Influence of Thermal Variations on the Behavior of Mooring Lines Using a Heterogeneous Extensible Catenary Model

Milton M. G. dos Santos[1], Eduardo N. Lages[2]

Laboratório de Computação Científica e Visualização, Universidade Federal de Alagoas
Av. Lourival Melo Mota s/n, Cidade Universitária, CEP: 57072-970, Maceió/AL, Brasil
[1]*milton.santos@ctec.ufal.br*, [2]*enl@lccv.ufal.br*

Abstract. This study investigates the mechanical behavior of mooring lines in floating offshore units subjected to thermal variations along the water column, employing a static numerical model based on a heterogeneous extensible catenary formulation. The growing global energy demand and the expansion of deepwater operations have increased the importance of mooring systems for platform stability and station-keeping. As key structural elements, mooring lines provide essential horizontal stiffness, govern restoring forces, and ensure structural integrity. However, conventional design models frequently neglect thermal effects, particularly the influence of depth-dependent temperature variations on deformed configuration of the line and its overall performance. To address this limitation, the proposed model incorporates both multimaterial line segments and vertical oceanic temperature profiles to evaluate their combined impact on horizontal stiffness and restoring capability. Results demonstrate that these thermal variations substantially alter the mechanical response of the line, directly affecting its interaction with the platform. This methodology enhances the reliability of mooring system design and contributes to a better understanding of thermo-mechanical behavior of mooring lines in offshore engineering.

Keywords: Thermal variations, Mooring lines, Static numerical model, Heterogeneous extensible catenary, Offshore engineering.

1 Introduction

The increasing global demand for energy and the intensification of deepwater activities have driven substantial technological progress in offshore systems, particularly in the mooring systems of floating units. These systems play a vital role in ensuring platform stability and station keeping by providing horizontal stiffness, governing restoring forces, and preserving the structural integrity of the entire configuration. Similar to mooring lines, risers and power cables are also subjected to self-weight, environmental loads, and accidental actions. Solano [1] highlights that risers are additionally exposed to functional loads such as internal and external pressures, installation effects, and thermal gradients, whereas Qiao *et al* [2] point out that power cables used in offshore wind platforms are subjected to thermal loads resulting from power transmission. Many studies have focused on the thermal stress analysis of these structures under internal temperature effects [2,3]. However, investigations concerning offshore structures subjected to external temperature loads — such as mooring lines exposed to temperature differentials along the marine profile — remain scarce. The most recent advance was proposed by Zhen *et al* [4], who developed a fully coupled dynamic water–mooring line model capable of capturing temperature differentials. Nevertheless, their study did not investigate the variations in mechanical associated with realistic thermal marine profiles. Such thermal loads can significantly alter the deformed length and axial stiffness of the materials, thereby modifying the mechanical response of the mooring lines — especially in deepwater scenarios, where thermal gradients are more pronounced. In this context, the present study proposes a simplified static numerical approach based on a heterogeneous extensible catenary model capable of representing multiple material segments along the line and incorporating vertical ocean temperature profiles. The developed formulation enables the evaluation of the influence of thermal expansion on the geometric shape, axial tension distribution, and restoring capability of the mooring system. The proposed methodology therefore aims to support the development of more realistic and robust

design models, while improving the understanding of thermal effects in offshore engineering.

2 Methodology

The proposed methodology is based on representing the mooring line as a system of elastic segments with thermal expansion capability, arranged in a catenary configuration and exhibiting constant physical properties within each segment. These segments are discretized into cable elements, allowing for a more accurate representation of the thermal gradient effects along the water column. The adopted formulation adapts the theory of cable structures under general loadings, originally proposed by Abad et al. [5], and explicitly accounts for varying axial stiffness, linear mass density, thermal expansion coefficients, and temperature distributions. The numerical procedure follows an iterative approach that begins by determining the mooring line geometry under a thermal condition — initially considered neutral for the first iteration. Based on this configuration, the average depth of each element is computed. These depth values are then used to update the thermal gradient, incorporating both the material's reference temperature and the oceanic temperature profile. The sequence of steps followed in the analysis is summarized in the flowchart shown in Fig. 1, which illustrates the thermo-mechanical evaluation process of mooring lines.

