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METHODOLOGY FOR OBTAINING A DIGITAL TWIN FOR A FPSO MOORING SYSTEM

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Abstract. A digital twin (DT) is an information model that represents a physical entity. Its main feature is to combine real and virtual data, in order to evaluate and monitor many systems and processes in different fields of knowledge. This paper proposes a particular application of DT in the Oil & Gas (O&G) industry. In this scenario, DT can be useful for life-cycle management and structural health monitoring of complex offshore structures, such as a Floating Production Storage and Offloading (FPSO). This work focuses on the analysis of an FPSO mooring system. Mooring systems play an important role in the FPSO global motion, being responsible for both the station-keeping and the dynamic response of the vessel. In this context, any failure could compromise their effectiveness and affect the expected production of the FPSO. Moreover, depending on the failure, environmental risks can be high. Thus, an accurate prediction for the behavior of mooring lines is essential. However, monitoring a whole system including the entire lines in real-time is unpractical in terms of data storage, installation, and data processing. Therefore, the possibility of the usage of virtual sensors can be seen as a welcome strategy for the context. For that, one needs to expedite tools to combine real and digital data that can help overcome the obstacles. This paper presents a methodology based on a hierarchical modeling for the lines for establishing DT for mooring systems. Distinct mooring models, including intact and damaged lines, are employed, covering analytical formulation and numerical solutions using the finite element method.

Keywords: digital twin, offshore structures, mooring system, methodology, FPSO.

1. INTRODUCTION

Mooring lines are important components of floating production systems (FPS), responsible for station-keeping of the vessel. Design and maintenance of mooring systems depend on environmental and operational conditions, which makes them a complex task. Because of that, FPS have many possibilities of failures, which may cause catastrophic economical consequences for the industry. According to Ma *et al.* (2013), which summarizes various incidents over the last decade, there are relevant probabilities of multiple line failures or single-line breakage, often in the early stages of operational life, due to weak points in lines structure, mostly in components as chain, connectors and wire rope. Accidents involving

mooring system failure can lead to vessel drift or, eventually, to rupture of the risers rupture. Despite all development in monitoring these elements, it stills a hard and costly task to maintain sensors for these components.

Aiming at predicting the system behavior and preventing it from major damages, the use of virtual sensors can be a viable alternative to maintain FPS integrity. It is possible to make indirect measures using input data, e.g. GPS (global positioning system) sensors and metocean data to feed models capable to predict or indicate changes in operation state of the system. Examples of models that could fulfill this task are reduced-order models (ROMs) and models based on machine learning (ML) techniques. Gumley *et al.* (2016), Ritto and Rochinha (2021) and Prislín and Maroju (2017) are examples of works involving ML studies with offshore systems, while Sharma *et al.* (2018) can be cited as an example of work with ROM techniques for the same area.

In this context, digital twin (DT) is a topic that has been discussed over the last two decades and has been applied for many purposes. Some works, such as Grieves and Vickers (2016) and Kritzingner *et al.* (2018), developed definitions and concepts about this term. A DT is a virtual information model that represents a physical object. Some differences between a DT and a default model digitally made are the holistic representation of an entity and real-time connection with the modeled object, creating a data exchange between the digital and real entities. Figure 1 shows a conceptual representation of a DT, adapted to offshore applications.

