(NREL), Golden, CO (United States), 2014.
- [122] Emanuele Rossi, Andrea Colagrossi, Benjamin Bouscasse, and Giorgio Graziani. The diffused vortex hydrodynamics method. *Communications in Computational Physics*, 18(2):351–379, 2015.
- [123] Sara Russo, Pasquale Contestabile, Andrea Bardazzi, Elisa Leone, Gregorio Iglesias, Giuseppe R Tomasicchio, and Diego Vicinanza. Dynamic loads and response of a spar buoy wind turbine with pitch-controlled rotating blades: An experimental study. *Energies*, 14(12):3598, 2021.
- [124] AA Shah, A Umar, and NA Siddiqui. A methodology for assessing the reliability of taut and slack mooring systems against instability. *Ocean engineering*, 32(10):1216–1234, 2005.
- [125] Zhirong Shen, Decheng Wan, and Pablo M Carrica. Dynamic overset grids in openfoam with application to kcs self-propulsion and maneuvering. *Ocean Engineering*, 108: 287–306, 2015.
- [126] SINTEF Ocean. RIFLEX 4.16.0 User Guide. Trondheim, Norway, 2019.
- [127] SINTEF Ocean. SIMO 4.16.0 User Guide. Trondheim, Norway, 2019.
- [128] Bjørn Skaare, Finn Gunnar Nielsen, Tor David Hanson, Rune Yttervik, Ole Havmøller, and Arne Rekdal. Analysis of measurements and simulations from the hywind demo floating wind turbine. *Wind Energy*, 18(6):1105–1122, 2015.
- [129] Christine Sloan, Matthew Hall, Stein Housner, Ericka Lozon, and Senu Sirnivas. Shared Mooring Systems for Deep-Water Floating Wind Farms. Technical Report NYSERDA Contract 142869, National Renewable Energy Lab.(NREL), Golden, CO (United States), 2022.
- [130] Gordon M Stewart, Matthew A Lackner, Amy Robertson, Jason Jonkman, and Andrew J

- Goupee. Calibration and validation of a fast floating wind turbine model of the deepcwind scaled tension-leg platform. In *ISOPE International Ocean and Polar Engineering Conference*, pages ISOPE–I. ISOPE, 2012.
- [131] Longbin Tao and Daniel Dray. Hydrodynamic performance of solid and porous heave plates. *Ocean engineering*, 35(10):1006–1014, 2008.
- [132] Giuseppe Roberto Tomasicchio, Felice D’Alessandro, Alberto Maria Avossa, Luigia Riefolo, Elena Musci, Francesco Ricciardelli, and Diego Vicinanza. Experimental modelling of the dynamic behaviour of a spar buoy wind turbine. *Renewable energy*, 127:412–432, 2018.
- [133] Nelson Tonui and David Sumner. Flow around impulsively started square prisms. *Journal of fluids and structures*, 27(1):62–75, 2011.
- [134] Tomoaki Utsunomiya, Tomoki Sato, Hidekazu Matsukuma, and Kiyokazu Yago. Experimental validation for motion of a spar-type floating offshore wind turbine using 1/22.5 scale model. In *International Conference on Offshore Mechanics and Arctic Engineering*, volume 43444, pages 951–959, 2009.
- [135] Jianhua Wang, Lu Zou, and Decheng Wan. Numerical simulations of zigzag maneuver of free running ship in waves by rans-overset grid method. *Ocean Engineering*, 162: 55–79, 2018.
- [136] William C Webster. Mooring-induced damping. *Ocean Engineering*, 22(6):571–591, 1995.
- [137] World Offshore Wind Forum WFO. Global offshore wind report 2023. Technical report, WFO, World Offshore Wind Forum, 2024.
- [138] Frank M White. *Fluid mechanics*. Tata McGraw-Hill Education, 1979.
- [139] Samuel Wilson, Matthew Hall, Stein Housner, and Senu Sirnivas. Linearized modeling and optimization of shared mooring systems. *Ocean Engineering*, 241:110009, 2021.
- [140] Xue Xu and Sandy Day. Experimental investigation on dynamic responses of a spar-type offshore floating wind turbine and its mooring system behaviour. *Ocean Engineering*, 236:109488, 2021.
- [141] Zhengqiang Xu and Shan Huang. Numerical investigation of mooring line damping and the drag coefficients of studless chain links. *Journal of Marine Science and Application*, 13:76–84, 2014.
- [142] Jun Yan, Dongsheng Qiao, Binbin Li, Bin Wang, Haizhi Liang, Dezhi Ning, and Jinping Ou. An improved method of mooring damping estimation considering mooring line segments contribution. *Ocean Engineering*, 239:109887, 2021.
- [143] Jie Yang, Yan-Ping He, Yong-Sheng Zhao, Yan-Lin Shao, and Zhao-Long Han. Experimental and numerical studies on the low-frequency responses of a spar-type floating offshore wind turbine. *Ocean Engineering*, 222:108571, 2021.

- [144] Haixuan Ye and Decheng Wan. Benchmark computations for flows around a stationary cylinder with high reynolds numbers by rans-overset grid approach. *Applied Ocean Research*, 65:315–326, 2017.
- [145] Momchilo M Zdravkovich. Flow around circular cylinders; vol. i fundamentals. *Journal of Fluid Mechanics*, 350(1):377–378, 1997.