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Comparative Numerical Analysis Fatigue Damage Based On Variation In Quantities Mooring Line On Aker Smart 2 FPSO

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Abstract

The Aker Smart 2 FPSO is the second FPSO from the Norwegian FPSO operator: Aker Floating Production, and will operate for Reliance in India. This FPSO will be moored with a mooring system catenary to the seabed. In its operation, the FPSO will be influenced by dynamic loads such as sea waves, ocean currents and wind on the mooring rope structure periodically. This may cause damage to the structure mooring line which influences the performance of the operational structure. The aim of this research is to investigate motion trajectory (surge & sway), mooring line stress, and deterministic fatigue on the mooring system catenary by making comparisons using variations in quantities mooring line. Dimensions mooring line type chain on fairlead with varying amounts mooring line namely 4x1, 4x2, and 4x3 which will then be analyzed fatigue damage-his. Numerical observations of FPSO motion on following seas, stern quartering seas, beam seas, bow quartering seas, and head seas show Response Amplitude Operator from movement surge, sway, heave, roll, pitch, and yaw due to harsh environments with Hs = 2.0 meters and T = 12 seconds. Observation Motion Trajectory it is found that the greater the number mooring line then value Offset or movement surge & sway will get smaller. Meanwhile, in observation Mooring Line Stress and Fatigue Damage obtained both are directly proportional where the greater the tension mooring line the greater the damage. This is because the mass of the rope used is not proportional to displacement boat. And in this numerical analysis simulation it only reaches the initial movement, namely at 100 seconds, where the ship's condition has not yet reached the stable condition it should be.

Keywords: Catenary Mooring System, Fatigue Damage, FPSO, Mooring Line, Mooring Line Stress, Motion Trajectory.

1. Introduction

The FPSO vessel Aker Smart 2 is the second FPSO from the Norwegian FPSO operator: Aker Floating Production, and will operate for Reliance in India. In the gas production phase, the FPSO will be affected by sea waves, ocean currents and wind due to the highest FPSO movement and the highest voltage response from the mooring system catenary, while the gas production process can damage these structures and other operational load factors. As a result, conditions become more critical. In addition, fatigue analysis is the most important effect in FPSO construction and production development. This study will discuss fatigue analysis in catenary mooring systems to determine fatigue damage based on variations in quantity mooring line in conditions of six degrees of freedom (movement surge, sway, heave, roll, pitch, and yaw).

A mooring system typically has 8 to 16 mooring lines consisting of heavy chains, steel wire ropes, and certain materials that connect the anchor to the seabed. System path catenary arrives at the seabed horizontally, even though the tight mooring is anchored at the angle formed. Another important difference is strength recovery on catenary mooring produced by the weight of the

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component [1].

When oil and gas extraction is carried out from shallow waters to deep waters, a mooring system catenary is more popular, but when identifying deep water to ultra-deep water production, the mooring system becomes a limiting factor [1]. To overcome this problem, a new solution was developed as a leg link mooring system. The tension that occurs in mooring ropes is divided into two, namely average tension and maximum tension. The average voltage is the voltage at mooring line associated with offset ship average while the maximum stress is the maximum average stress under the combined influence of wave frequency and low voltage frequency.

The aim of this research is to analyze the comparison of motion trajectory (surge & sway), mooring line stress, and deterministic fatigue on mooring lines based on variations in quantity mooring line in improving the quality and safety of the Aker Smart 2 FPSO productivity activities in the oil drilling process.

2. Materials and Methods

This research was conducted using literature studies and numerical studies. Supporting data is contained in the following tables. This simulation aims to analyze fatigue damage to the mooring system catenary. The FPSO mooring modeling design is shown in Figure. Analyze the FPSO motion response to obtain the tension range for each mooring rope. Mooring line stress obtained from time domain analysis of the motion response based on the mooring system catenary so that tension is produced due to each other mooring lines. Next, analysis will be carried out fatigue damage further on variations in quantity mooring lines.

Table 1. Main sizes of FPSO

Aker Smart 2	
Length	207.43 m
Breadth	32.25 m
Height	16.75 m
Draft	12.603 m

Table 2. FPSO mooring data

Mooring Properties – Chain on fairlead	
Mass / Unit Length	438.90 kg/m
Outer Diameter	0.1588 m
Cross-sectional Area	0.0198 m^2
Section Length	140.208 m
Stiffness, EA	1,842,397,80 kN
Maximum Tension	19,563.30 kN

Environmental data includes wave data, wind data, current data.

Table 3. Wave distribution data for the Masela Block in Maluku Province

		Hs (m)					**Total**
		0.1 -1	**1.1 - 2**	2.1 - 3	3.1 - 4	4.1 – 5	
Tp (s)	0.1 – 2	0	0	0	0	0	0
	2.1 – 4	0.58	0	0	0	0	0.58
	4.1 – 6	9.51	4.43	0	0	0	13.94
	6.1 – 8	5.12	6.9	4.74	0.03	0	16.79
	8.1 – 10	8.2	3.5	5.	0.78	0.04	18.12
	10.1 – 12	10.8	**20.8**	0.15	0.01	0.01	31.77
	12.1 – 14	9.3	2.68	0.02	0	0	12
	14.1 – 16	2.93	2.46	0.04	0	0	5.43
	16.1 – 18	0.42	0.77	0.03	0	0	1.22
	18.1 - 20	0.05	0.096	0	0	0	0.146
Total		46.91	41.636	10.58	0.82	0.05	**100.0**
Cumulative		46.9	99.1	99.1	99.9	**100.0**	

The wave data used is a wave height of 2 m and a wave period of 12 seconds.

