XLVI CILAMCE
VITÓRIA - ES - BRAZIL - 2025
XLVI IBERO-LATIN AMERICAN CONGRESS ON COMPUTATIONAL METHODS IN ENGENEERING

Structural Optimization of Mooring Systems for Geometric Efficiency

Eduardo N. Lages[1], Gabriel R. Domingos[1], Adeildo S. Ramos Jr.[1], Alan P. de Abreu[2], Anderson T. Oshiro[3], Mauro C. de Oliveira[3]

[1]*Laboratory of Scientific Computing and Visualization, Center of Technology, Federal University of Alagoas*
Av. Lourival Melo Mota, 57072-970, Alagoas, Brazil
enl@lccv.ufal.br, gabriel.domingos@lccv.ufal.br, adramos@lccv.ufal.br
[2]*Direction of Engineering, Technology and Innovation, PETROBRAS*
EdiSen, Av. Henrique Valadares, 20231-030, Rio de Janeiro, Brazil
alan_patrik@petrobras.com.br
[3]*Center of Research Leopoldo Américo Miguez de Mello, PETROBRAS*
Av. Horácio Macedo, 21941-915, Rio de Janeiro, Brazil
anderson.oshiro@petrobras.com.br, mauro@petrobras.com.br

Abstract. Structural optimization of mooring systems is an effective strategy for reducing design effort and cost in the offshore industry. This study builds on previous work that introduced efficient optimization methodologies. Here, we extend the approach to a practical goal: minimizing the total length of the mooring system while satisfying performance and geometric constraints. Using the Equivalent Static Analyses (ESA) methodology proposed by Domingos et al. (2023), the optimization framework allows each mooring line to vary independently in total length, horizontal projection (fairlead-to-anchor distance), and azimuthal orientation. This design flexibility enables the exploration of a broader design space while complying with the physical and operational constraints of offshore systems. By integrating these variables and leveraging the computational benefits of earlier research, the method produces optimized mooring layouts that are computationally efficient and readily applicable to practical offshore engineering scenarios. The resulting configurations reached the lower bounds on line lengths while satisfying all design criteria, demonstrating the method's capability to achieve effective layouts under realistic constraints.

Keywords: Structural Optimization, Offshore Structures, Mooring Systems, Equivalent Static Analyses

1 Introduction

This work builds upon previous research to develop an optimization tool intended to support professionals in the design of offshore mooring systems. The tool aims to reduce reliance on manual trial-and-error procedures through embedding key performance and operational criteria directly into the optimization formulation. By doing so, it enables designers to systematically explore viable solutions while accounting for complex real-world constraints.

To demonstrate the capabilities of the proposed framework, this study explores an example in which each mooring line is allowed to vary – within adjusted and realistic design bounds – in total length, horizontal projection (fairlead-to-anchor distance), and azimuthal orientation. This adds flexibility and expands the design space while promoting more efficient, performance-driven layouts, while maintaining operational integrity.

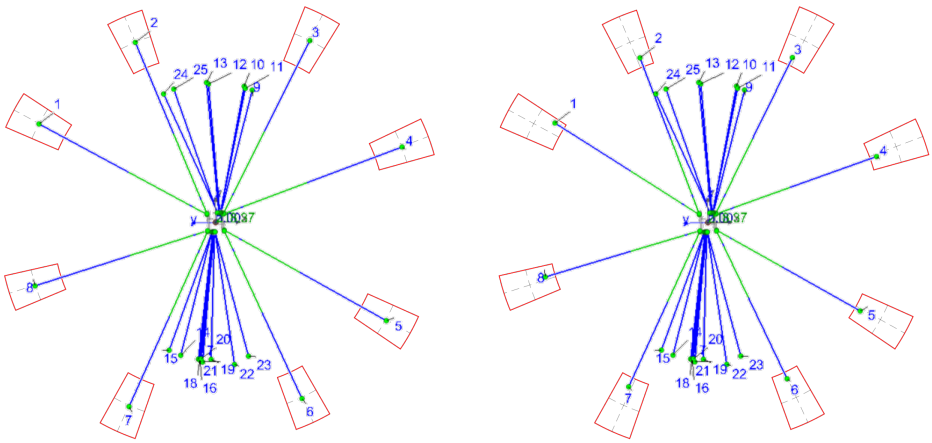
In contrast to Pillai et al. [1], who employed a multi-objective approach to minimize both material cost and cumulative fatigue damage in a similar problem, this work focuses on minimizing the total length of the mooring system while allowing the algorithm to autonomously determine the anchor positions on the seabed. While Cruces Girón et al. [2] and Monteiro et al. [3] addressed the integrated design of mooring and riser systems from scratch, do Prado et al. [4] introduced an optimization approach based on metamodels to improve computational efficiency. Similarly, both Domingos et al. [5] and the present work employ metamodel-based optimization; however, whereas Domingos et al. [5] focused on the repositioning of an existing floating production unit, the current study targets the initial design of a mooring system.

