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Assessing the influence of nonlinear mooring restoring forces in the optimization and design of FOWT

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Abstract. The design of mooring systems plays a pivotal role in the success of Floating Offshore Wind Turbine (FOWT) projects. This process naturally involves iterations, as design and analysis are intricately linked. Despite the inherent nonlinearity of mooring system restoring forces, many designers opt for employing an equivalent linear mooring system stiffness matrix to expedite the optimization process in early design stages. This article aims to underscore the limitations associated with relying on the equivalent linear model when compared to accounting for nonlinear restoring forces during optimization processes. To illustrate this point, a case study was conducted using the reference semi-submersible platform VolturnUS-S. The study considered intermediate to large water depths and addressed three different mooring configurations: catenary, semi-taut, and taut lines. The analysis focused on several critical aspects, including offset watch circles, line tensions (including those at the anchors), and a cost estimate based on the different models. The findings indicate that, for catenary-based mooring systems, the linear model remains a good approximation, leading to no significant loss of accuracy in the context of early design stages. As the lines become tauter, however, the nonlinearities become more pronounced and the errors involved in the linear model can reach unacceptable levels.

Keywords: Floating Offshore Wind Turbine FOWT, Mooring System Optimization, Nonlinear Modeling, Deep-water conditions

1. Introduction

In the field of Floating Offshore Wind Turbines (FOWTs), initial design stages frequently rely on equivalent linear stiffness models, a practice that overlooks the fundamentally nonlinear nature of mooring systems. This reliance may lead to a significant misrepresentation of mooring restoring forces, creating a gap in the accurate optimization of mooring lines. Such oversimplification adversely affects the performance and cost-efficiency of the mooring system.

This paper aims to highlight the limitations inherent in using equivalent linear models for FOWT optimization. It builds upon a previous work, see Mas-Soler et al. (2022), which focused on optimizing FOWTs for powering an Oil & Gas unit under Brazilian deep and ultra-deep water conditions (500 – 2000m), utilizing an equivalent linear stiffness model for the mooring system. Despite the valuable insights gained, the previous study left open questions about the impact of linear modeling on the optimization outcomes of the mooring system.

In response, the present study conducts an optimization of various mooring systems across different water depths, with a predetermined anchor radius and three different mooring line configurations (i.e. catenary, semi-taut and taut leg), to thoroughly evaluate the response of mooring systems. This effort includes a detailed comparison between linear and nonlinear mooring models, particularly examining offsets and anchor tensions, to assess the effectiveness of linear models in accurately depicting the behavior of FOWT mooring systems.

Contributing to the broader discourse on FOWT optimization, this article highlights the early-stage design challenges when equivalent linear stiffness models are often used despite the nonlinear nature of mooring systems. Leveraging the prior study's focus on FOWT optimization in deep Brazilian waters (Mas-Soler et al., 2022), it extends the investigation to a more nuanced analysis of mooring systems' optimization.

2. State-of-the-art

This section explores the optimization frameworks that have increasingly become a cornerstone in the modeling and design process of FOWTs, aiming to address the technical challenges associated to the unique interactions between the system, wind, and waves. Recent literature (Tracy, 2007; Birk, 2009; Gilloteaux and Bozonnet, 2014; Uzunoglu and Soares, 2019) has made substantial contributions toward this goal, advancing the development of optimization processes tailored for FOWT systems.

Hall et al. (2013) pursued the optimization of hull and mooring systems for diverse FOWT concepts through both single and multi-objective optimization processes. Their findings revealed that the Pareto Frontier (PF) is populated with concepts characterized by intricate geometries. This research topic was further extended by Karimi et al. (2017), who refined the model and optimization framework, focusing on minimizing system costs influenced by structural masses and mooring characteristics. These studies leveraged the Multi-Niche Crowding Genetic Algorithm strategy (Cedeño, 1995), ensuring a diverse concept population over generations and avoiding premature local minima convergence.

Notably, prior studies on FOWT design optimization have encountered limitations in assessing the coupled dynamics of hull-mooring systems. With turbines growing larger and suitable offshore wind energy generation regions often located in deep waters, it becomes imperative to model mooring behavior accurately, considering the platform's correct offset position for each sea condition (Pesce et al., 2018; Amaral et al., 2022). Furthermore, these studies typically engage a limited selection of environmental conditions during optimization, whereas employing comprehensive environmental series could enhance the evaluation of hull-mooring dynamics and fulfillment of the safety standards.

3. Methodology

This study employs a case-based approach, focusing on the VolturnUS-S semi-submersible platform, to investigate the impact of nonlinear mooring restoring forces on the optimization and design of FOWTs. The research examines a range of intermediate to large water depths, specifically 500, 1000, and 2000 meters, and evaluates three distinct mooring configurations: catenary, semi-taut, and taut line.

The optimization of different FOWT mooring systems was conducted using an optimization framework based on a Genetic Algorithm strategy, as detailed by Mas-Soler et al. (2022). In the optimization process, systems with six mooring lines were considered, each consisting of three segments: Chain R4 Stud, Polyester, and Chain R4 Stud. Notably, both chain segments were specified to have the same diameter. The mooring line parameters optimized included segment lengths and segment diameters, aiming to identify the lightest line in terms of mass. Anchor radius were set equal for each optimization. This framework enabled the design of mooring systems that are optimized for different water depths, anchor radius, and uplift line angle at the anchor position (from now on referred as anchor angles for conciseness) at far equilibrium positions of the platform. For the purposes of this study, the anchor radius was set equal to 1.5 of the water depth while three different anchor angles were compared across the specified water depths.