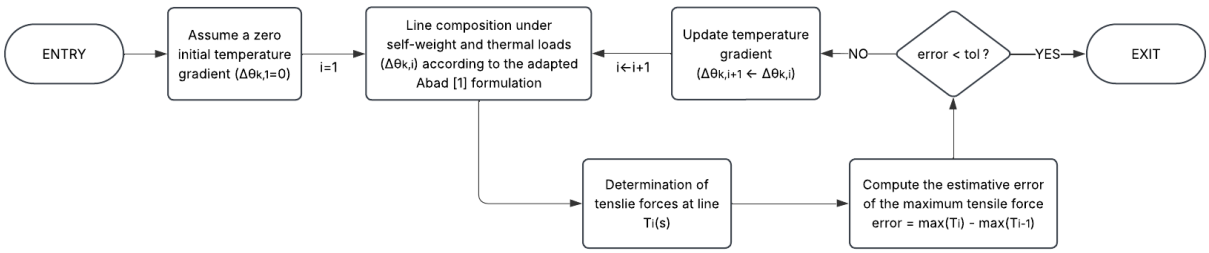
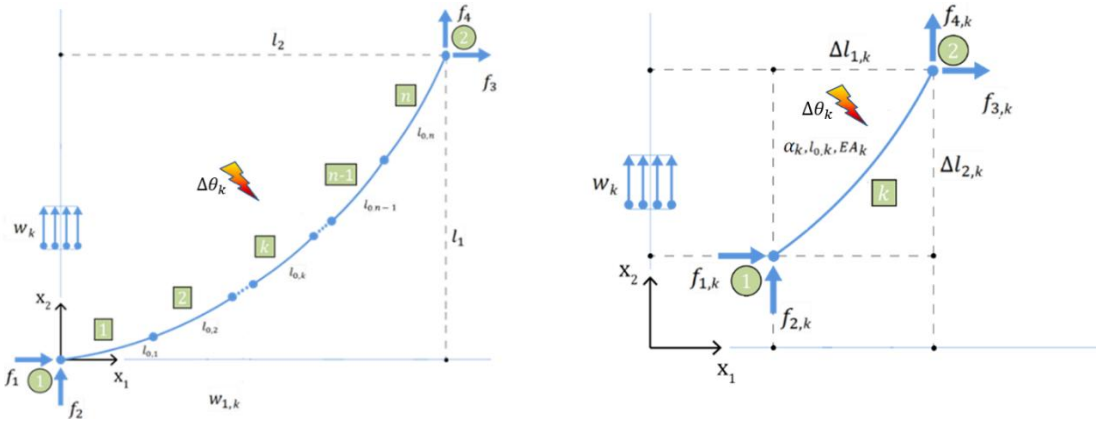


Figure 1. Flowchart of the thermo-mechanical analysis strategy for mooring lines in catenary configuration.

2.1 Adapted Formulation of Cable Structures under General Loadings Including Thermal Effects

The mooring line is modeled as a series of elastic cable elements subjected to vertically distributed mechanical and thermal loads, following the adaptation of the formulation proposed by Abad et al. [5], as illustrated in Fig. 2a. Each element k of the line is treated as a structural element subjected to thermal action and axial tension, while bending, shear, and torsional stiffnesses are neglected. It is assumed that the physical properties of each element k remain constant along its length. Figure 2b shows the free-body diagram of an element under general loadings, with undeformed length $l_{0,k}$, axial stiffness EA_k, thermal expansion coefficient α_k and temperature gradient $\Delta\theta_k$.



