Analysis of inertial influence and damping of mooring lines on fatigue damage

Christie de V. P. Machado [1], Magnus C. de V. Prata [1], Breno P. Jacob [1], Fabrício N. Corrêa [1]

[1]*Civil Engineering Program – PEC/COPPE, Federal University of Rio de Janeiro – UFRJ*
Avenida Pedro Calmon, s/n, Cidade Universitária, Ilha do Fundão, 21941-596, Rio de Janeiro/RJ, Brazil
christie@coc.ufrj.br, magnus@coc.ufrj.br, breno@lamcso.coppe.ufrj.br, fabricio@lamcso.coppe.ufrj.br

Abstract. The oil exploration sector has been extensively using floating platforms anchored by mooring lines composed of steel chains/cables and polyester cables that restrict platform movements within a project region. Offshore platforms are exposed to environmental loads of waves, wind, and currents, which are responsible for generating hull motions and tension variation in the mooring lines. This tension history, in turn, is directly associated with fatigue failure of the lines. Despite efforts to correctly estimate the fatigue life of mooring lines, premature failures of the mooring system have been observed in recent decades, indicating that the fatigue damage estimated during the design phase may be less than the actual damage occurring in the field. Several factors influence the initial estimation of fatigue life, for instance, the analysis method used to represent the lines behavior, such as quasi-static and dynamic analysis. The first ignores inertial and damping effects, while the dynamic analysis accurately represents the dynamic behavior of the mooring lines. Therefore, the present work carries out a critical analysis based on the comparison between the fatigue life resulting from the two forms of analysis, evaluating the influence of inertia and damping of the moorings on fatigue damage.

Keywords: mooring lines, fatigue, quasi-static and dynamic analysis.

1 Introduction

The high demand for oil pushed its exploration into increasingly deeper waters, which required significant scientific and technological advances. In this context, floating platforms have become widely used in the oil and gas sector. One of this type of platform is based on the concept of a ship, with mooring lines to keep the floating unit in the design region foreseen by the riser's project. The mooring lines are made up by different materials such as chain, steel cables or polyester cables, fixed to the seabed using anchors.

Offshore platforms are constantly exposed to environmental wave, wind and current loads that generate hull movements and consequently, tension variations in the mooring system. In turn, the recurrence of this behavior is directly associated with fatigue failure of the mooring lines. Despite constant efforts to estimate the fatigue life of mooring lines to ensure their integrity during platform operation, premature failures in the mooring system have been observed in recent decades, as described by Ma *et al.* [1]. This serves as a warning that the fatigue damage estimated during the design phase may be less than the actual damage occurring in the field.

The line modeling method is one of the factors that influences the definition of damage in the construction phase, and it is in this context that the present work is inserted, since two different ways of representing the behavior of the lines are studied: quasi-static and dynamics analysis. The first ignores inertial and damping effects similar with catenary equation approach – as used in mooring system designs in the 90s and early this century due to its low computational cost – , but in this work using finite element model solved by Newton-Rapson method; while dynamic analysis are evaluated via finite elements, according to Leal [2], that considers inertial and damping effects, accurately represents the dynamic behavior of mooring lines, being increasingly used today.

Therefore, this work will evaluate the influence of inertia and damping of the moorings on fatigue damage, comparing the quasi-static and dynamic approaches studied with a numerical model of a floating unit. For this purpose, previous movement data from the year 2017 of a platform with a water depth of approximately 900m is used, which uses a conventional catenary mooring system combined by chain and wire rope segments. In this way, a critical analysis is carried out based on the comparison between the fatigue life resulting from the two forms of analysis.

2 Fatigue in mooring systems

It can be said that fatigue is the process of degradation of the mechanical properties of a material characterized by the slow growth of a crack leading to the failure of the material. The phenomenon of fatigue in mooring lines is directly related to the action of environmental loads (current, wave and wind) that impose tension fluctuations on the lines, which over time can lead to their rupture. Thus, fatigue failure requires that not only extreme loading conditions be considered, but also other possible scenarios, as it is a phenomenon that can occur for loads that generate stresses lower than the resistant capacity of the material. Furthermore, Pfeil and Pfeil [3] explains that, fatigue resistance is strongly reduced at points where there is a concentration of stress, caused, for example, by: imperfections on the surface of the material, sudden variations in the shape of the section, welds, etc.

The assessment of fatigue life in structural design can be carried out using T-N or S-N experimental curves. As in the analysis of fatigue in mooring lines the data analyzed are the tensions of the lines, the use of T-N curves in these cases becomes quite intuitive. Furthermore, according to Xue *et al*. [4], the approach based on T-N curves is slightly more conservative than using S-N curves.