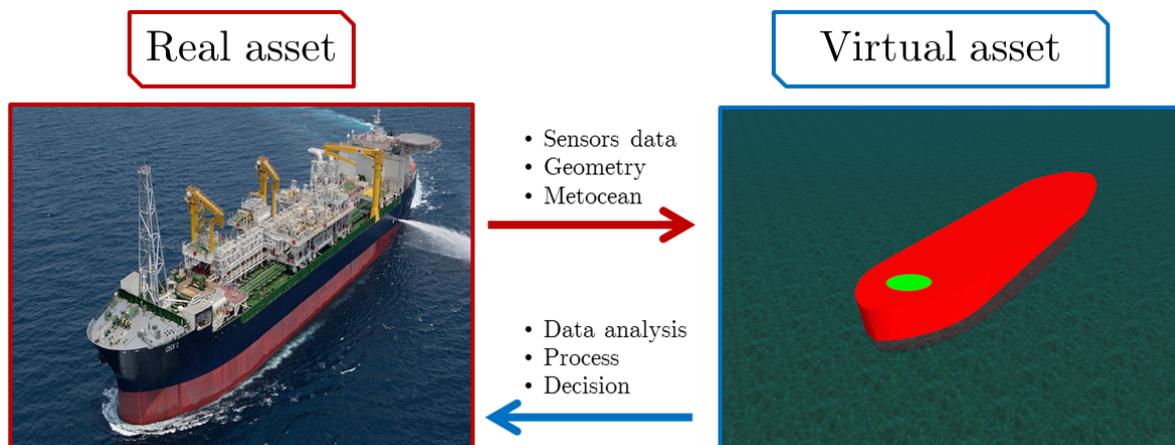


Figure 1. Conceptual diagram of digital twin for an offshore entity. FPSO photo extracted from <http://mpckr.blogspot.com/2011/04/osx-brasil-receives-order-for-three-new.html>.

Relating digital twins with offshore systems, the development of a DT model could assist operational and management decisions in O&G platforms, integrating data collected from the physical system with real-time analysis with expedite tools. Some examples of DT applications in offshore researches can be seen in Schirmann *et al.* (2019) and Tygesen *et al.* (2018).

For the purpose of this research, a framework of a digital twin creation is developed in this work. Focusing in explain the steps and possibilities to obtain it, this research has the objective to show manners to deal with inputs and outputs for an embarked system. Also, tests involving intact and damaged systems were proposed to show the possibilities to use the DT model as a virtual sensor. Since the use of DT in the offshore scenario is quite recent, methodologies for its definition are not found in the literature and brings a novel aspect of the present paper.

2. METHODOLOGY

The entire methodology process can be described in four parts that are completely interconnected. Figure 2 shows the holistic process developed to simulate a digital twin of an FPSO system, simplified as a ship-line configuration. There are three partitions representing the virtual asset (blue boxes and arrows), arranged as an input-process-output system, while there is one partition representing the real asset (red box). This sketch is a detailed version of Figure 1, adapted for the purpose of this work. Also, it is revisited along the entire section, provided it summarizes the research.

Along this section, each part of the DT system is explained in details, focusing on inputs, outputs, data process type and possibilities to process all the generated data.

2.1 Ship (real asset)

For DT, the real asset works as a database for the virtual model operations. As a matter of fact, the entire cycle of DT starts and finishes in the real entity, since that the main objective of the digital asset, in this case, is to assist in the management and maintenance of the FPSO, increasing its operational life and reducing damage chances.