(a) (b)

Figure 2. Mooring line with "n" elements under mechanical vertical and thermal loads (a) and element k (b).

The geometric characterization of an element k is defined by the coordinates of its endpoints, which establish the horizontal $\Delta l_{1,k}$ and vertical $\Delta l_{2,k}$ projections — also denoted as ΔH_k and ΔV_k, respectively — aligned with the Cartesian directions x_1 and x_2. Structural continuity between successive elements is ensured by imposing compatibility of nodal forces. Specifically, the force applied at the initial end of element k must match the force at the final end of the preceding element $k-1$, such that:

$$f_{i,k} = f_{i+2,k-1}, \quad i = 1 \dots 2. \tag{1}$$

Additionally, equilibrium requires:

$$f_{3,k} = -f_{1,k} \tag{2}$$

and

$$f_{4,k} = -\left(f_{2,k} + w_k l_{0,k}\right). \tag{3}$$

The force components can be generalized for the global structure of the mooring line and expressed as functions of the undeformed arc length s_k at an arbitrary section of element k. For this system, the horizontal force component f_1 remains constant across all elements, while the vertical component for a given element k varies according to Eq. (4).

$$f_{2,k}(s_k) = -\left(f_2 + \sum_{j=1}^{k-1}\left(w_j l_{0,j}\right) + w_k s_k\right). \tag{4}$$

Thus, the tensile force magnitude in element k is given by:

$$T_k(s_k) = \sqrt{f_1^2 + \left(f_2 + \sum_{j=1}^{k-1}\left(w_j l_{0,j}\right) + w_k s_k\right)^2}. \tag{5}$$

Considering that each element k has projections in Cartesian directions based on its end positions, the horizontal projection between its nodes is expressed as

$$\Delta l_{1,k} = -\frac{l_{0,k} f_1}{EA_k} + \frac{1+\alpha_k \Delta\theta_k}{{W_k}^3}\left[\left({W_k}^2 f_1\right) ln\left(\frac{\frac{f_{2,k} w_k}{W_k} + T_{1,k}}{l_{0,k} W_k + \frac{f_{2,k} w_k}{W_k} + T_{2,k}}\right)\right], \tag{6}$$

while the vertical projection is given by

$$\Delta l_{2,k} = -\frac{l_{0,k} f_{2,k}}{EA_k} - \frac{l_{0,k}^2 w_k}{2EA_k} + \frac{1+\alpha_k \Delta\theta_k}{{W_k}^3}\left[W_k w_k \left(T_{1,k} - T_{2,k}\right)\right], \tag{7}$$

in which $W_k = \sqrt{w_k^2}$, $T_{1,k} = T_k(0)$ and $T_{2,k} = T_k\left(l_{0,k}\right)$.

Given that each element of the mooring line contributes projection components along the Cartesian directions, in order to construct the mooring line geometry according to the previously established horizontal l_1 and vertical l_2 (H and V, respectively) projections, it is necessary to ensure that:

$$l_i = \sum_{k=1}^{n} \Delta l_{i,k}\,, \quad i = 1 \dots 2 \tag{8}$$

Equations (6) and (7) contain as unknowns the horizontal (f_1) and vertical (f_2) components of the force applied at the initial end of the first element ($k = 1$), forming a nonlinear system of equations. This system can be solved using appropriate numerical techniques, such as the Newton-Raphson method (Ruggiero and Lopes [6]). Once f_1 and f_2 are determined, the tensile force T_k (Eq. 4) can be computed, followed by the full geometric profile of the line using Eqs. (9) and (10).

$$l_1(s_k) = -\frac{s_k f_1}{EA_k} + \frac{1+\alpha_k \Delta\theta_k}{{W_k}^3}\left[\left({W_k}^2 f_1\right) ln\left(\frac{\frac{f_{2,k} w_k}{W_k} + T_{1,k}}{s_k W_k + \frac{f_{2,k} w_k}{W_k} + T_k(s_k)}\right)\right] + \sum_{k=1}^{k-1} \Delta l_{1,k} \tag{9}$$

$$l_2(s_k) = -\frac{s_k f_{2,k}}{EA_k} - \frac{s_k^2 w_k}{2EA_k} + \frac{1+\alpha_k \Delta\theta_k}{{W_k}^3}\left[W_k w_k \left(T_{1,k} - T_k(s_k)\right)\right] + \sum_{j=1}^{k-1} \Delta l_{2,k} \tag{10}$$

Thus, the required parameters are established, and the mooring line is spatially defined and discretized.