2.1 T-N curves

The T-N curves, represented by eq. (1) present in the API [5], are empirical curves that relate a given tension variation to the number of cycles that leads to rupture of a given material so that, the greater the tension variation, the lower the number of cycles.

$$N = K \cdot R^{-m} \tag{1}$$

where N is the number of cycles until failure, R is the ratio between the average tension amplitude and the minimal breaking load (MBL), and K and m are parameters of the T-N curve available in the API [5], specific for each material and obtained by experimental tests.

2.2 Cumulative Damages Law (Palmgren-Miner Rule)

The Palmgren-Miner Rule says that the total damage associated with a given period is the linear accumulation of individual damages for that same period. Since the individual damage, defined by eq. (2), corresponding to each tension range that occurs in the analyzed period, as shown by Ruschel [6] and Borzacchiello [7].

$$d_i = \frac{n_i}{N_i} = \frac{n_i}{K \cdot {R_i}^{-m}} \tag{2}$$

where N_i is the limit number of cycles associated with a given tension variation R_i (range) and n_i is the number of occurrences of variation in this tension R_i. According to Ruschel [6], the total damage accumulated in each period of time, defined by the sum of individual damages, can be obtained from eq. (3).

$$D_{total} = \sum_{i=1}^{N_{range}} d_i \tag{3}$$

where N_{range} is the number of voltage ranges identified in the analysis period. Fatigue failure occurs when the total accumulated damage assumes a value equal to unity ($D_{total} = 1$). And after obtaining the total damage associated with a certain period T, the fatigue life (FL) can be calculated using eq. (4) as shown by Rubi [8].

$$FL = \frac{T}{D_{total,T}} \tag{4}$$

In general, the fatigue life is calculated in years so the period T is 1 year and the total damage ($D_{total,T}$) is the annual damage.

2.3 Cycle counting: Rainflow method

Cycle counting is one of the fundamental steps for calculating accumulated damage, as it allows the identification and counting of each tension range, enabling the subsequent application of the Palmgren-Miner Rule. Counting methods can be based on the time domain or the frequency domain, with those based on the time domain counting from the tension time series itself, making them present more accurate results. Figure 1 shows an example of a tension time series with irregular behavior, highlighting how the identification and counting of cycles can be complex.

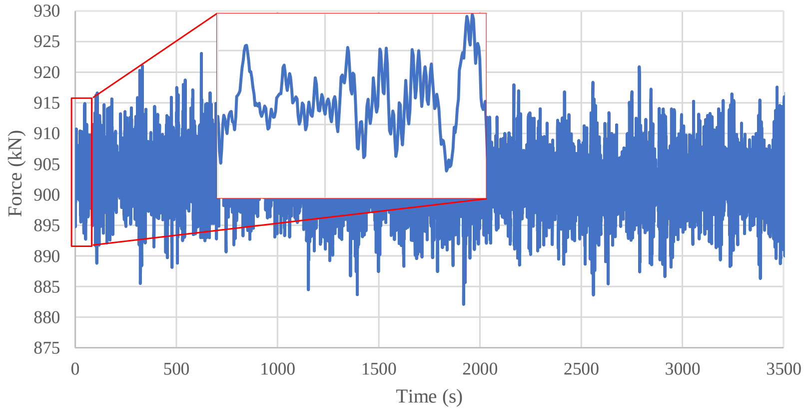


Figure 1. Example of irregular tension time series

According to Rubi [8], there are currently some cycles counting methods available; the more relevant is the Rainflow method, presented by ASTM [9], presenting more accurate results. To identify and calculate tension cycles in a time series using the Rainflow method, different numerical algorithms can be used. To know the details of each of them, it is recommended to consult ASTM [9].

As a result of the Rainflow method, a relationship is obtained between the range values of each tension cycle identified in the series and the number of occurrences of each of these cycles. And on this result, the Palmgren-Miner Rule is applied, defining the total damage and enabling the fatigue life to be found.