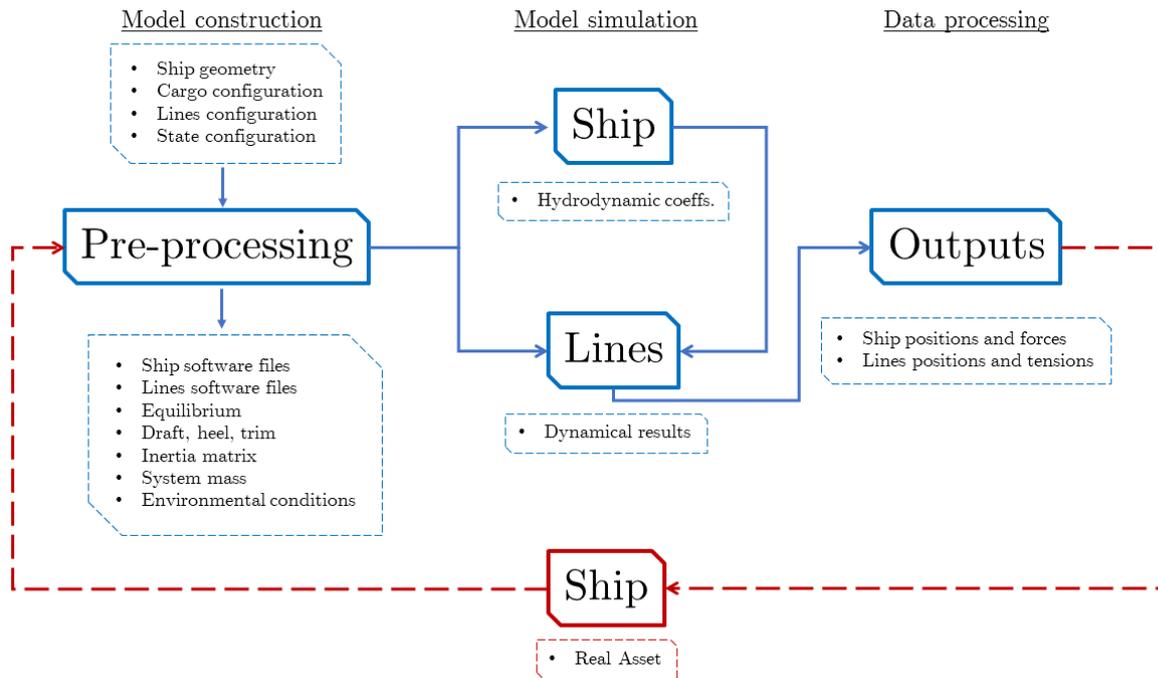


Figure 2. Schematic diagram of digital twin framework.

In this first application, the real asset is only a provider of information for pre-processing of the model, in the model construction stage. First data that is obtained from the FPSO system is the ship geometry, usually in .pdf or .cad files. In this case, to convert this information into a three-dimensional mesh format is the most manual step required for the DT process. In this work, the ship geometry is converted into geographic data files (.gdf) to use as an input for another software at model simulation.

Also, information about lines configuration, such as coordinates, arrangement, position and material composition are needed to process data before sending it to specific software. The same occurs with cargo configuration, relevant information for mass distribution, equilibrium and inertia matrix calculation and as inputs for the simulations. Lastly, it is possible to get environmental information about sea and climate state with sensors installed on the real asset, but it is also possible to get metocean information by specific databases or models for that.

2.2 Model construction

With all the data from the FPS as an input, the next step is to make the pre-processing of collected data, transforming it into useful data for simulation software for each specific part of the offshore system. For this task, some data-processing simple tools were developed to calculate ship properties and set the equilibrium position for the whole system.

Considering the ship properties such as draft, heel and trim; inertia matrix, external damping matrix, the mass distribution of mass along its length can be found using analytic analysis considering the system equilibrium. Some parameters as mass distribution (due to cargo physical configuration) and environmental conditions can be changed as desired, whether to test specific situations or to create a database for another process. The same process occurs for the mooring lines and in this work using the analytical formulation presented in Pesce *et al.* (2018) to set equilibrium state for whole mooring system.

Finally, with all the data pre-processed needed for model simulation, files for software simulations are created as inputs for the next stage of the DT. In the next step, in addition to inputs and outputs considered for each model, a discussion about the software that can be used for the simulation of part of the system is made.

2.3 Model simulation

Here, model processing is divided into two interconnected parts. The first one refers to the ship model to obtain hydrodynamic coefficients as inputs for the line model. In this case, WAMIT[®] is used for this task. The mentioned software uses potential flow theory applied to solve the linearized boundary value problem (BVP) in the frequency domain by using the boundary element method (panels). These numerical methods solve the Laplace equation (mass conservation) with boundary conditions of impermeability and specific Green functions according to the domain/problem studied. Another

software option identified for the same function is Ansys AQWA[®], that does the same process of using CAD files and ship properties as inputs to export the same type of results. From this analysis, one obtains displacement, loads and wave drift response amplitude operators (RAOs) associated with the vessel.

After that, generated RAOs from vessel are used as one of the data inputs for line models to couple both entities. For the purpose of dynamic simulation of lines, this is important for studying the influence of the interaction between ship configuration and environmental conditions, which affects lines offset and positions and, consequently, line tensions. For this task, software such as OrcaFlex[®] (2021), Flexcom[®] (2021) and Giraffe^{®1} were considered. In this work, OrcaFlex[®] was the choice due to its API developed for MATLAB[®] and Python languages, same as used to develop tools at model construction stage. These APIs allow users to create codes to automate all steps of the case simulation, from objects creation (such as vessels, connections and lines) to the execution of the simulation and obtaining its results, being very useful to transform the entire process in an expedite routine.