Table 4. Masela Block wind and current data

Parameter	Speed (m/s)
Wind	16.91
Current	0.5

The type of mooring used is: catenary mooring system which is widely used in shallow to deep waters. In this simulation, the focus is on quantities mooring line the variations are 4x1, 4x2, and 4x3 with an angle of 30°, 45° and 60° with a mooring line length of 3100 meters at a depth of 1000 meters. The FPSO model and its coordinates are obtained to analyze the characteristics of structure movement in waves in the modeling process. The model configuration based on variations in the number of ropes is shown in Figure 1.

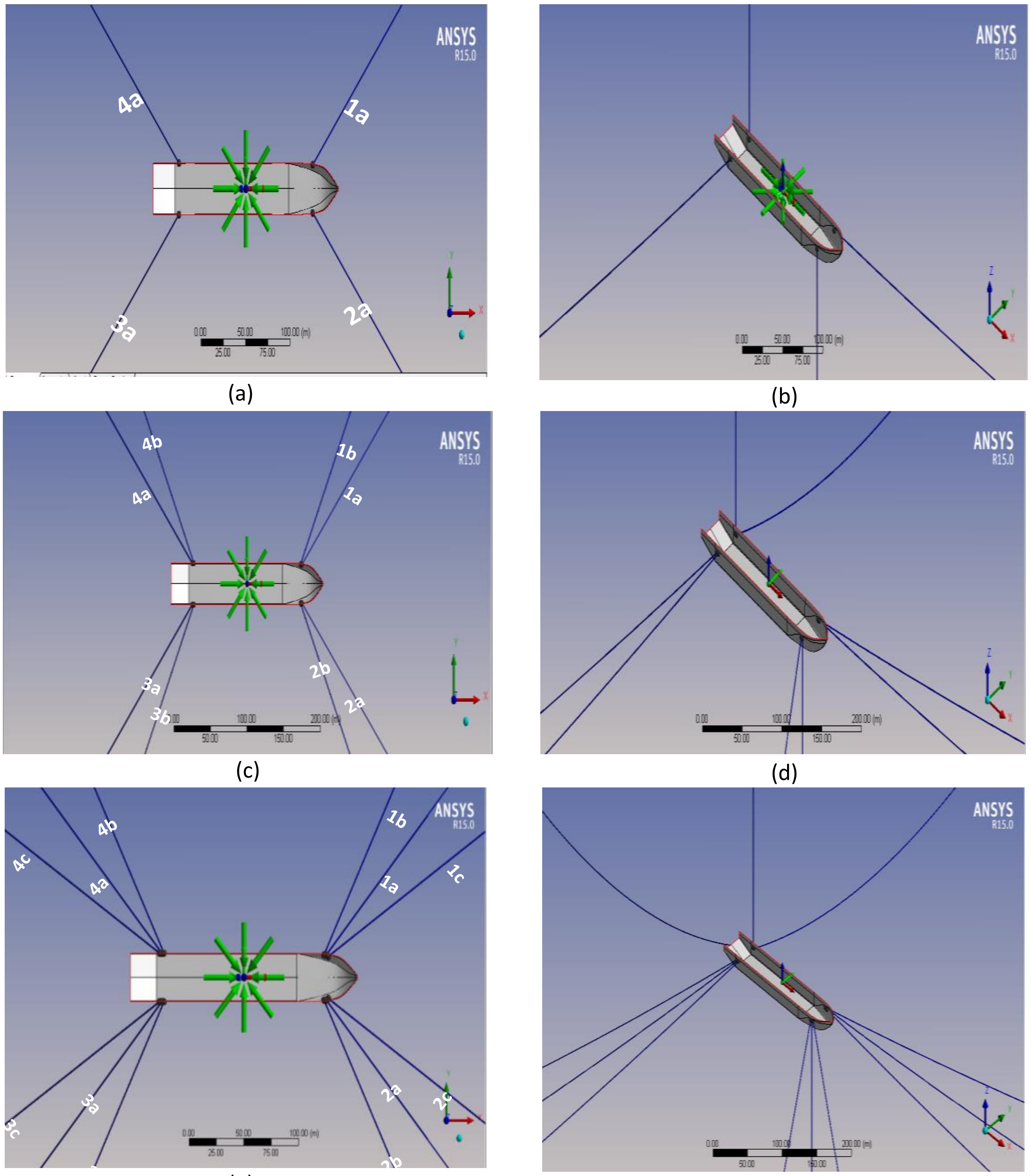


Fig. 1. Mooring numbering & FPSO modeling in moored conditions; (a) Variation mooring 4 x 1; (b) Variation mooring 4 x 2; (c) Variation mooring 4 x 3.