A critical component of the methodology is the evaluation of the final systems' responses, which involved comparing equivalent linear and nonlinear mooring models. The comparison focused on key parameters such as offsets and anchor tensions, providing a comprehensive understanding of the systems' performance under different modeling assumptions.

The nonlinear model accounts for the generalized mooring forces **Q**. Consider q_j as the "generalized coordinates" for the horizontal plane motions (surge, sway, and yaw). Consider also a moored vessel with N_m mooring lines. Suppose mooring line m is attached to the vessel at point $\overrightarrow{P}_m$. From Analytical Mechanics, the generalized force of a mooring line is the projection of its force $\overrightarrow{f}_m$ on the "generalized direction" $\partial\overrightarrow{P}_m/\partial q_j$.

$$Q_{j,m} = \overrightarrow{f}_m \cdot \frac{\partial \overrightarrow{P}_m}{\partial q_j} \tag{1}$$

where $Q_{j,m}$ is the generalized restoring force in direction j, acting on the body at the fairlead associated with the m-th line.

After some algebraic manipulation, the generalized restoring forces from the mooring system for the horizontal plane motions can be written as:

$$Q_1 = \sum_{m=1}^{N_m} f_m \cos\alpha_m \tag{2}$$

$$Q_2 = \sum_{m=1}^{N_m} f_m \sin\alpha_m \tag{3}$$

$$Q_3 = \sum_{m=1}^{N_m} f_m l_m \sin(\alpha_m - q_3 - \beta_m) \tag{4}$$

Here, Q_1, Q_2, and Q_3 represent the generalized restoring forces in the surge, sway, and yaw directions, respectively. The parameters f_m, α_m, l_m, and β_m correspond to the force in the mooring line, the angle of the mooring line, the length to the attachment point, and the orientation angle, respectively. For a detailed description of the formulation, please refer to Pesce et al. (2018) and Amaral et al. (2022).

The equivalent linear model can be obtained using the stiffness matrix formulation. It is a linearization from the generalized mooring forces, as presented by Pesce et al. (2018) (for horizontal plane motions) and Amaral et al. (2022) (for all six DoFs). Thus, the stiffness matrix can be written as:

$$k_{11} = \sum_{m=1}^{N_m} k_m \cos^2\alpha_m + \bar{k}_m \sin^2\alpha_m \tag{5}$$

$$k_{22} = \sum_{m=1}^{N_m} k_m \sin^2\alpha_m + \bar{k}_m \cos^2\alpha_m \tag{6}$$

$$k_{33} = \sum_{m=1}^{N_m} k_m l_m^2 \sin^2(q_3 + \beta_m - \alpha_m) + \bar{k}_m l_m^2 \Big[\cos^2(q_3 + \beta_m - \alpha_m) + \frac{h_m}{l_m}\cos(q_3 + \beta_m - \alpha_m)\Big] \tag{7}$$

$$k_{12} = k_{21} = \sum_{m=1}^{N_m} (k_m - \bar{k}_m)\cos\alpha_m \sin\alpha_m \tag{8}$$

$$k_{13} = k_{31} = \sum_{m=1}^{N_m} k_m l_m \cos\alpha_m \sin(q_3 + \beta_m - \alpha_m) - \bar{k}_m l_m \sin\alpha_m \cos(q_3 + \beta_m - \alpha_m) \tag{9}$$

$$k_{23} = k_{23} = -\sum_{m=1}^{N_m} k_m l_m \sin\alpha_m \sin(q_3 + \beta_m - \alpha_m) + \bar{k}_m l_m \cos\alpha_m \cos(q_3 + \beta_m - \alpha_m) \tag{10}$$

$$\tag{11}$$

where: $k_m = \partial f_m/\partial h_m$ is the local horizontal stiffness of the m-th line and $\bar{k}_m = f_m/h_m$ is its string stiffness, associated to the tensioning of each mooring line at a given point **q**.

Optimization constraints were carefully defined, with a maximum allowable offset set at 10% of the water depth, using the nonlinear model. The calculation of the far equilibrium position was based on a root-finding problem using the Newton-Raphson method, where the stiffness matrix is used as the inverse of the Jacobian matrix and it is computed at each iteration position. For further details on the methodology for computing the equilibrium position, see Amaral et al. (2024).

The objective function defined for this analysis is a single-objective function, focused on the cost of the mooring system, including the anchor costs. These costs are calculated based on the type of anchor, which is determined by the anchor angle at the far equilibrium position. Details of the cost model are outlined in Table 1.

Table 1: Cost model features from (Bjerkseter and Ågotnes, 2013) and (Karimi et al., 2017). Three different types of anchor are used, named: Drag Embebed Anchor (DEA), Vertically Loaded Anchor (VLA) and Suction Plate Anchor (SPA).

Anchor type	Acquisition cost [MUSD/kN]	Angle limit [deg]
DEA	100	<10
VLA	120	45
SPA	150	>45

The study's methodology indicates alternatives in accurately assessing the influence of nonlinear mooring forces on FOWT design and optimization. By comparing linear and nonlinear models across a variety of conditions, the research offers insights into the potential performance and cost implications of different mooring configurations, underscoring the importance of incorporating nonlinear dynamics in the design process.