The optimization formulation considers a comprehensive set of constraints related to operation, maintenance, safety, good practices, and life-cycle management. The evaluation of candidate configurations relies on the Equivalent Static Analyses (ESA) methodology introduced by Domingos et al. [5], which substantially reduces the

computational cost of the optimization process. To ensure accuracy and reliability, all ESA results are validated through dynamic analyses (DA), using the proprietary simulation software DYNASIM [6, 7], ensuring consistency with the dynamic behavior of the moored system.

2 Optimization model

All optimization routines were implemented in the Julia programming language (Bezanson et al. [8]), using the NLopt optimization library (Johnson [9]). The studied model was the same submersible with 8 mooring lines (1–8) and 17 risers (9–25) explored by Domingos et al. [5], as seen in Fig. 1(a).



(a) (b)

Figure 1. Studied model in (a) original and (b) optimized configuration along with the upper and lower bounds for azimuth and horizontal distance for each line (red annular sectors)

The optimization model is defined mathematically as follows, with each component explained in the subsequent subsections.

$$
\begin{aligned}
\min_{\boldsymbol{L},\boldsymbol{HDist},\boldsymbol{Az}} f(\boldsymbol{L},\boldsymbol{HDist},\boldsymbol{Az}) = & \sum_{l=1}^{N} \frac{L_l}{L_l^0} \\
\text{subject to } & Hull(\boldsymbol{\Delta}) \leq Hull(\text{SAFOP}) \\
& HeadingL \leq Heading \leq HeadingU \\
& \frac{T_i^{\text{ECs}}}{MBL_i} \leq TMBLMaxRatio_i \\
& TopAngVarL_i \leq TopAng_i - TopAng_i^0 \leq TopAngVarU_i \\
& LRatioL_i \leq \frac{L_i}{L_i^0} \leq LRatioU_i \\
& HDistRatioL_i \leq \frac{HDist_i}{HDist_i^0} \leq HDistRatioU_i \\
& AzVarL_i \leq Az_i - Az_i^0 \leq AzVarU_i \\
\text{with } i = 1...N, & \text{ where } N \text{ is the number of optimized mooring lines.}
\end{aligned}
\tag{1}
$$

2.1 Design variables

The design variables of the problem are the total lengths ($\boldsymbol{L}$), the horizontal distances ($\boldsymbol{HDist}$) between fairlead and anchor and the azimuthal orientations ($\boldsymbol{Az}$) for the set of optimized mooring lines.

2.2 Objective function

The model aims to minimize the total length of the mooring system, using an initial configuration – typically defined by an expert based on their experience – as a reference. The algorithm then searches for a feasible solution that reduces overall material usage.