3. Results and Discussion

3.1 Hydrostatic Analysis

To obtain reliable results from FPSO modeling that match reality, the model design needs to be validated. The hydrostatic quantities compared include: Displacement, shape coefficient, location of the center of buoyancy (Center of Buoyancy), Wetted Surface Area (WSA), and others. Hydrostatic analysis results are obtained from hydrodynamic diffraction which considers movement heave, roll, and pitch. Hydrostatics results from the geometric characteristics of the FPSO model [3].

The hydrostatic modeling carried out is for volumetric displacement, position of center of buoyancy, distance of COG to COB and metacentric height due to the vertical mode of motion (heave, roll and pitch). This model has a stiffness factor that can influence the damping factor to be smaller, so that it will produce the highest characteristic results as shown in Table 5.

Table 5. Hydrostatic Analysis Results

Hydrostatic Stiffness						
Centre of Gravity Position :	**X:**	0. m	**Y:**	0. m	**Z:**	0. m
		Z:		**RX:**		**RZ:**
Heave (Z) :		63620224 N/m		5.5749898 N/°		5827306.5 N/°
Roll (RX) :		319.4234 N.m/m		14114681 N.m/°		37.60862 N.m/°
Pitch (RY) :		3.3388e8 N.m/m		37.60862 N.m/°		3.56464e9 N.m/°
Hydrostatic Displacement Properties						
Actual Volumetric Displacement :		73897.656 m³				
Equivalent Volumetric Displacement :		73908.289 m³				
Centre of Buoyancy Position :	**X:**	-3.7790623 m	**Y:**	-1.977e-4 m	**Z:**	-6.03824 m
Cut Water Plane Properties						
Cut Water Plane Area :		6329.2266 m²				
Small Angle Stability Parameters						
C.O.G. to C.O.B.(BG) :		6.03824 m				
Metacentric Height (GMX/GMY) :		1.0887256 m		272.59692 m		
COB to Metacentre (BMX/BMY) :		7.1269655 m		278.63516 m		
Restoring Moments/Degree Rotations (MX/MY) :		246347.63 N.m/°		61680928 N.m/°		

3.2 Analysis Response Amplitude Operator (RAO)

Response amplitude operator (RAO) is a mathematical function to determine the response by a floating building based on its amplitude as a result of wave excitation loads in a certain frequency range or period [2].RAO (Response Amplitude Operator) or often referred to as Transfer Function is the response function that occurs due to waves in a frequency range hitting a structure. RAO is referred to as Transfer Function because RAO is a tool for transferring wave loads in the form of a response to a structure [4]. Motion response that occurs for each direction (heading) is divided into 2, namely, RAO translational motion and RAO rotational motion. Where for RAO translational movement includes movement surge, sway, and heave, with units (m/m). Meanwhile, for RAO, rotational movements include movement roll, pitch, and yaw, with units (deg/m). The results of the RAO analysis can be seen in Figure 3. It can be seen that there is a change in the amplitude response. Wave entry angle (wave heading) is the direction of the wave arrival measured from 0° at the stern of the ship to 180° at the bow of the ship.

As for heading direction or the direction of RAO loading is carried out in five directions, namely as follows.

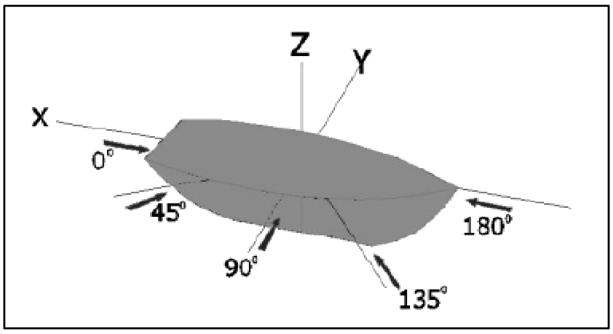
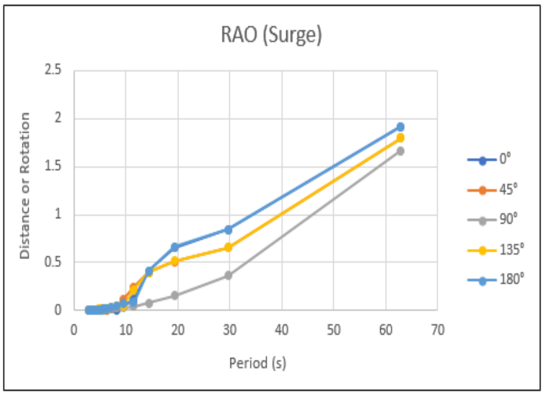


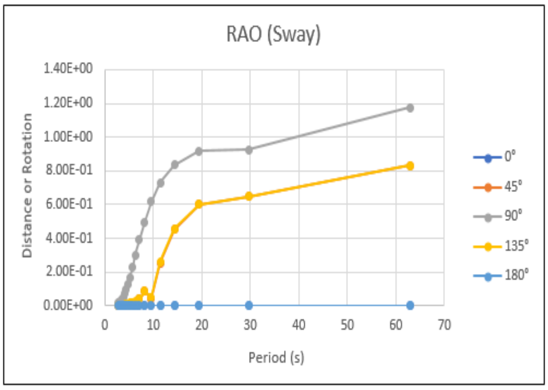
Fig. 2. Heading direction on the ship [1]