4. Case study and results

This section presents a comprehensive case study aimed at evaluating the effects of the mooring model on the responses. It is organized into three main parts for clarity and depth of analysis. Initially, the case study is introduced, setting the stage for the subsequent detailed examination of results at a 2000m water depth. This specific focus on 2000m depth is chosen to illustrate certain patterns that become apparent when comparing linear and nonlinear modeling approaches, serving as a paradigm for understanding the broader implications of mooring system modeling. To maintain the conciseness, this detailed analysis is confined to the 2000m depth, providing clear, focused insights into the modeling discrepancies. Additionally, this section offers a comparative analysis of the outcomes observed across the three specified water depths: 500m, 1000m, and 2000m. This assessment provides a comprehensive prespective on the study's findings, highlighting the importance of adopting accurate modeling techniques for optimizing FOWT mooring systems.

4.1. Introduction to the Case study

This research aims at providing a comprehensive case study utilizing the VolturnUS-S semi-submersible platform (Allen et al., 2020), outfitted with the International Energy Agency's (IEA) 15MW wind turbine (Gaertner et al., 2020). This platform and turbine combination serves as a critical model for exploring the optimization of FOWTs across a spectrum of water depths, specifically targeting deep to ultra-deep conditions (i.e. 500, 1000, and 2000 meters).

The environmental conditions for this study were obtained from a 12-year environmental series, available at 3-hour intervals, extracted from the ERA5 database (Hersbach et al., 2020) specifically for the installation site, situated approximately 180km offshore Rio de Janeiro, Brazil. This extensive dataset, comprising 35,065 environmental conditions, provides a robust foundation for assessing the mooring system's responses under a myriad of operational scenarios.

One significant drawback of utilizing a nonlinear model, as compared to a linear model, lies in the practical challenges of computing the far equilibrium position under various conditions. The linear model offers the convenience of handling this computation in a matrix form, allowing for the simultaneous processing of all conditions. In contrast, the nonlinear model relies on the recalibration of the stiffness matrix at different position for each iteration, resulting in a computationally expensive and time consuming process that cannot be handled in parallel.

For the purposes of optimization, the scenario resulting in the most significant forces was prioritized. This consideration included the four main components of the mean steady force, which are supposed aligned: wind acting on the structure, thrust force from the rotor, the mean force from waves and the current drag force. The main values of these loads are detailed in Table 2. This comparison shows that the thrust force emerges as the most critical component, as could be expected, followed by the drag force, which also plays a significant role. Table 2 present the values for all components and the resulting force.

Table 2: Components of the maximum resulting force considered for the optimization.

Component	Magnitude [kN]	Magnitude [%]
Wind (structure)	116.85	3.54
Wind (thrust)	2375.43	72.12
Wave mean	109.65	3.34
Current drag	691.82	21.00
Resulting	3293.75	100

Regarding the optimization process, the study employs a Genetic Algorithm to design mooring systems optimized for a fixed anchor radius while comparing three distinct anchor angles across the chosen water depths. For an in-depth description of the optimization framework, the reader is referred to (Mas-Soler et al., 2022). This optimization framework allows the identification of the most effective mooring configurations that regard the nonlinear dynamic behavior inherent to the mooring systems for FOWTs.

4.2. Results for Depth of 2000m

Within the scope of this study, at a water depth of 2000 meters, three distinct mooring system configurations (i.e. catenary, semi-taut, and taut-leg) were selected for in-depth analysis, as shown in Figure 1. In the figure, the blue lines indicate the chain R4 stud segments, while the red lines represent the intermediate polyester segment. This selection was made to encompass a wide array of mooring configurations. The catenary configuration is characterized by both near and far anchor angles[1] set to zero. In contrast, the semi-taut configuration, with a near anchor angle of zero and a positive far anchor angle, stands as a transition towards tauter lines. Finally, the taut-leg configuration, characterized by positive near and far anchor angles, exemplifies the most tensioned system under consideration.

The analysis of offset watch circles for the 2000m water depth cases, as presented in Figure 2, offers a detailed visualization of the system's behavior under the different configurations: catenary (Figure 2a), semi-taut (Figure 2b), and taut-leg (Figure 2c). These figures depict the offset limits with a red line, set at 10% of the water depth, and illustrate the offset watch circles for both the nonlinear (black line) and linear (blue line) models.

The results show a variance in system stiffness across various directions, with increased stiffness observed in directions where the mooring lines are tensioned, resulting in smaller offsets when using the nonlinear model. This enhancement is particularly evident in the vertical plane that contains the mooring line, which establishes a primary restoring direction. On the contrary, directions in which the

[1] Anchor angles θ_{anc} are defined with respect to the seabed, where $\theta_{anc} = 0°$ indicates that the force in the anchor is horizontal.