2.4 Data processing

Lastly, all generated data is compiled into graphs and tables for analysis. As the same for model construction, in this step, tools to facilitate data analysis are created utilizing codes already developed in the previous stages. Data generated in this step can be used directly (e.g. automatized feeding line systems) or indirectly (support for the technical decision of offshore operators).

In this paper, just to introduce an example of working methodology, only sensitivity analysis to find line failures using tension data is shown. However, the entire data generated by vessel and lines simulation can be used to perform inspections on the system (DT working as a virtual sensor) or to test the system subject to specific work and environmental conditions.

3. MODEL

Herein, a FPSO model with a single-point mooring (SPM) system is developed. Mooring system is composed of nine equal lines with a chain-wire rope-chain composition for each one. Figure 3 shows the entire system modeled with OrcaFlex[®], using WAMIT[®] output (vessel RAOs) as the vessel input. As it turns out, in addition to the ship and lines, there is a turret object connecting both systems, responsible for allowing yaw rotations. One important information is the global axes, located at the ship's bow, as indicates the XZ view. Also, relevant vessel parameters, such as geometric dimensions and mass, are listed in Table 1. All information related to the vessel comes from a real ship model from confidential sources.

Table 1. Vessel model parameters.

Vessel parameters	Value
Displacement (ton)	228217
Length overall (LOA) (m)	322
Length between perpendiculars (LBP) (m)	310
Beam (m)	56
Depth (m)	29
Draft (m)	16
Deadweight tonnage (DWT) (ton)	29366

Table 2 presents the composition for each segment of each line. For the sake of brevity, lines are separated into three groups, as one can see in Figure 3 at XY view. For each segment (1 corresponding to the segment that has the line fairlead, 2 the middle segment and 3 with the anchor segment), it is described its material, length and number of elements used to model for FEM (finite element method) simulation. Also, Table 3 shows material parameters, such as line diameter, mass per length and axial stiffness.

Anchors and fairleads positions of the model lines are shown in Table 4. All anchors are configured at the same depth, corresponding to the regular sea depth (1535 m). As aforementioned, the vessel is associated with a SPM system. However, to present an arrangement more coherent with reality, a distance radius of 5 m was defined between the fairleads in relation to the point $X = 279.7$ m, $Y = 0$ m and $Z = -16.96$ m, which represents the turret center. Because of this, end line coordinates shown in Table 4 are relative to the turret local axis, while anchor coordinates are relative to the global axis.

¹Giraffe[®] is a platform coded using C++ language, with the objective of generating a base-interface to be used by researchers to implement their own finite element formulations. For more details, see Gay Neto (2014)