Table 6. Heading durection or RAO loading direction

Direction	Description
0°	Following Seas
45°	Stern Quartering Seas
90°	Beam Seas
135°	Bow Quartering Seas
180°	Head Seas



(a)



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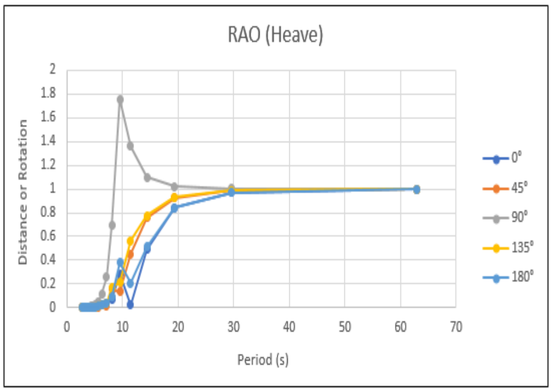
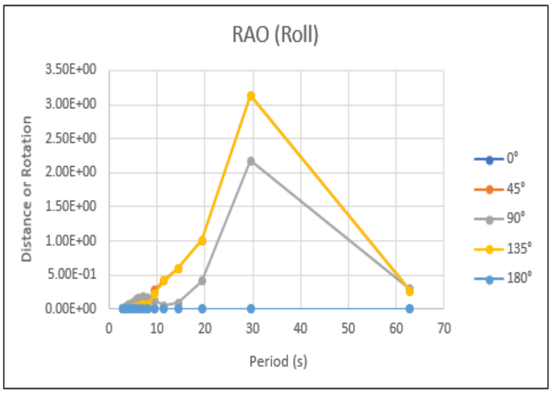
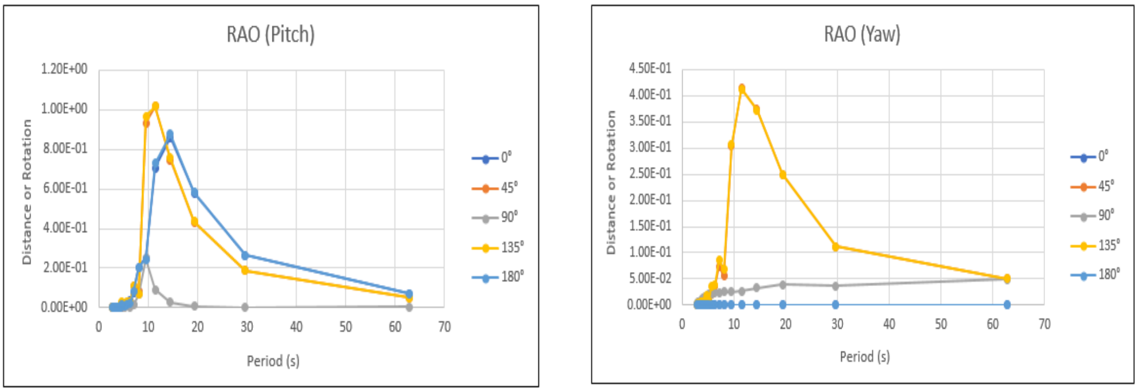


(c)



(d)



(e) (f)

Fig. 3. Comparison graph of RAO against direction Following seas 0°, Stern Quartering seas 45°, Beam seas 90°, Bow Quartering seas 135°, and Head seas 180°; (a) Surge motion; (b) Sway motion; (c) Heave motion; (d) Roll motion; Pitch motion; and (f)Yaw motion.

Table 7. Maximum Value of RAO Comparison

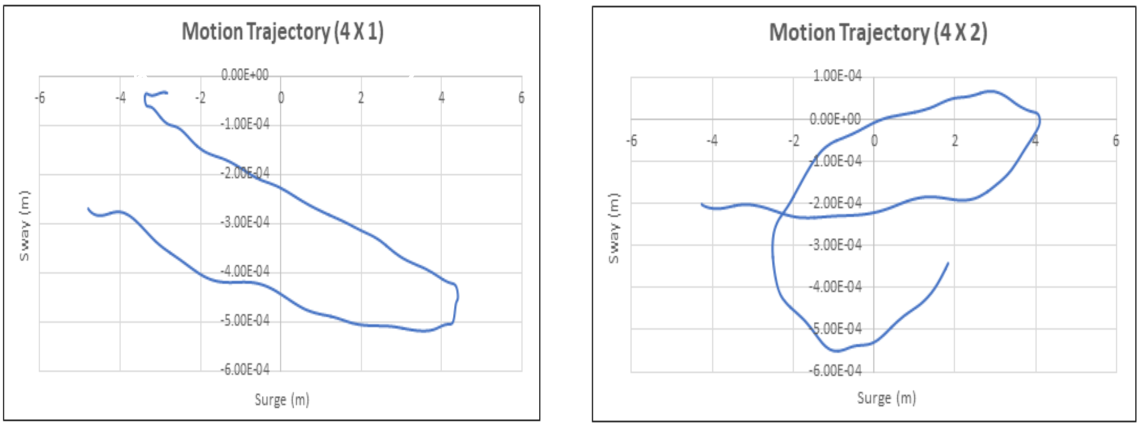
Motion	Unit	RAO Maximum				
		0°	45°	90°	135°	180°
Surge	m/m	1.9193465	1.7963004	1.6636791	1.7964845	1.9195789
Sway	m/m	2.71E-05	0.8314544	1.1769812	0.8314499	2.58E-05
Heave	m/m	0.9973756	0.9985199	1.7548679	0.9985378	0.9974006
Roll	deg/m	2.32E-04	3.1317149	2.1776895	3.1315679	2.36E-04
Pitch	deg/m	0.860034	1.0159096	0.2484747	1.01571	0.8763763
Yaw	deg/m	3.67E-05	0.4142021	4.89E-02	0.4123162	3.09E-05