2.2 Thermal Gradient Along the Line

Li et al. [7] emphasize that temperature significantly affects the materials used in offshore mooring systems, especially polyester ropes. Exposure to thermal gradients induces variations in the longitudinal elastic modulus (E) and in the line length, as a result of thermal expansion or contraction caused by heat exchange at material points along the line within the water column. Consequently, the geometry of the catenary line undergoes changes: positive thermal gradients promote elongation and reduce axial tension, while negative gradients lead to contraction and line straightening, increasing tensile forces. These effects highlight the necessity of incorporating thermal influences into structural modeling of mooring lines.

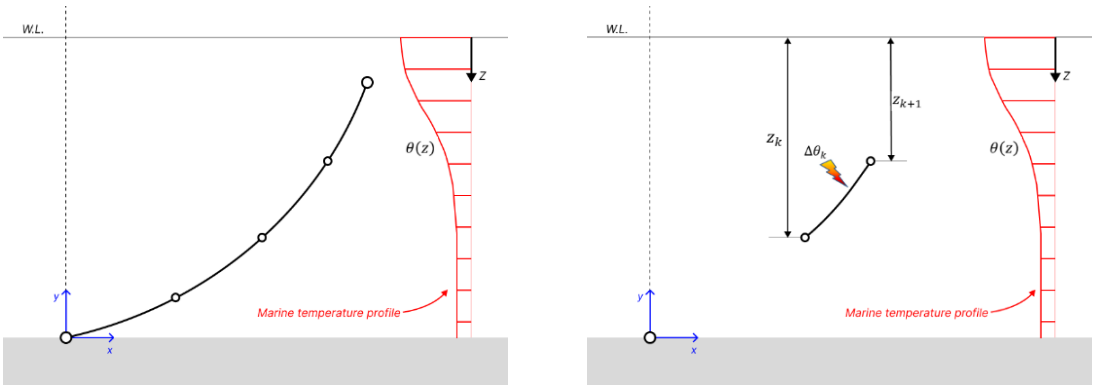
Prior to installation, the mooring line elements are at a reference temperature θ_R, which serves as the baseline for computing the thermal gradients along the line according to its deployed configuration (Fig. 3a). From this reference, the temperature variation at a generic depth z is defined as $\Delta\theta$, representing the difference between the local temperature and θ_R, expressed as

$$\Delta\theta(z) = \theta(z) - \theta_R, \tag{11}$$

in which $\theta(z)$ is the ocean temperature as a function of depth z. Considering z_k and z_{k+1} as the depths of the initial and final endpoints of element k, respectively, as shown in Fig. 3b, the thermal gradient $\Delta\theta_k$ for that element is estimated by Eq. (12).

$$\Delta\theta_k = \left(\frac{\Delta\theta(z_k)+\Delta\theta(z_{k+1})}{2}\right) \tag{12}$$

Once the thermal gradients $\Delta\theta_k$ for each element are obtained, a new geometric configuration of the mooring line is defined. This process is carried out iteratively until convergence is achieved, at which point the mooring line reaches its final arrangement in response to the thermal conditions imposed by the marine environment.



(a) (b)

Figure 3. Mooring line (a) and isolated element (b) subject to a marine temperature profile.