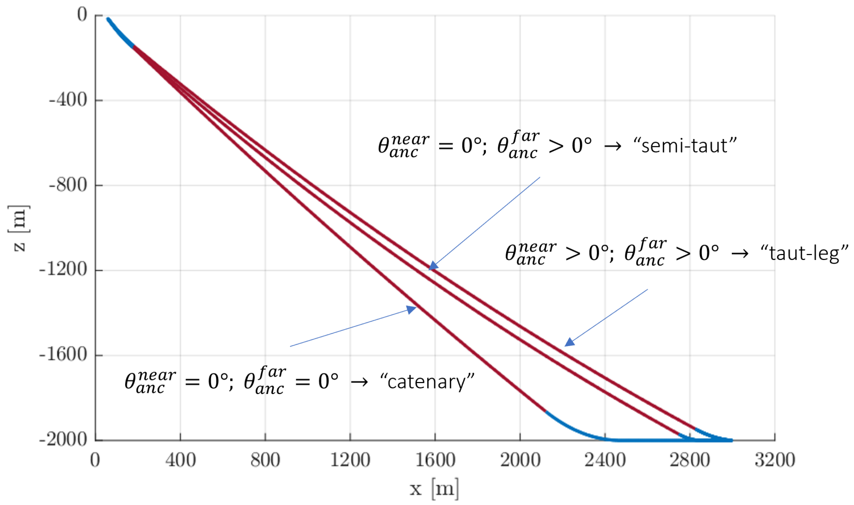
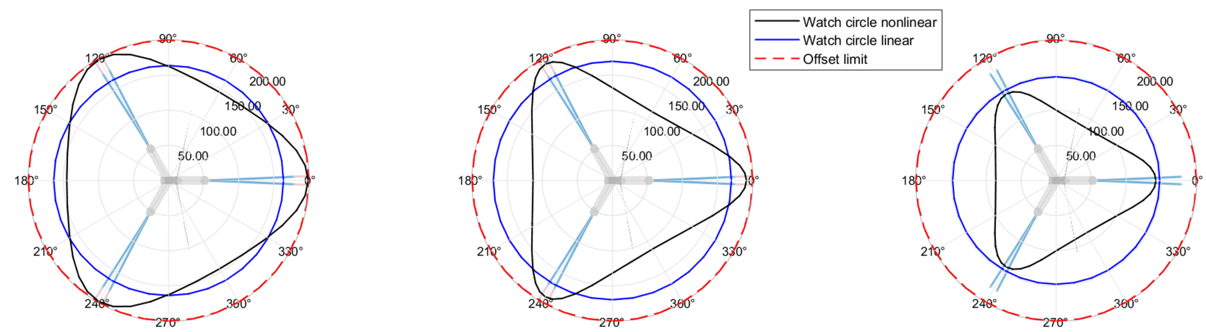


Figure 1: Selected line configurations for depth of 2000m.



(a) $\theta_{anc} = 0°$ ("catenary") (b) $\theta_{anc} = 20°$ ("semi-taut") (c) $\theta_{anc} = 50°$ ("taut-leg")

Figure 2: Offset watch circles for depth of 2000m.

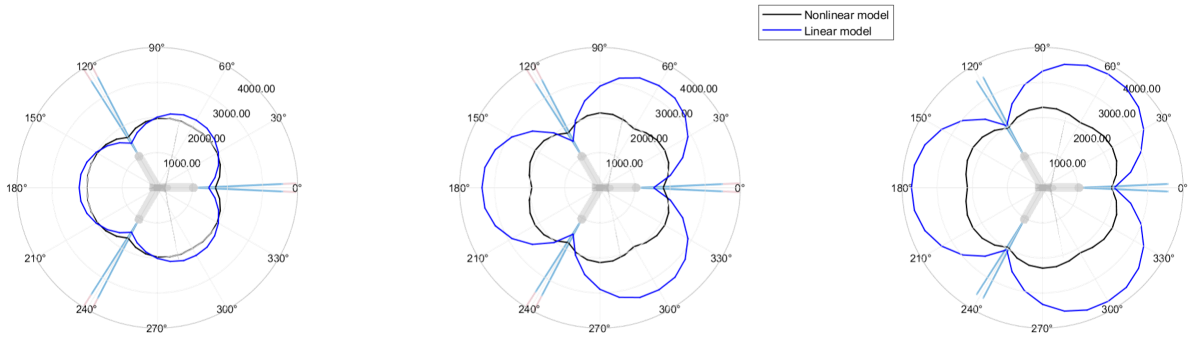
system stiffness is diminished (predominantly where the lines slacken) demonstrate larger offsets when the non-linearity is considered.

For the catenary configuration, the comparison between linear and nonlinear models shows minimal differences in offsets, especially in the main restoring directions, such as at 180 degrees. The results of both models are similar. However, in directions characterized by decreased stiffness, where the lines slack, the differences are pronounced.

Moving on to tauter configurations, such as the semi-taut and taut-leg, the differences between the models in terms of offsets become more evident, especially in the main restoring directions. This observation highlights the dominance of axial stiffness over geometric stiffness in these scenarios. Notably, the taut-leg configuration stands as a system that features a stiffer response in the nonlinear model compared to the linear model across all examined directions.

The analyses of anchor tensions for the three mooring configurations at 2000m depth, as shown in Figure 3, illustrate the mechanical loads exerted on the mooring systems. The results from the nonlinear model indicate that the tensions across the catenary, semi-taut, and taut-leg configurations are of a similar magnitude. However, the taut-leg configuration exhibits slightly higher tensions due to its inherent vertical component.

The trade-off between offsets and anchor tensions is significant. As aforementioned, the offset watch circles for the catenary configuration (Figure 2a) show minimal discrepancies between the linear and



(a) $\theta_{anc} = 0°$
("catenary")

(b) $\theta_{anc} = 20°$
("semi-taut")

(c) $\theta_{anc} = 50°$
("taut-leg")

Figure 3: Anchor tensions for depth of 2000m. Unit: kN.

nonlinear models, which is consequently reflected in the similarities in the estimated anchor tensions for both models (Figure 3a). This correlation suggests that for catenary systems, the linear approximation is more accurate in predicting the tension loads under normal operating conditions.

In contrast, as the mooring lines become more taut, the disparity between the linear and nonlinear model estimations grows, particularly in the main restoring direction. For instance, for an angle of 180 degrees, the difference in estimated tensions reaches an order of magnitude of 70%. This attest the necessity of adopting nonlinear modeling for the accurate prediction of anchor tensions, particularly in taut-leg configurations (Figure 2c).