From the table above, the maximum RAO comparison value in each direction is obtained. Obtained in each loading direction, the dominant motion that influences the ship's motion is:

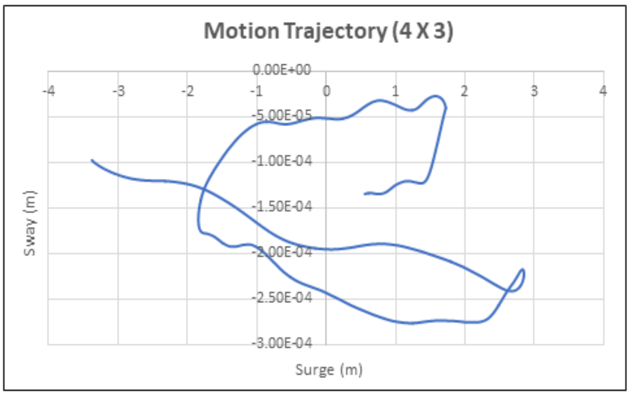
1. Following seas 0° and Head seas 180°
   In this direction the dominant movement that occurs is surge, heave, and pitch.
2. Stern Quartering seas 45°, Beam seas 90°, and Bow Quartering seas 135°
   In this direction the dominant movement that occurs is surge, roll, and pitch.

3.3 Motion Trajectory (Surge and Sway)

The following are the characteristics of the trajectory of the structure regarding movement surge (front & back) and sway (left & right) on different variations in the number of mooring ropes so that variations in the number of ropes that are most ideal for use in FPSO mooring can be identified.



(a) (b)



(c)

Fig. 4. Translational movement graph surge and sway on FPSO; (a) Variation mooring 4 x 1; (b) Variation mooring 4 x 2; (c) Variation mooring 4 x 3.

Table 8. Maximum value of translational movement surge and sway on variations in the number of ropes mooring.

Movement	**Variation in Number Mooring Lines**					
	4 X 1		**4 X 2**		**4 X 3**	
	Surge (m)	**Sway (m)**	**Surge (m)**	**Sway (m)**	**Surge (m)**	**Sway (m)**
$Offset_{max}$	4.4	-0.0000352	4.1	0.0000667	2.85	-0.0000272
$Offset_{min}$	-4.79	-0.000519	-4.26	-0.000551	-3.32	-0.000277
ΔOffset	9.19	0.000484	8.36	0.000618	6.17	0.000250

3.4 Mooring Line Stress

After obtaining the data above, the tension range can be determined by the maximum and minimum mooring rope tension in different time periods. Mooring line stress used to identify critical areas on mooring ropes that experience high stress or high fatigue. This area is the starting point for fatigue which can cause the mooring rope to break. The rope tension equation is stated as follows.

$$\sigma = \frac{F}{A} \tag{1}$$

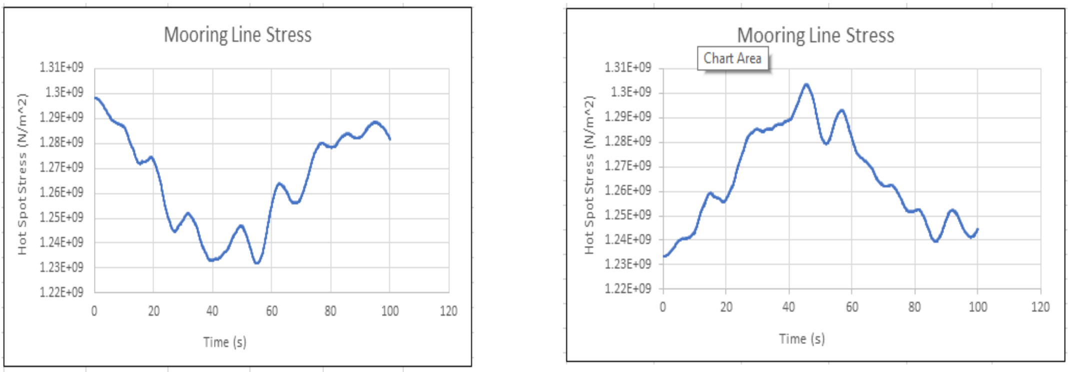
Where:

F : Force tension (kN)

A : Cross-sectional area (m^2)

Table 9. Maximum and Minimum Values Mooring Line Stress 4 X 1 variation.