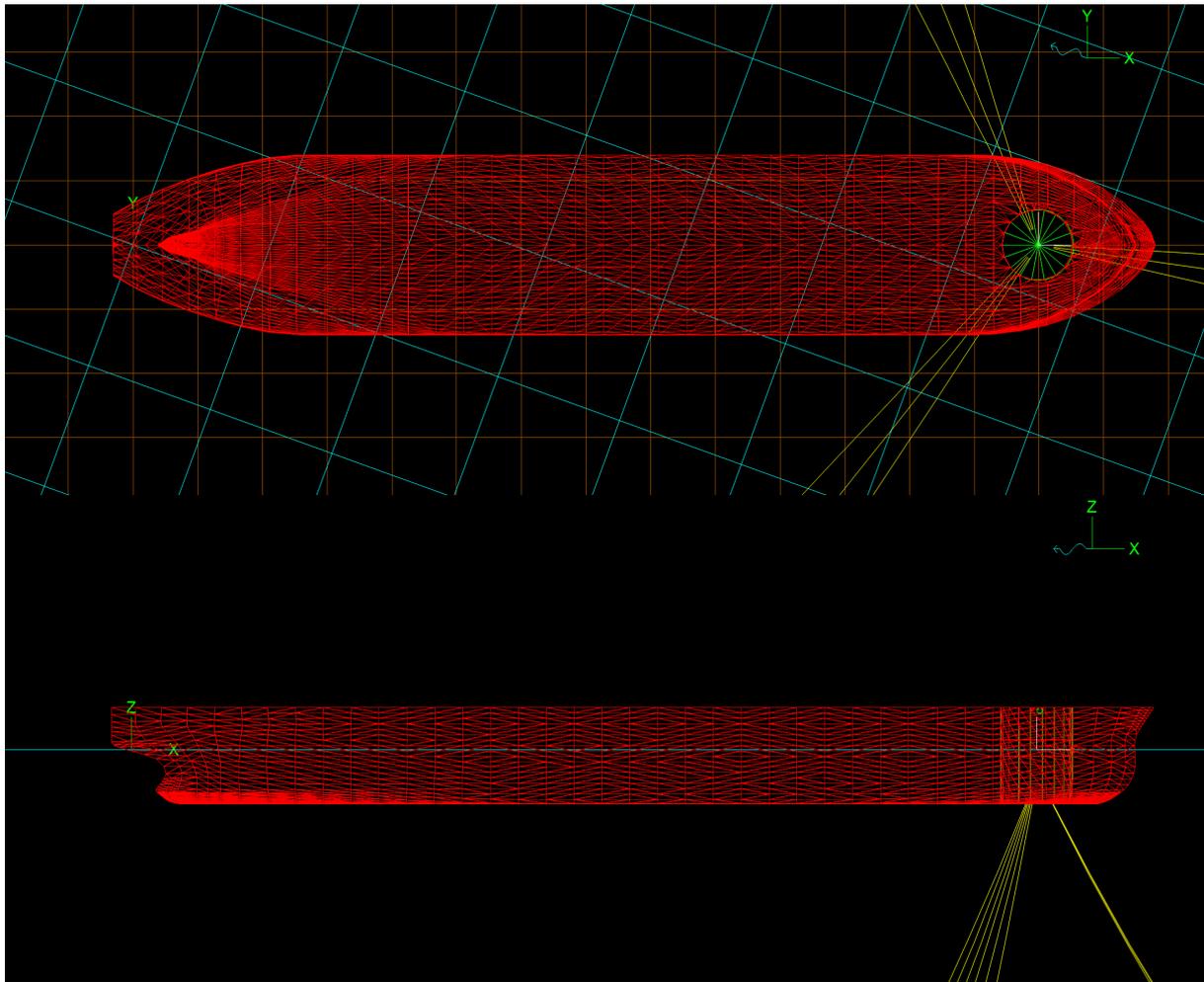


Figure 3. FPSO model. Modeled with OrcaFlex[®]

Table 2. Mooring system model parameters.

Lines	Segment	Material	Length (m)	Number of elements
1 2 3	1	Chain	200	8
	2	Wire rope	1965	80
	3	Chain	300	12
4 5 6	1	Chain	200	8
	2	Wire rope	1965	80
	3	Chain	300	12
7 8 9	1	Chain	200	8
	2	Wire rope	1965	80
	3	Chain	300	12

Table 3. Material segments parameters.

Material	Diameter (mm)	Mass (kg/m)	Axial stiffness (kN)
Chain	87	139.16	576841
Wire Rope	175	30.10	130052

4. RESULTS

For the purpose of testing the digital twin model as a virtual sensors, simulations involving intact system and damaged mooring systems (specifically, line 5 breakage) are performed. Dynamic simulations in time domain are performed using OrcaFlex[®]. Vessel motion is set according to environmental conditions, considering all six degrees-of-freedom

Table 4. Anchor and fairleads positions.