Now, it is possible to assess the effects of the line configuration on the stiffness maps. They depict how the stiffness coefficients are affected by the floater mean position. For further information on the methodology used to derive these maps, references can be made to the works of Pesce et al. (2018) and Amaral et al. (2022).

The stiffness maps presented in Figures 4, 5, and 6 illustrate the variations in stiffness coefficients from Eqs. 5 to 10 for varying mean position for the catenary, semi-taut, and taut-leg configurations, respectively. These maps reveal that the stiffness coefficients exhibit higher nonlinearities, which could result in a nonlinear behavior of the system's natural periods of oscillation.

For the catenary configuration, the stiffness map (Figure 4) shows a continuous increase from lower to higher stiffness coefficients moving from the maximum positive to the maximum negative offset, with the greatest gradient of increasing stiffness near the maximum negative offset. This gradient change is indicative of axial stiffness becoming more influential when the mooring lines are under greater tension.

The semi-taut model's map (Figure 5) transitions more rapidly to higher stiffness coefficients, with a remarkable region of high stiffness, indicating a significant change in values. Interestingly, the system exhibits a slight increase in stiffness for offsets greater than x = 150 m after reaching a minimum stiffness point near x = 90 m.

The changes in the stiffness map for the taut-leg system (Figure 6) display even more pronounced and sudden variations. The system shows an increase in stiffness for relatively small positive offsets (around 10 m), suggesting that the system gains stiffness across all directions. This highlights the pronounced impact of the line's tension on the equivalent stiffness for the taut-leg configuration.

4.3. Comparative results for water depths of 500, 1000 and 2000m

Moving forward to the comparative examination, the results spanning the water depths of 500, 1000, and 2000 meters are presented. This analysis provides an in-depth understanding of the influence of water depth on mooring system behavior and informs on the adaptability of FOWT design strategies to varying oceanic conditions.

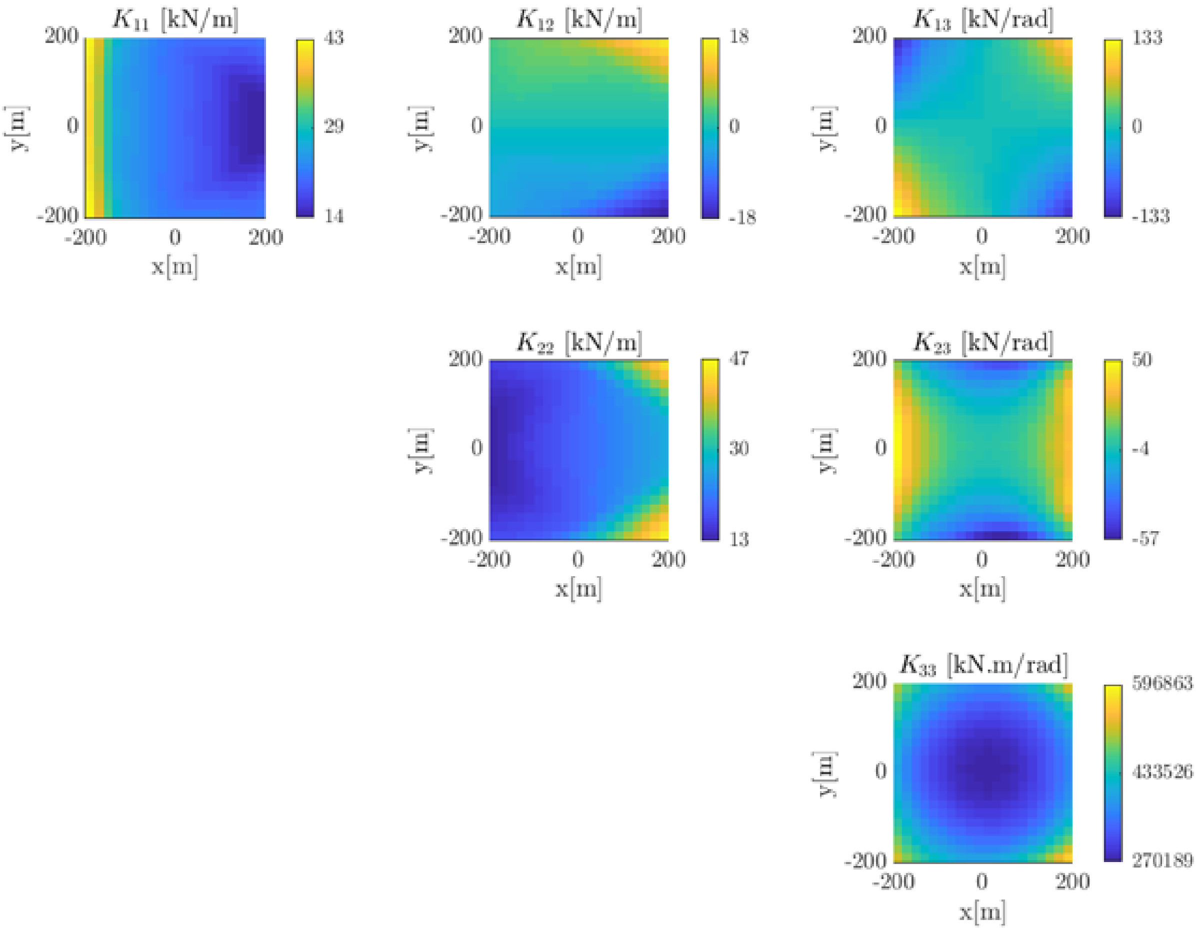


Figure 4: Stiffness coefficients as function of the position for depth of 2000m. θ_{anc} = 0° – Catenary.