2.3 Set of constraints

The constraints are defined as follows: the first ensures compliance with SAFOP (Safe Operational Zone for the risers), limiting the envelope of vessel displacements ($Hull(\mathbf{\Delta})$) to within acceptable bounds; the next restricts the equilibrium heading of the production unit to within specified limits, for operational reasons. A third constraint requires that line tensions remain below a specified percentage of their Minimum Breaking Load (MBL) under all environmental conditions, in accordance with standard regulations. Additionally, the top angle of each line in equilibrium must not deviate (in either direction) from its initial value by more than the prescribed range. Finally, box constraints limit the variation of design variables within specified bounds.

For this work, we specified SAFOP the same way as Domingos et al. [5], defined the limit for maximum tension as $\boldsymbol{TMBLMaxRatio} = \mathbf{0.6}$ and prescribed lower and upper limits for vessel heading as $HeadingL = 90^\circ$ and $HeadingU = 92^\circ$, for maximum top angle variation as $\boldsymbol{-TopAngVarL} = \boldsymbol{TopAngVarU} = \mathbf{1}^\circ$, for variation in total lengths as $\boldsymbol{LRatioL} = \mathbf{0.90}$ and $\boldsymbol{LRatioU} = \mathbf{1.50}$, for variation in horizontal distance as $\boldsymbol{HDistRatioL} = \mathbf{0.85}$ and $\boldsymbol{HDistRatioU} = \mathbf{1.15}$, and for azimuth variation as $\boldsymbol{-AzVarL} = \boldsymbol{AzVarU} = 5^\circ$.

3 Equivalent Static Analyses

The Equivalent Static Analyses (ESA) methodology proposed by Domingos et al. [5] is used in this model. In this method, loads are treated as permanent, and the goal is to find the system's equilibrium under static loads. This is achieved via an internal procedure in DYNASIM (Nishimoto et al. [6]; Fucatu et al. [7]). A key step in defining the static model is the calibration of a penalty factor k, determined by comparing displacement fields from both dynamic and static analyses using the initial model. The factor k is chosen so that the peak magnitudes of the displacements match, improving alignment between the two models. In this work, $k = 1.25$.

Although this penalization does not yield a perfect match, it performs adequately for extreme scenarios such as the one studied here. The final step in constructing the static model involves selecting critical environmental load cases. Since only a subset of all possible combinations produces displacements that activate optimization constraints, a filtering strategy is used to retain only the most critical cases.

4 Results

The tool solved the problem in around 17 minutes of wall-clock time using a Windows 11 64-bit operating system, an Intel i7-12700H CPU and 16 GB of installed RAM. All the constraints were satisfied at the end of the optimization, whose result was validated via Dynamic Analyses using all the original environmental conditions for the model.

As can be seen in Fig. 2, the total lengths of the mooring lines were optimized to their respective lower bound values, resulting in a 10% reduction in the total length of the mooring system. The horizontal distances were close to their lower bounds while remaining within the box constraints. This result contributed to reducing the mooring line lengths – optimized to their lower limits – while still satisfying the top angle constraint and ensuring a balanced tension distribution throughout the mooring system. The azimuths also remained within their bounds, contributing significantly to load distribution and SAFOP compliance.

The distribution of the final anchor points in the optimized scenario, shown in Fig. 2, is also visible in Fig. 1(b). It is important to note that the model calibration was performed manually, and in the optimized configuration Line 2 appears to be positioned slightly too close to Riser 24. In this case, the algorithm simply follows the defined input; therefore, if the result is considered unsuitable, the user must adjust the calibration and rerun the model to obtain a revised solution.