Mooring Line	**Mooring Line Stress**		
	Maximum	**Minimum**	**Range**
1a	1,298,179,902	1,231,768,619	66,411,282.47
2a	1,298,182,022	1,231,772,153	66,409,868.73
3a	1,303,480,287	1,233,324,835	70,155,451.25
4a	1,303,492,404	1,233,323,926	70,168,477.78

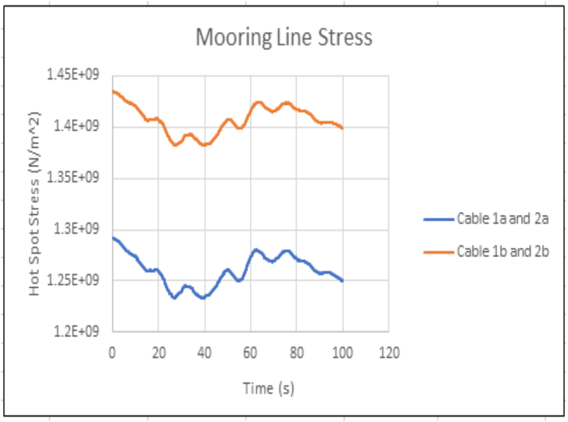


(a) (b)

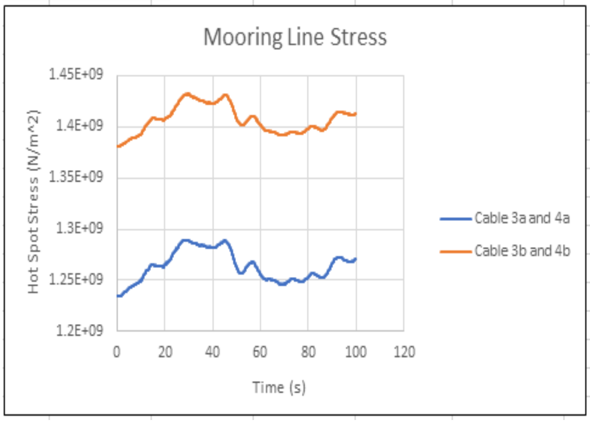
Fig. 5. Mooring line stress variation 4 X 1; (a) Mooring line 1a and 2a; (b) Mooring line 3a and 4a

Table 10. Maximum and Minimum Values Mooring Line Stress 4 X 2 variation

Mooring Line	Mooring Line Stress Maximum	Minimum	Range
1a	1,291,106,191	1,233,087,530	58,018,661.19
2a	1,291,106,595	1,233,097,729	58,008,866.04
3a	1,289,410,521	1,234,128,138	55,282,382.49
4a	1,289,393,253	1,234,128,239	55,265,013.78
1b	1,434,645,049	1,382,516,602	52,128,446.9
2b	1,434,644,746	1,382,539,423	52,105,322.28
3b	1,432,221,912	1,380,731,462	51,490,449.75
4b	1,432,158,092	1,380,732,875	51,425,216.11



(a)

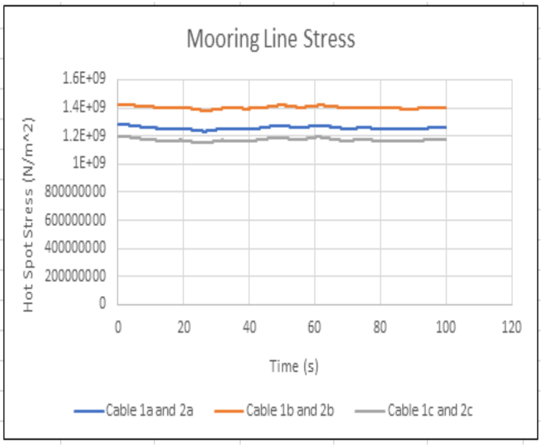


(b)

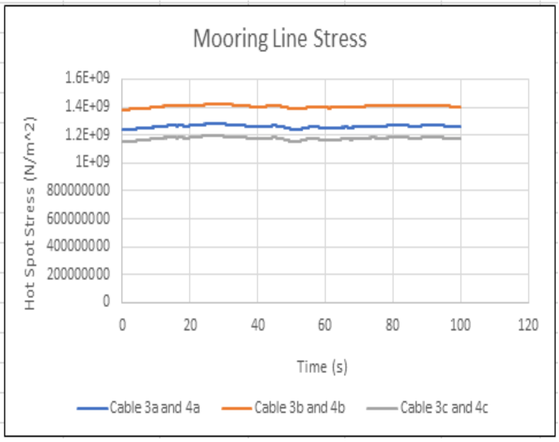
Fig. 6. Mooring line stress variation 4 X 2; (a) Mooring line 1a and 2a, 1b and 2b; (b) Mooring line 3a and 4a, 3b and 4b.