Lines	Anchor		Fairlead	
	X (m)	Y (m)	X (m)	Y (m)
1	-580.26	1702.40	-2.26	4.46
2	-428.61	1770.90	-1.86	4.64
3	-271.57	1825.90	-1.45	4.79
4	2158.20	-105.03	4.99	-0.28
5	2141.90	-268.35	4.95	-0.71
6	2111.40	-429.63	4.87	-1.14
7	-759.49	-1588.00	-2.74	-4.18
8	-893.94	-1491.40	-3.09	-3.93
9	-1019.50	-1383.50	-3.42	-3.64

(DoF). Aiming at simplifying the simulation, only irregular waves are considered to induce the vessel displacement. The JONSWAP wave spectrum model was chosen, using a significant wave height (H_s) of 2 m and peak period (T_p) of 5 s. Also, a wave incidence angle of 20° is considered for the irregular wave, as indicated by blue lines in Figure 3.

To study the effects of damaged conditions on each line tension along its length, scalograms are elaborated to facilitate the comparison between each case. Each scalogram shows a colormap representing a tension time series for each segment of unstretched length at each time-step, with color scale indicating tension magnitude. With this method of post-processing data generated, a simple view of a plot can lead to ideas about oscillation frequency, tension variation along the line and time, for examples.

Figure 4 shows a comparison between scalograms: the first one (a) refers to a case in which one of the lines (line 5) is broken (a simulation in which the specific line is omitted from the system), while the second (b) represents an intact mooring system. The first thing to notice is the color difference between each of them, as the intact system presents light shades of blue in the wire rope section (middle section) and red color in the fairlead, while damaged case presents dark shades of blue with less color modulation in the middle section, that is a difference of 150 to 200 kN of tension in this section. Before the tests, it was expected that all the lines would increase their tension magnitude along all their extension considering a line breakage in the system. However, depending on how lines system is placed, what type of material is used for line composition and which line breaks, lines tension can increase or decrease.

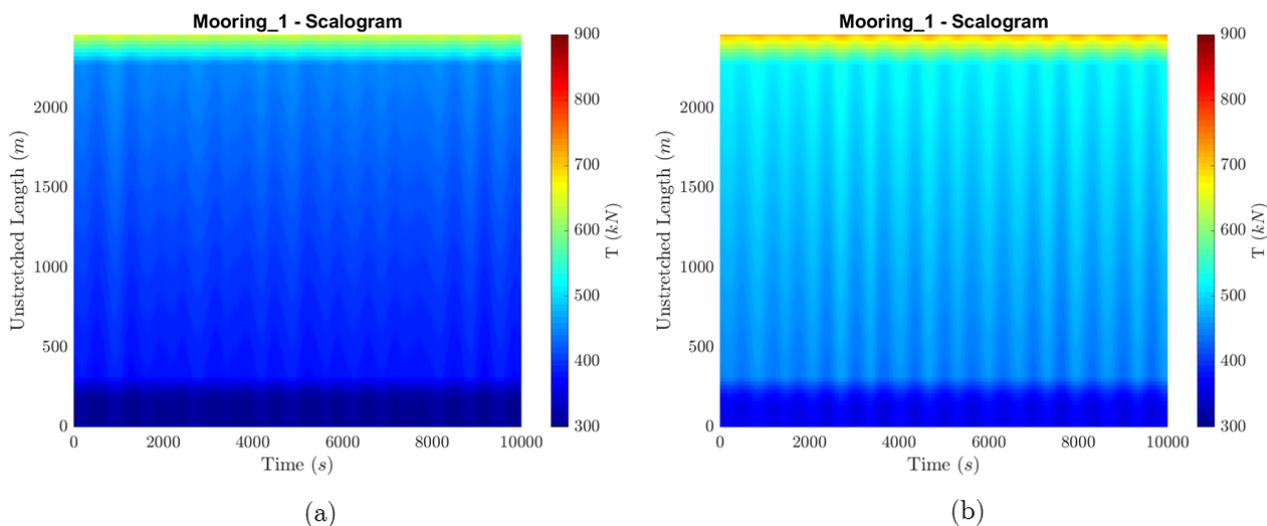


Figure 4. Scalograms for tension along line 1 length. (a) Line 5 breakage; (b) Intact system.