The comparative analysis of maximum offsets across varying water depths illustrates the performance characteristics of different mooring line configurations. Figure 7(a) shows the normalized maximum offsets for the catenary, semi-taut, and taut-leg configurations at water depths of 500, 1000, and 2000 meters, for both linear and nonlinear mooring models.

The nonlinear model, depicted with black lines, demonstrates a correlation wherein tauter mooring lines correspond to smaller maximum offsets. This relationship, observed consistently across various water depths, does not emerge as clearly in the linear model. This discrepancy could stem from the optimization process itself, during which systems are refined using the nonlinear model. In such cases, the equivalent linear stiffness model fails to accurately capture the nonlinear behavior of the system. This phenomenon is particularly evident in the analysis at a 1000m water depth, where the taut-leg and catenary systems display similar offsets, suggesting comparable stiffness coefficients in the x-direction. However, their nonlinear responses diverge, leading to distinct offsets in nonlinear analyses.

This phenomenon underscores the potential inaccuracies that may arise from the linear model's simplifications, particularly in its failure to account for the complex interplay between stiffness and the resultant mooring system behavior at varying depths. The nonlinearity inherent in the mooring system behavior, as accurately captured by the nonlinear model, is critical for the optimization and design of FOWTs, specially for tauter lines.

The analysis of anchor tensions for the three mooring line configurations across water depths, presented in Figure 7(b), elucidates a critical aspect of mooring system design. It reveals a tendency for anchor tensions to increase as the mooring lines become tauter, a trend observed across both linear

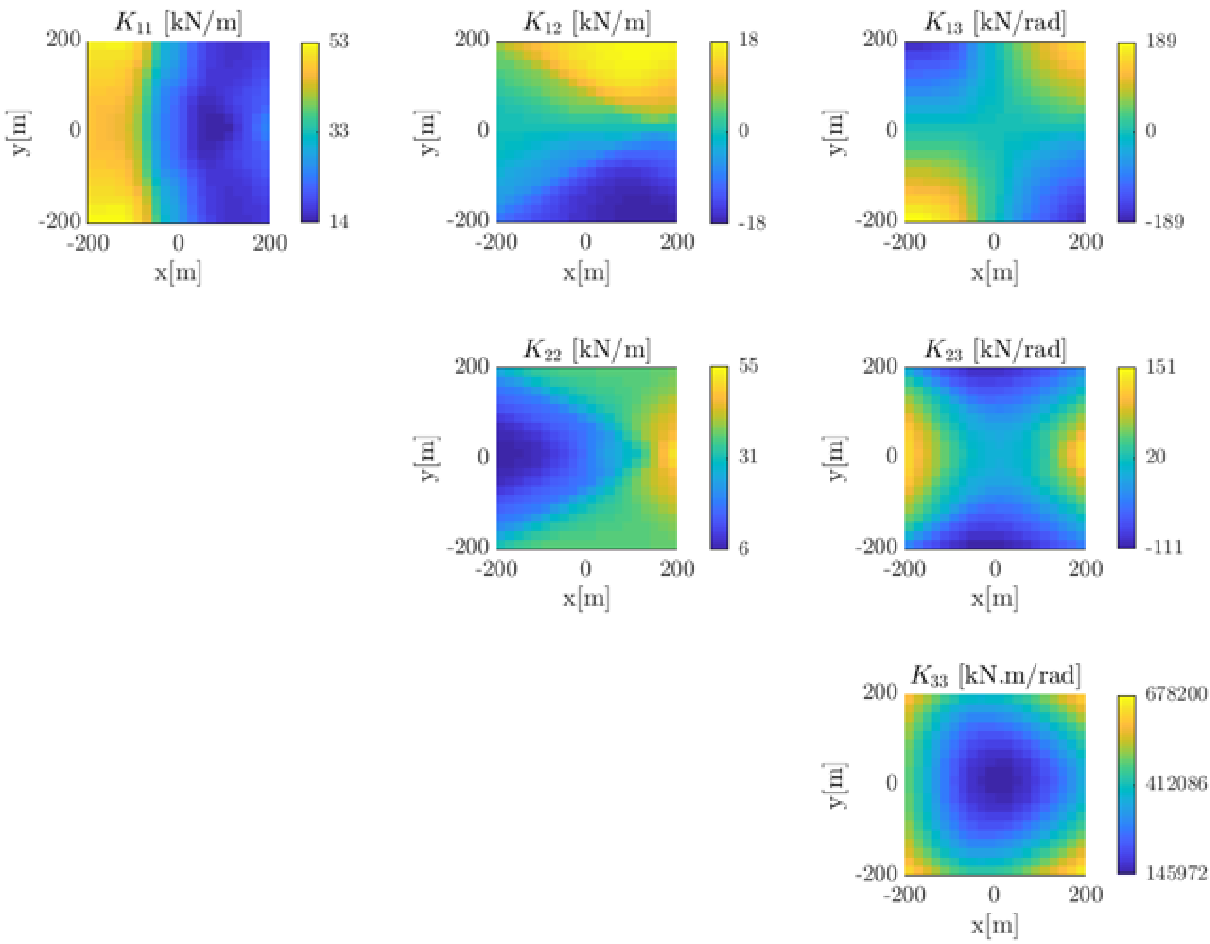


Figure 5: Stiffness coefficients as function of the position for depth of 2000m. θ_{anc} = 20º – Semi-taut.

and nonlinear models. Notably, the nonlinear model demonstrates that anchor tensions exhibit minimal variation with changes in water depth. In contrast, the linear model tends to significantly overestimate anchor tensions. Such overestimation could lead to unnecessarily robust and costly anchor designs, skewing the optimization process towards catenary systems and away from potentially more efficient tauter configurations. This discrepancy underscores the importance of employing nonlinear modeling for accurate tension prediction, ensuring cost-effective and optimized mooring system designs across varying ocean depths.