3 Results

To assess the effects of seawater temperature on mooring lines, a case study was conducted involving a mechanical analysis of the mooring line response under a marine temperature profile. The fairlead position was fixed according to the scenario illustrated in Fig. 4, and the physical and geometric properties of the line are provided in Tabs. 1 and 2.

Table 1. Mechanical properties of mooring line segments according to material type

Type	Segments	EA [kN]	Diameter [m]	w_0 [kN/m]	α_k
Amarra	A, C, E and G	1164903	0.12	2.439	1.2×10^{-5}
Poliéster	B, D and F	222113	0.225	0.0833	8.0×10^{-5}

Table 2. Lengths (m) and number of cable elements per segment.

Parameter	A	B	C	D	E	F	G
Length [m]	350.00	839.10	10.00	888.46	10.00	888.46	177.65
Elements	43	83	1	89	1	89	19

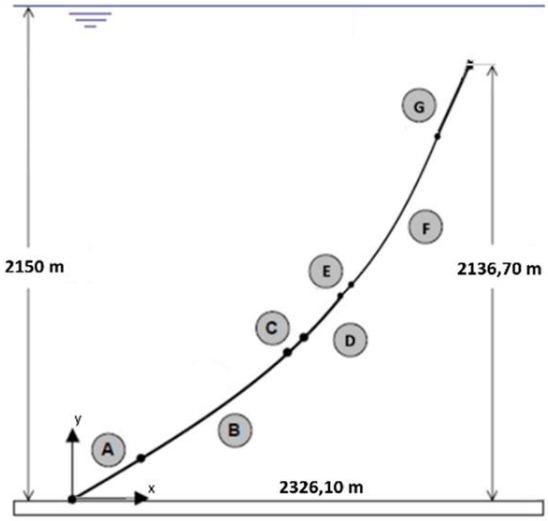
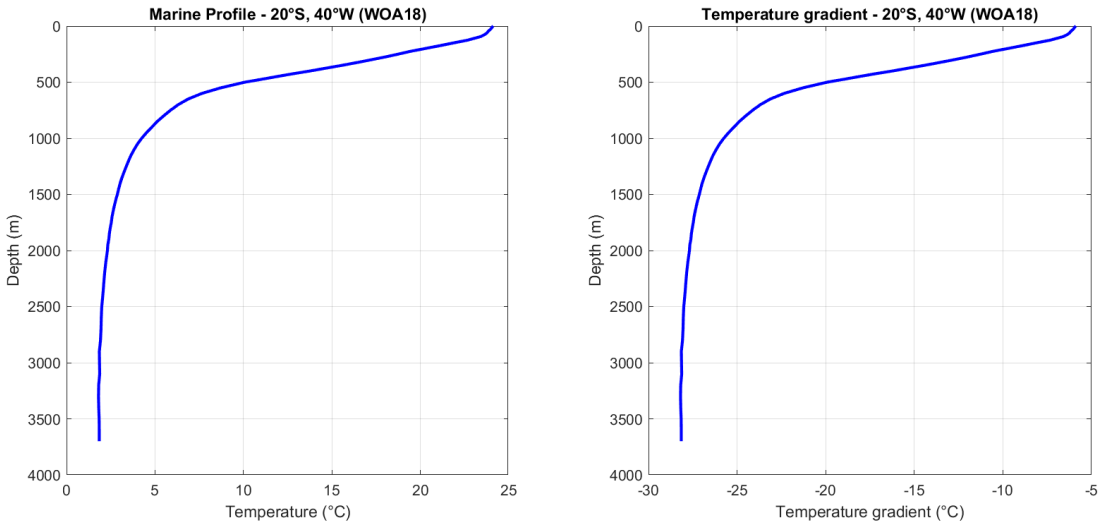


Figure 4. Deepwater scenario for the study.