As another example, one can have a look at line 4 scalogram, as shown in Figure 5. In this case, there is a great increase of tension along all the line length when the line 5 breakage is considered. The main reason for this behavior difference is the fact of line 4 and 5 belong to the same line arrangement. In this way, a majority part of line 5 tension is now supported by lines 4 and 6, overloading both lines with the unbalanced distribution of tension along all lines system.

As cited in Introduction section, a digital twin from a offshore system could be used as a virtual sensor, being a warning tool about accidents or failures with lines system, for example. With this methodology and format results display,

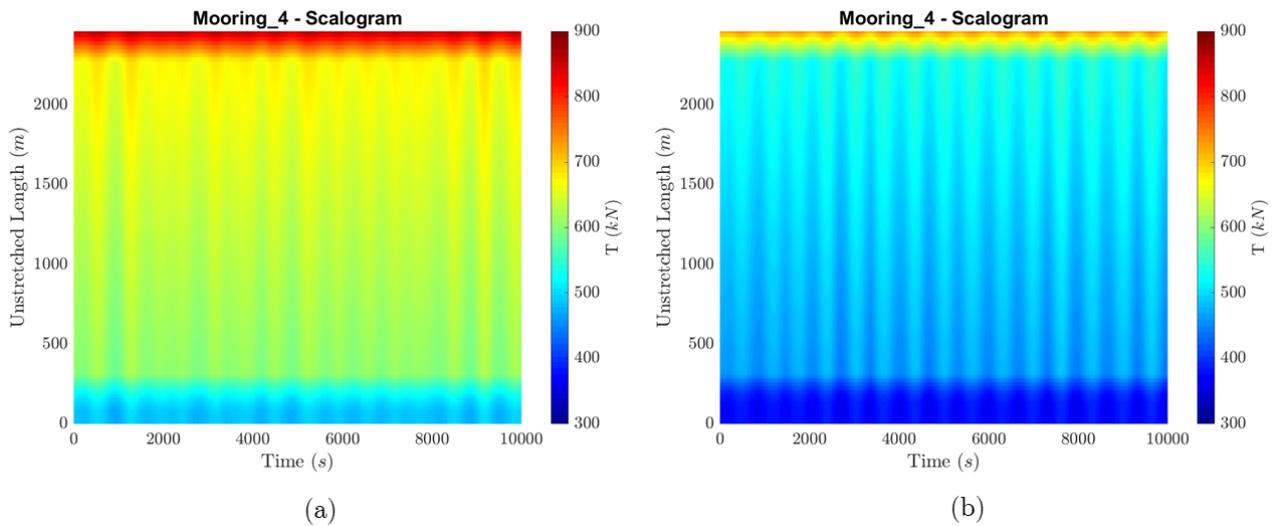


Figure 5. Scalograms for tension along line 4 length. (a) Line 5 breakage; (b) Intact system.

an offshore operator could interpret these generated data and change or interrupt operational tasks on a FPSO, preventing the risk of a vital system failure. Thinking of a more automatized way of make the connection between outputs generated by virtual data being used as inputs by the real asset, one way to influence FPSO operations is creating a warning system based on tension results. After detect a worrisome signal of tension magnitude or frequency, this system would stop some specific activities on vessel or activate other, such as feeding lines, as cited before as an example.

5. CONCLUSION

Digital twin (DT) is a trend in creating new methods and technologies of managing and controlling real assets. For offshore systems, a DT has the possibility to be used as a virtual sensor, getting data that would be hard to obtain with real instruments. DT can be also employed as a management tool for the whole vessel system, working as a holistic implementation for offshore operations preview.

In this work, a novel methodology for an FPSO digital twin is described. The entire process of using data from vessel and providing analysis for its operation is developed, showing a roadmap on how to interconnect each of the steps, from obtaining data from the real asset to creating system models and simulating each one of them, coupling information between them. Also, it is showed how a line tension analysis at its entire length can detect failures in the system, working as an example of virtual sensor.

Finally, this example could lead an extension in data processing step of DT workflow, as it opens the possibility to develop methods to create classification systems working as warning tools. This possibility could be addressed with machine learning algorithms that work with identification of patterns in data.

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