Turning attention to the anchor angle at the far equilibrium position, Figure 7(c) provides insightful observations. It is evident that the linear model consistently overestimates this angle across all mooring line configurations and water depths examined. This systematic overestimation by the linear model could introduce biases in the design and optimization processes, potentially affecting the selection of mooring configurations and the overall stability of the FOWT systems. The linear model's inclination to predict higher anchor angles than the nonlinear model may lead to designs that are not only less efficient but also more costly, highlighting the crucial need for nonlinear analysis in accurately determining mooring system configurations.

Figure 7(d) presents the estimated anchor acquisition costs, calculated using a model from Table 1. The figure reveals significant cost discrepancies when comparing the linear and nonlinear models, especially in the evaluation of taut systems using the linear model. The linear model's tends to overestimate the tension requirements and leads to inflated cost projections, which could inadvertently

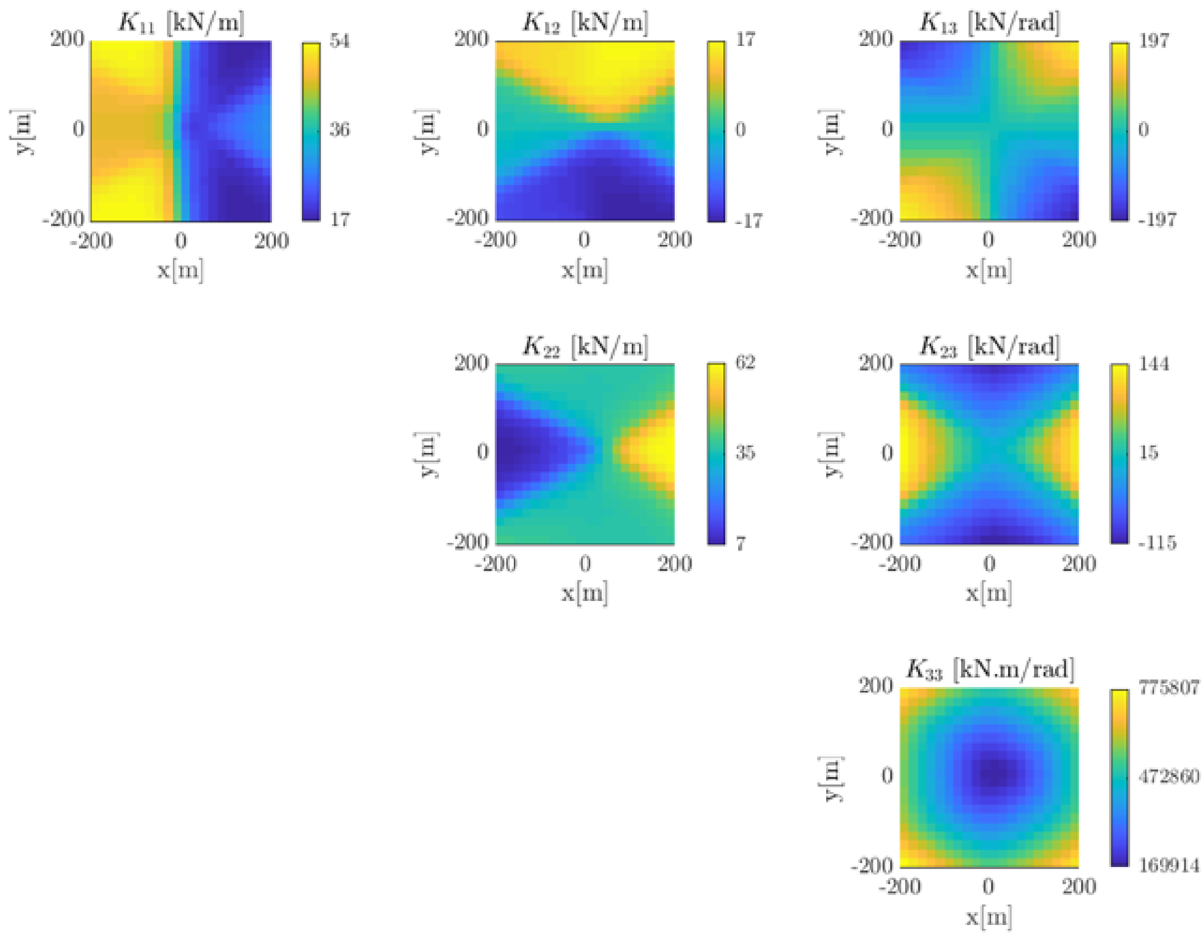


Figure 6: Stiffness coefficients as function of the position for depth of 2000m. $\theta_{anc} = 50^{o}$ – Taut-leg.