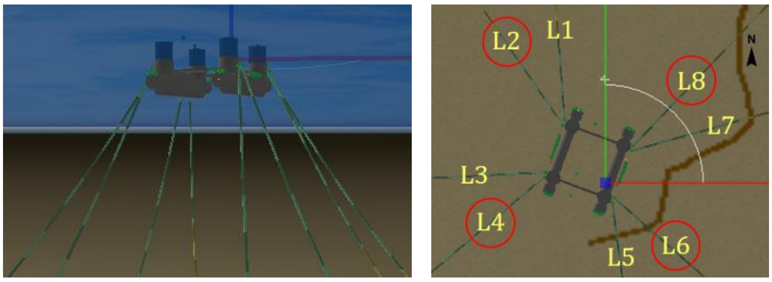
3 Monitored data

To carry out a retroanalysis it is necessary to use data measured in the field of the platform's movements, and this measurement is usually done using GPS (Global Positioning System) and OCTANS. The GPS is the device responsible for providing data with only the position of the platform, which are low frequency (slower) movements generated by the effects of wind, current, mean drift and slow drift of the wave. Latitude and longitude data are collected at a regular time interval, generally at 1-second intervals, to be later converted into UTM coordinates. OCTANS is made up of accelerometers, gyroscopes and a real-time computer forming an Inertial Measurement Unit (IMU), as described by Borzacchiello [7] and Nogueira [10]. The data provided by OCTANS includes the platform's heading and surge, sway, heave, pitch and roll movements.

It is important to highlight that the quality of the data measured by these devices can greatly impact the results of the fatigue analysis. Therefore, according to Borzacchiello [7], an inspection of the data must be carried out in order to identify possible measurement errors, such as: time jumps, incorrect data, gaps in data acquisition, etc.

4 Case study

This work was dedicated to study fatigue in mooring lines, and for this purpose a model of a semi-submersible platform was used, with a heading of 20º, located in a water depth of approximately 900m. Its mooring system consists of 8 lines in a conventional catenary arrangement, two at each corner of the platform. For this study, one line was chosen from each corner of the platform, totaling 4 lines. The dynamic and quasi-static analyzes was performed using previous motion data from 2017, through uncoupled simulations in the context of mooring lines, with prescribed movements representing the hull behavior. Figure 2 (a): shows the model of the platform used for the study and (b): a top view of this model, numbering each of the mooring lines, highlighting with a red circle the lines chosen for fatigue analysis.



(a) (b)

Figure 2. (a): Model of the studied platform; (b) top view of the model with numbered mooring lines. The lines chosen for the study are circled in red

To model the mooring lines, several specifications were considered, Tab. 1 presents some of them. And to calculate the fatigue damage using the T-N curve, the use of a “Common studless link” type chain was considered, which according to API [5], has the following curve parameters: $M = 3$ and $K = 316$. Furthermore, an $MBL = 7207.5$kN was used for these moorings. Thus, using eq. (1) it is possible to know the number of cycles until failure.

Table 1. Some characteristics of the mooring lines of the studied model

Line	Upper chain length (m)	Azimuth (°)	Top of the line tension (kN)
L1	156	355.53	943.79
L2	231	325.41	902.11
L3	302	267.11	1226.56
L4	307	229.92	1042.06
L5	231	172.38	1044.34
L6	206	131.27	984.66
L7	182	74.40	1121.25
L8	189	43.75	1211.05

4.1 Scientific workflow

In this study, a step-by-step guide was followed to estimate the fatigue life of the moorings. Initially, a base model of the platform was created comprising the hull and mooring lines. To create the base model and subsequent analysis of the models created, the program developed by the Laboratory of Computational Methods and Offshore Systems - LAMCSO called SITUA-Prosim was used.

Concomitantly with the creation of the base model, data on environmental loads (wave, wind and current) for the period of interest are selected and grouped. In the case of this study, only the current load for the year 2017 was considered and the data on this load were grouped into 1-hour intervals.

Furthermore, the movement data from GPS and OCTANS were combined to generate the displacements, rotation and heading for each hour of the year 2017. With these files, together with the environmental loading and the base model, a routine implemented in python is used to generate models for each hour of the year 2017, considering environmental loads and movement data referring to the respective hour.

As it would be unfeasible to simulate all models for each hour of the year for this study, 10 representative models were selected for each month, totaling 10 hours per month. The choice of these representative models was made based on the models that simultaneously had the most recurrent current and wave data for the month. That is, considering the current directions and speed, and wave directions, heights, and periods that occurred most in each month, 10 models with these characteristics were selected.

With the 120 selected models, analyses were carried out using the SITUA-Prosim program. Two "batches" of simulations were carried out, one considering the dynamic modeling of the lines and the other quasi-static. Then, damage for each hour was calculated using FadPro, another program developed by LAMCSO. This program applies the Rainflow cycle identification and counting method to the line tension time series generated during the simulations. And finally, knowing the fatigue damage for the selected hours, an estimate of the monthly and annual damages is made (sum of the monthly damages) and the definition of fatigue life.

4.2 Monthly Damage and Fatigue Life Results

After carrying out the entire scientific workflow described previously, Tab. 2 and Tab. 3 present the estimated damages for each of the months of 2017 of the 4 mooring lines studied, with Tab. 2 referring to the damages obtained considering the dynamic modeling of the lines and the Tab. 3 quasi-static modeling.