The analysis was performed comparatively between two configurations: the proposed strategy without thermal effects and the same model subjected to thermal variations imposed by the marine environment. For this purpose, the seawater temperature profile shown in Fig. 5 was constructed based on oceanographic data obtained from the National Oceanic and Atmospheric Administration (NOAA [8]), through the World Ocean Atlas (WOA). The used dataset "woa18_decav_t15_01.nc" was collected in the southern Atlantic Ocean (coordinates: 20°S, 40°W), a maritime region near the coast of Espírito Santo, Brazil.



(a) (b)

Figure 5. Maritime temperature profile (a) and thermal gradient in relation to $T_R = 30\ °C$ (b).

For the simulations, the reference temperature of the mooring line materials (θ_R) was assumed to be 30°C. The results of the analysis are presented in Figs. 6 and 7, the geometric configuration and mechanical response of the mooring line under the two thermal conditions.

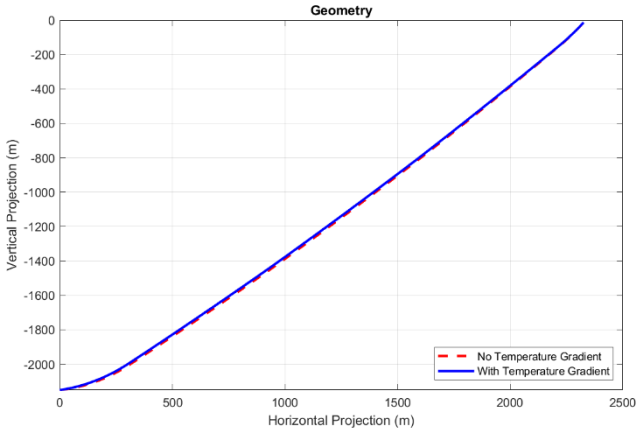


Figure 6. Geometry of the mooring line of the studied scenario.

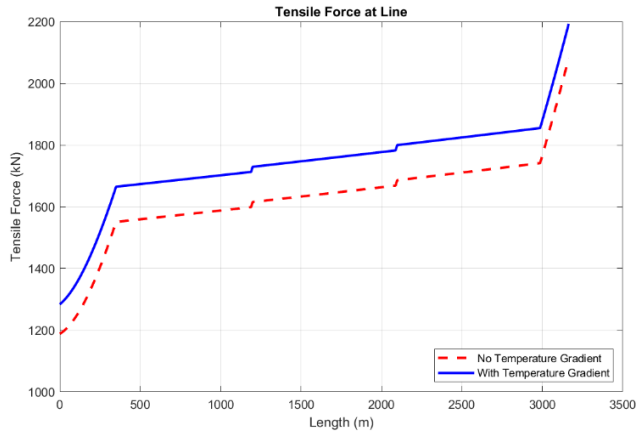
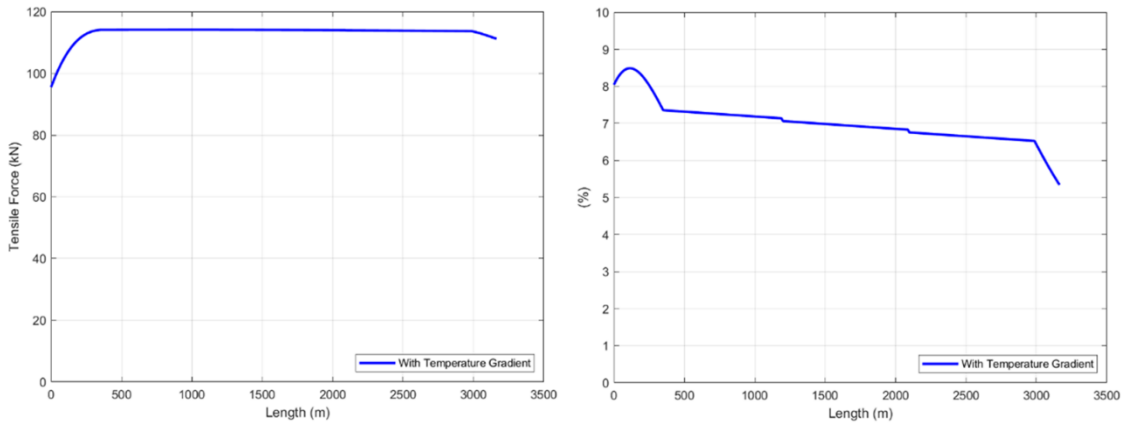


Figure 7. Tensile force along the mooring line of the studied scenario.