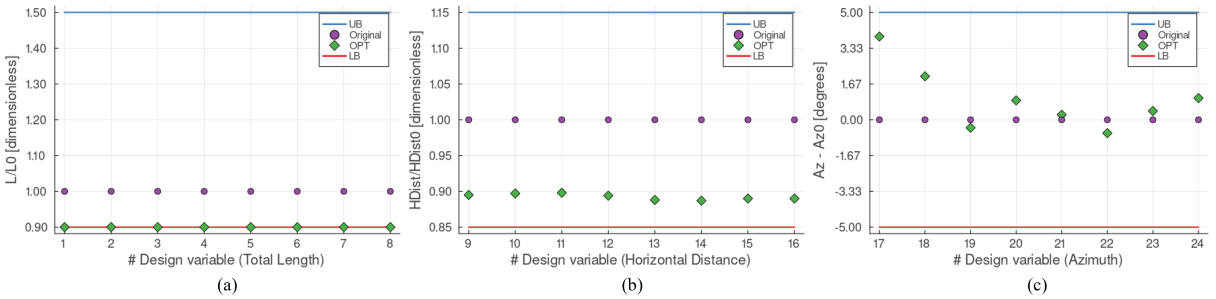


Figure 2. Design variables values before (purple circles) and after (green diamonds) optimization, along with their specified upper (blue line) and lower (red line) bounds. Since this example had 8 mooring lines, 24 design variables were considered, with results (a) corresponding to total lengths (design variables 1–8), (b) to horizontal distances (design variables 9–16) and (c) to azimuthal orientations (design variables 17–24)

5 Conclusions

The main objective of this work was to test the proposed optimization tool on a more complex task and assess its ability to automatically find valid and efficient solutions. The results demonstrate that the tool successfully identified a final configuration satisfying all constraints across environmental conditions while reducing the total mooring length. This was achieved in a fraction of the time typically required by conventional design practices. The strategy significantly reduces reliance on manual trial-and-error procedures and offers a robust, rapid-response solution for field applications. Furthermore, the proposed approach is flexible and can be extended to alternative objective functions, constraint sets, and more complex design tasks.

Acknowledgements. The authors acknowledge PETROBRAS and CNPq for the financial support.

Authorship statement. The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work, and that all material that has been herein included as part of the present paper is either the property (and authorship) of the authors, or has the permission of the owners to be included here.

References

[1] A. C. Pillai, P. R. Thies, and L. Johanning. Mooring system design optimization using a surrogate assisted multi-objective genetic algorithm. *Engineering Optimization*, vol. 51, n. 8, pp. 1370–1392, 2019.
[2] A. R. Cruces Girón, F. N. Corrêa, A. O. Vázquez Hernández, and B. P. Jacob. An integrated methodology for the design of mooring systems and risers. *Marine Structures*, vol. 39, pp. 395–423, 2014.
[3] B. F. Monteiro, J. S. Baioco, C. H. Albrecht, B. S. L. P. Lima, and B. P. Jacob. Optimization of mooring systems in the context of an integrated design methodology. *Marine Structures*, vol. 75, pp. 102874, 2021.
[4] V. G. do Prado, da B. Fonseca Monteiro, B. S. L. P. de Lima, and B. P. Jacob. Optimal design of mooring systems for floating production units based on metamodel-assisted differential evolution. *Ocean Engineering*, vol. 266, pp. 112752, 2022.
[5] G. R. Domingos, E. N. Lages, A. S. Ramos Jr., A. T. Oshiro, and M. C. Oliveira. Nonlinear dynamic structural optimization of offshore structures using equivalent static models. In *Proceedings of the XLIV Ibero-Latin-American Congress on Computational Methods in Engineering*, 2023.
[6] K. Nishimoto, C. H. Fucatu, and I. Q. Masetti. Dynasim – a time domain simulator of anchored FPSO. *Journal of Offshore Mechanics and Artic Engineering-Transactions of the ASME*, vol. 124, n. 4, pp. 203–211, 2002.
[7] C. H. Fucatu, E. A. Tannuri, E. N. Lages, E. S. S. Silveira, F. M. G. Ferreira, K. Nishimoto, and M. C. Oliveira. Dynasim. Registration number: BR512014001550-5, 2016.
[8] J. Bezanson, A. Edelman, S. Karpinski, and V. B. Shah. Julia: A fresh approach to numerical computing. *SIAM Review*, vol. 59, n. 1, pp. 65–98, 2017.
[9] S. G. Johnson. The NLopt nonlinear-optimization package. `https://github.com/stevengj/nlopt`, 2007.