Table 2. Estimated monthly data: Dynamic analysis

Mês	L2	L4	L6	L8
January	9.59E-06	8.16E-06	9.44E-06	1.67E-05
February	1.13E-05	1.31E-05	1.27E-05	1.87E-05
March	1.91E-05	3.64E-05	2.28E-05	2.83E-05
April	1.91E-05	3.64E-05	2.28E-05	2.83E-05
May	2.43E-05	2.33E-05	3.04E-05	1.75E-05
June	2.52E-05	3.23E-05	3.68E-05	3.33E-05
July	2.97E-05	4.74E-05	3.74E-05	3.91E-05
August	1.69E-05	1.76E-05	1.98E-05	1.86E-05
September	3.37E-05	7.59E-05	4.69E-05	6.32E-05
October	2.15E-05	3.56E-05	2.56E-05	4.44E-05
November	2.02E-05	1.93E-05	2.34E-05	2.25E-05
December	2.87E-05	3.45E-05	3.23E-05	3.77E-05

Table 3. Estimated monthly data: Quasi-static analysis

Mês	L2	L4	L6	L8
January	1.27E-11	1.52E-10	1.94E-10	5.70E-10
February	7.41E-11	4.83E-10	1.33E-10	2.98E-10
March	5.37E-10	5.78E-09	2.58E-09	5.17E-09
April	5.37E-10	5.78E-09	2.58E-09	5.17E-09
May	7.96E-10	1.54E-09	2.79E-09	5.08E-09
June	4.79E-10	1.02E-09	2.16E-09	1.48E-08
July	4.19E-10	2.26E-09	1.31E-09	2.87E-09
August	2.39E-10	1.18E-09	1.18E-09	1.42E-09
September	4.53E-10	6.34E-09	2.45E-09	5.55E-09
October	1.31E-10	1.90E-09	1.12E-09	9.03E-10
November	9.94E-11	6.53E-10	8.20E-10	2.18E-09
December	2.21E-10	1.61E-09	1.15E-09	1.95E-09

To obtain the fatigue life (in years), the damages from all months of 2017 were added and the eq. (4) was used. In projects, a safety factor must be considered, therefore, the fatigue life value must be divided by ten. Table 4 and Tab. 5 present the values of annual damage, fatigue life and fatigue life reduced by the factor. Table 4 presents the results obtained considering the dynamic modeling of the lines and Tab. 5 the quasi-static modeling.

Table 4. Annual damage and fatigue life: Dynamic analysis

	L2	L4	L6	L8
Annual damage:	2.593E-04	3.802E-04	3.205E-04	3.682E-04
Fatigue life (years):	3856.8	2630.5	3119.8	2715.6
Fatigue life/10 (years):	385.7	263.1	312.0	271.6

Table 5. Annual damage and fatigue life: Quasi-static analysis

	L2	L4	L6	L8
Annual damage:	3.997E-09	2.871E-08	1.847E-08	4.593E-08
Fatigue life (years):	250162480.7	34835396.0	54129042.3	21772786.7
Fatigue life/10 (years):	25016248.1	3483539.6	5412904.2	2177278.7

Aiming to complement the understanding of the great difference between the results obtained by simulations that used the dynamic line solution method and the quasi-static method, a graph was plotted in Fig. 3. In this graph, it is presented two tension time series of the same time window of one mooring line. The series represented in blue was evaluated by the dynamic analysis and the series in orange by the quasi-static analysis.

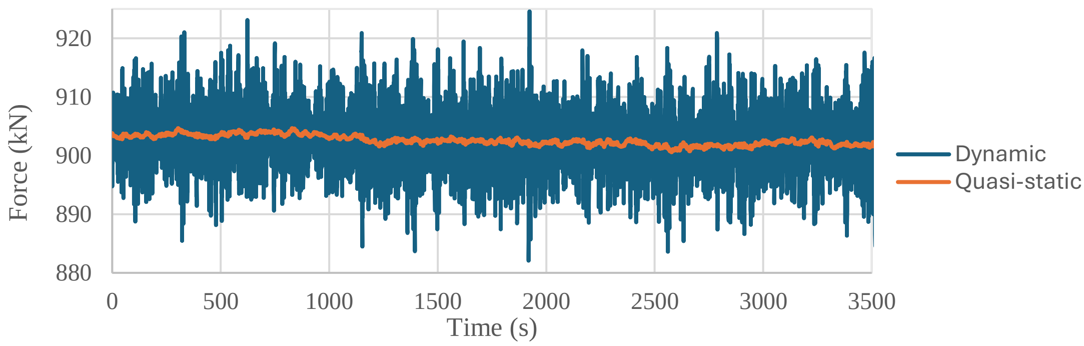


Figure 3. Graph of the tension series of a mooring line: Dynamic vs. Quasi-static