Table 11. Maximum and Minimum Values Mooring Line Stress 4 X 3 variation

Mooring Line	Mooring Line Stress Maximum	Minimum	Range
1a	1,282,072,948	1,233,480,245	48,592,702.64
2a	1,282,073,957	1,233,508,822	48,565,134.86
3a	1,282,415,778	1,237,377,905	45,037,872.99
4a	1,282,397,197	1,237,376,996	45,020,201.34
1b	1,425,639,271	1,381,165,680	44,473,591.87
2b	1,425,640,180	1,381,206,779	44,433,401.49
3b	1,424,544,437	1,382,811,567	41,732,870.02
4b	1,424,542,013	1,382,811,264	41,730,749.42
1c	1,198,581,861	1,148,770,723	49,811,137.84
2c	1,198,583,073	1,148,842,622	49,740,451.23
3c	1,196,192,553	1,150,451,954	45,740,598.88
4c	1,196,174,780	1,150,450,540	45,724,239.98



(a)



(b)

Fig. 7. Mooring line stress variation 4 X 3; (a) Mooring line 1a and 2a, 1b and 2b, 1c and 2c; (b) Mooring line 3a and 4a, 3b and 4b, 3c and 4c.

3.4 Deterministic Fatigue Analysis on Mooring Lines

Fatigue analysis is defined as research that includes global dynamic movements and local stresses of mooring tension catenary. Existing methodologies lack the consistency and level of transparency necessary to independently demonstrate the level of safety and conservatism in design catenary.

3.4.1 Wave Probability (Pi)

The wave probability value is obtained fromwave scatter or selected wave distribution data. The wave probability value used is 20.8% or 0.208.

3.4.2 Dynamic Amplification Factor

DAF parameters are used to determine the dynamic response of structures due to dynamic loads. This is important because the structure can provide a much greater response when considering only static loads. As for the equationDynamic Amplification Factor (DAF) is stated as follows.

$$DAF = \frac{1}{\sqrt{\left\{1-\left(\frac{T_n}{T}\right)^2\right\}^2 + 2\beta\left(\frac{T_n}{T}\right)^2}} \quad (2)$$

Where:
T_n : Period natural structure (sec)
T : Wave period (sec)
b : Damping ratio (20%) based on API RP2A

Based on the equation above, the DAF value is 0.038.

3.4.3 Stress Range (S)

In mooring rope fatigue analysis, stress range (S) is an important parameter that gives an idea of how large the stress variations will be experienced by the material during a certain load cycle. Mark stress range obtained using the following equation.

$$S = MLS \times DAF \quad (3)$$

Where:
MLS_{max} : Mooring Line Stress Maximum
DAF : Dynamic Amplification Ratio

3.4.4 Number of wave events per wave Stress Range (In)

This value is obtained from the S-N curve. The basis of the S-N curve is mentioned between the voltage plot (S) and the number of cycles (N). This curve is used to express the fatigue characteristics of a material due to cyclical loads with a constant magnitude. The level of accuracy is influenced by determining the slope and intercept parameters of the S-N curve, the analytical expression of the S-N curve is:

$$Ni(s) = aD.s^{-m} \quad (4)$$

Where:
Ni(s) : Cycle of failure
s : Stress Range (N/m^2)
aD : Intercept parameter of S-N curve
m : S-N curve slope

Meanwhile, an explanation of the parameters aD and m is shown in Table 12.

Table 12. Parameter curve S-N [1].

Tipe Mooring	aD	M
Stud Chain	1.2×10^{11}	3.0
Studles Chain (Open Link)	6.0×10^{10}	3.0
Six-Strand Wire Rope	3.4×10^{14}	4.0
Spiral Strand Wire Rope	1.7×10^{17}	4.8

By linearizing the above equation using logarithms, the Ni equation can be expressed as follows.

$$\log\left(n_c(S)\right) = \log(aD) - m\,.\log\,(s) \quad (5)$$

By using type mooring Stud Chain then we get,

$$Ni = \frac{1.2\times10^{11}}{S^3} \quad (6)$$

3.4.5 Fatigue Damage

Each mooring lines take further process on fatigue damage between number of cycles-voltage range and characteristics mooring line. Fatigue damage is damage that occurs to the mooring rope material as a result of repeated stress that continuously occurs so that the material will experience fatigue. As for the equation fatigue damage stated as follows.

$$D = \frac{Pi}{Ni\times Ti} \quad (7)$$

Where:
Pi : Wave probability
In : The number of wave events per wave Stress Range
Of : Wave period

Based on the equations above, it is obtained fatigue damage in each variation, namely,

Table 13. Fatigue damage mooring line variation in the number of ropes 4 x 1.

Mooring Line	Fatigue Damage (Ratio)
1a	1.675E+10
2a	1.675E+10
3a	1.695E+10
4a	1.695E+10

Table 14. Fatigue damage mooring line variation in the number of ropes 4 x 2.

Mooring Line	Fatigue Damage (Ratio)
1a	1.648E+10
2a	1.648E+10
3a	1.641E+10
4a	1.641E+10
1b	2.260E+10
2b	2.260E+10
3b	2.249E+10
4b	2.249E+10

Table 15. Fatigue damage mooring line variation in the number of ropes 4 x 3.