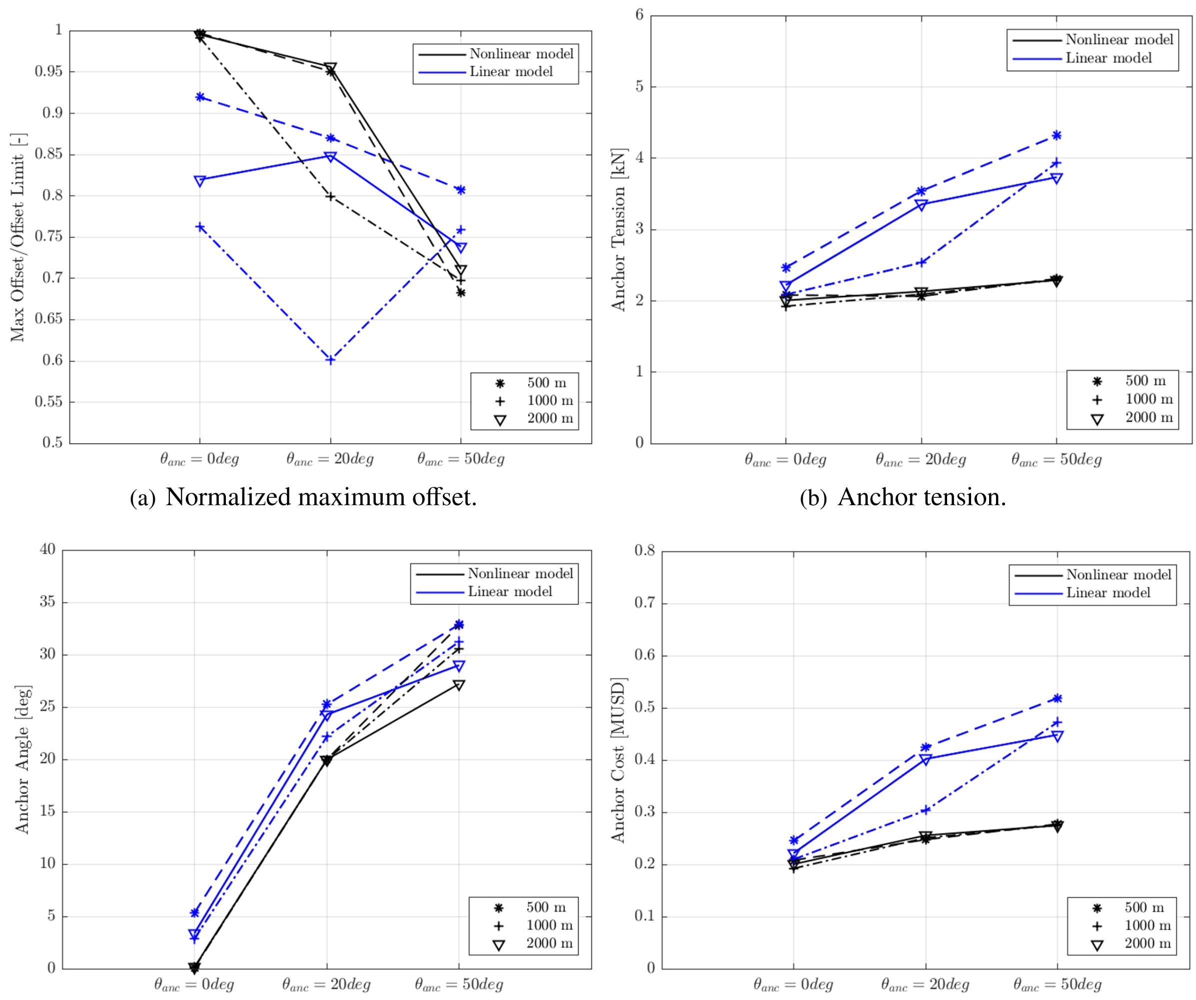
bias the optimization process towards favoring catenary systems due to their seemingly lower cost implications.

5. Conclusion and further works

The comprehensive analysis provided in this study underscores the importance of incorporating nonlinear optimization techniques in the design and optimization of FOWTs mooring systems. The findings reveal that while catenary lines feature minimal discrepancies when the results from the nonlinear model are compared to linear one, significant deviations are observed in semi-taut and taut-leg configurations. Notably, linear models tend to significantly overestimate offsets in the main restoring directions, particularly in tauter mooring systems. This overestimation extends to anchor tensions as well, for which linear models predict higher tensions than nonlinear models, potentially leading to unnecessarily costly anchor designs. Such overestimations invariably bias the optimization process, favoring catenary systems over more efficient taut configurations.

The study further highlights the pronounced nonlinearity observed in stiffer mooring systems, as evidenced by the stiffness maps, which reveal large variability with changes in offsets. Adopting nonlinear models provides a more accurate representation of mooring system behavior and contributes to the robustness of optimization schemes, particularly those that incorporate anchor costs. This approach ensures a more realistic assessment of system performance.

Further work involves extending the scope of this investigation to include a wider range of anchor



(a) Normalized maximum offset.

(b) Anchor tension.

(c) Anchor angles at far equilibrium position.

(d) Anchor acquisition cost.

Figure 7: Comparative results for water depths of 500, 1000 and 2000m.

radius/water depth ratios, aiming to generalize the optimization strategies for FOWT mooring systems. Additionally, conducting comparative studies in the frequency domain would offer deeper insights into how different mooring models respond to dynamic loading conditions. Finally, performing in numerical simulations with higher-order mooring models, as those in software like FAST and Orcaflex, will be crucial in evaluating the potential design errors that may arise from the choice of mooring model, further refining the optimization process for FOWT mooring systems.

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