(a) (b)

Figure 8. Absolute (a) and relative (b) deviation between the tensile force in the mooring line with temperature gradient and without temperature gradient in the studied scenario.

The comparative analysis shows that, although the consideration of thermal effects leads to negligible changes in the overall geometry of the structure (Fig. 6), it significantly alters the mechanical response along the line, as illustrated in Fig. 7. Figure 8 presents the structural response errors that arise when thermal effects are neglected in the analysis, revealing absolute and relative deviation of up to 114.1 kN and 8.5%, respectively, in tensile force estimates along the mooring line.

4 Conclusions

This study proposes a strategy for incorporating thermal effects into the analysis of mooring lines, based on the formulation of cable structures under general loadings, with the aim of evaluating their impact on the geometric configuration and static mechanical response of mooring lines, particularly in deepwater scenarios. The results indicate that neglecting thermal effects associated with marine temperature profiles leads to an underestimation of axial tensions in mooring lines. The proposed methodology predicts tensile forces values up to 8.5% higher than those estimated by conventional models that disregard offshore thermal influences. These findings confirm that thermal gradients in offshore environments represent a relevant environmental action that can significantly affect the mechanical response of mooring lines. Future research may consider the influence of temperature on the mechanical properties of the line — specifically, changes in the axial stiffness of its segments — as well as hydrostatic pressure effects, to investigate their combined impact on the structural behavior of mooring lines.

Acknowledgements. The authors gratefully acknowledge the financial support provided by CNPq and Petrobras.

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] R. F. Solano. Flambagem térmica de um sistema pipe-in-pipe dual em águas profundas. M.Sc. Ocean Engineering thesis, Federal University of Rio de Janeiro, 2021.
[2] D. Qiao, G. Zou, H. Chen, G. Tang, L. Lu and J. Ou, “Influence of thermo-mechanical coupling effects on the stiffness characteristics of dynamic cables”. *Applied Ocean Research*, vol. 158, 104583, 2025.
[3] K. D. Luo, J. Li, H. W. Yang, J. S. Wang and X. Zhang, “Influence of the Riser Boost Line on the Thermal Stress of Riser in Deepwater Drilling”. *Materials Science Forum*, vol. 944, pp. 1005-1010, 2019.
[4] X. Zheng, M. Seaid, A. S. Osman, “A fully coupled dynamic water-mooring line system: Numerical implementation and applications”. *Ocean Engineering*, vol. 294, 116792, 2024.
[5] M. S. A. Abad, A. Shooshtari, V. Esmaeili and A. N. Riabi. "Nonlinear analysis of cable structures under general loadings". Finite Elements in Analysis and Design, vol. 73, pp. 11–19, 2013.
[6] M. A. G. Ruggiero and V. L. R. Lopes. *Cálculo numérico: Aspectos teóricos e computacionais (2° Ed.)*. Makron Books do Brasil, 1997.
[7] W. Li, X. Liu, G. Li, S. Lin, H. Li and Y. Ge, “Temperature and Humidity Effects on the Dynamic Stiffness of a Polyester Mooring Rope”. *Journal of Marine Science and Engineering*, vol. 11, ed. 1, n. 91, 2023.
[8] National Oceanic and Atmospheric Administration, “woa18_decav_t15_01.nc”, NOAA, 2019. Available at: https://www.ncei.noaa.gov/thredds-ocean/catalog/ncei/woa/temperature/decav/1.00/catalog.html