5 Conclusions

The damage to the moorings obtained using the quasi-static solution method is much lower than the values found using the dynamic line solution method. Consequently, the fatigue life values using the quasi-static solution will be significantly higher than using the dynamic solution. This in turn was expected, once the quasi-static solution inertial and damping effects of the lines are disregarded, which does not occur in the dynamic solution. Therefore, it was expected that the damages found by the dynamic simulations would be more significant, and they would better represent the behavior that occur in the mooring lines in the field.

As expected, it is observed that, although the average values of line tension from the dynamic and quasi-static analysis remain close in both time series, the tension ranges of the dynamic time series are much higher than those of the quasi-static series. And as the Rainflow method, used to calculate the damage, is based on the range values of the series, the damages of the dynamic time series will be much greater than those of the quasi-static series.

Considering that the operating time of the platforms is in the range of 30 years and that line ruptures have still occurred during this period, it is evident that the calculated fatigue life presented in this work has considerably high values. Even for the case in which the dynamic line solution method was used, the lowest reduced fatigue life value was 263 years. This is an indication there are factors that significantly impact the damage but are not being considered in the fatigue analysis. Discovering these factors is complex but extremely important task, reinforcing the need for more studies about this topic. The impact of corrosion on the fatigue life is one of the factors that deserves attention, as observed by Silva's [11] that shows the corrosion predicted by the standards is lower than that which occurs in the field.

It is important to observe the fatigue life presented here was estimated assuming the selected 10 hours per month of 2017 was adequate to represent the damage along that year, but it still must be verified in future works. Besides, it also must be studied if the damage observed in 2017 can be extended for the following years.

However, recalling the objective of this work, it is concluded that the solution method applied to the mooring lines has a great impact on damage, showing that inertial and damping effects – via dynamic analysis – must be considered for fatigue life of the mooring lines in a typical catenary configuration.

Acknowledgements. The first author thanks the Brazilian program PRH – 09 from COPPE/UFRJ and the agencies ANP 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] K. Ma *et al*., "A Historical Review on Integrity Issues of Permanent Mooring Systems", *Offshore Technology Conference*, Houston, TX, USA, 2013.
[2] G. S. Leal. Avaliação de Metodologia de Projeto de Sistemas de Ancoragem de Plataformas Flutuantes em Relação à Fadiga. M.Sc. thesis, COPPE/UFRJ, Rio de Janeiro, Brazil, 2016.
[3] W. Pfeil and M. Pfeil, "Estruturas de Aço: Dimensionamento Prático", 8 ed., Rio de Janeiro, LTC. PINHEIRO, 2009.
[4] X. Xue *et al*., "Mooring system fatigue analysis for a semi-submersible". *Ocean Engineering*, v. 156, p.550–563, 2018.
[5] API RP 2SK, *Design and Analysis of Stationkeeping Systems for Floating Structures*, 3rd ed., American Petroleum Institute, 2005.
[6] A. Ruschel. Método da Redução de Dimensão Univariada Aplicado à Análise de Fadiga de Estruturas de Cabeças de Poços de Petróleo Considerando o Efeito Simultâneo de Ondas de Mar Local e de *Swell*. M.Sc. thesis, COPPE/UFRJ, Rio de Janeiro, RJ, Brazil, 2021.
[7] G. R. Borzacchiello. Análise Global de Fadiga em Linhas de Ancoragem Considerando Ultra-Baixas Frequências de Dados de Movimentos Medidos. M.Sc. thesis, COPPE/UFRJ, Rio de Janeiro, RJ, Brazil, 2019.
[8] V. A. S. Rubi. Comparação entre métodos de cálculo da vida útil à fadiga de linhas de ancoragem considerando espectros bi-modais de tração. M.Sc. thesis, COPPE/UFRJ, Rio de Janeiro, Brazil, 2013.
[9] ASTM International, "E1049-85: Standard Practices for Cycle Counting in Fatigue Analysis", 2011.
[10] S. Nogueira. Sistemática para Executar Teste de Inclinação em Unidades Semissubmersíveis de Produção Operando na Locação. M.Sc. thesis, COPPE/UFRJ, Rio de Janeiro, RJ, Brasil, 2010.
[11] M. Silva. Estudo da Influência do Desgaste na Falha Prematura de Componentes de Linhas de Ancoragem. M.Sc. thesis, University of Brasilia, Brasília, DF, Brazil, 2016.