Mooring Line	Fatigue Damage (Ratio)
1a	1.613E+10
2a	1.613E+10
3a	1.615E+10
4a	1.614E+10
1b	2.218E+10
2b	2.218E+10
3b	2.213E+10
4b	2.213E+10
1c	1.318E+10
2c	1.318E+10
3c	1.310E+10
4c	1.310E+10

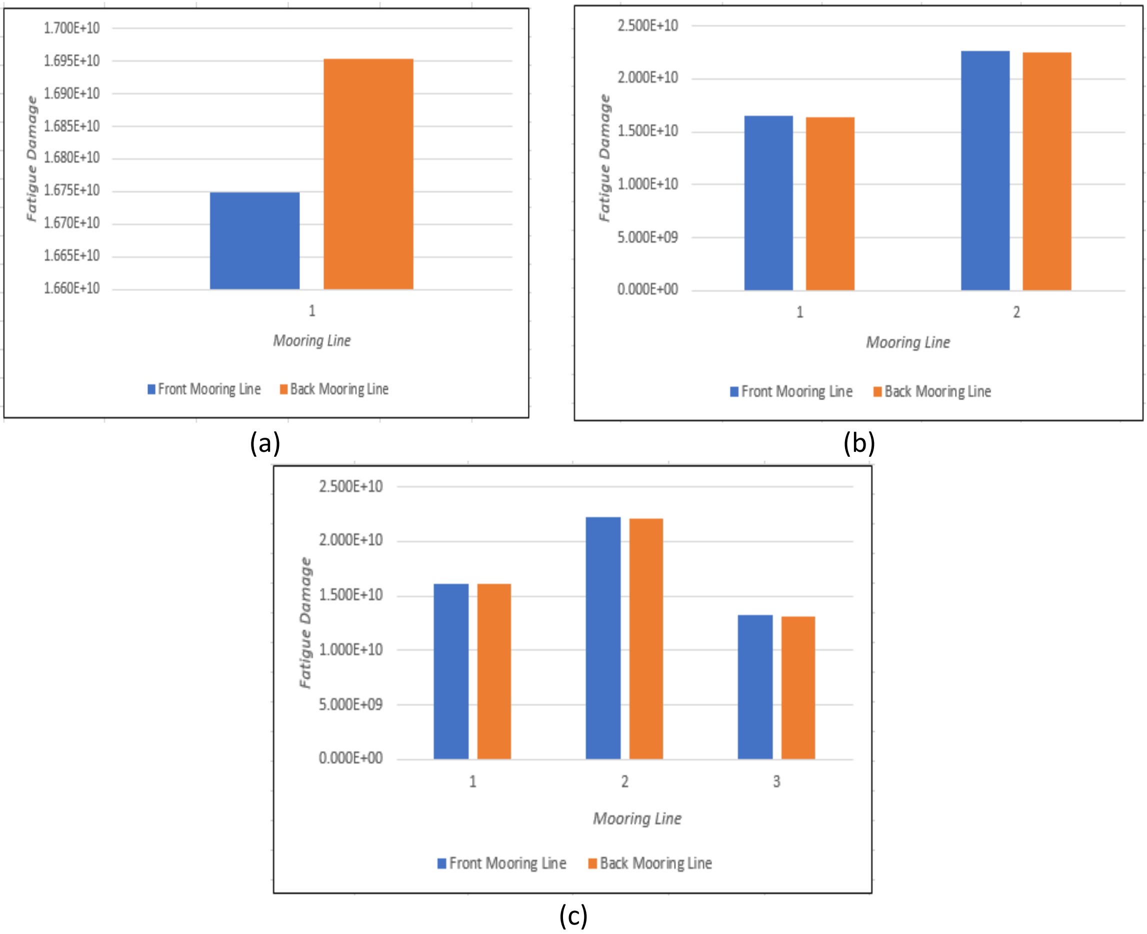


Fig. 8. Chart Fatigue Damage; (a) Variation mooring line 4 x 1; (b) Variation mooring line 4 x 2; (c) Variation mooring line 4 x 3.

4. Conclusions

Based on the results of the simulation that has been carried out, it is found that the number is increasing mooring line used, the stronger the mooring system on the FPSO will be in an environment with Hs = 2.0 meters and T = 12 seconds. In the RAO parameter, it is found that the domain motion occurs in the direction Surge on wave heading Head Seas 180° namely 1.9195789 m/m and direction Roll on wave heading Stern Quartering Seas 45° namely 3.1317149 deg/m. Next on motion trajectory it was found that the number increased mooring line then less movement Surge and Sway that happened. Where in the variation in quantity mooring line 4x3 values Offset which is obtained for direction Surge of 6.17 m and for direction Sway of 0.000250 m. Furthermore, in the Mooring Line Stress calculation, the largest range value is obtained in the number variation mooring line 4x1 which is 70,168,477.78 N/m2 what happened to mooring line 4a (rear side of the ship), this shows that there are fewer numbers mooring line for Mooring Line Stress her breasts will get bigger. Next, the last step is analysis fatigue damage The largest ratio of damage due to fatigue was obtained in the number variation mooring line 4x2 is 2.260E+10 at mooring line 1b and 2b (front side of the ship).

From the results of the numerical analysis obtained above, it can be concluded that the operational process of the mooring system is in progress catenary mooring The Aker Smart 2 FPSO experienced loads that caused damage which had a risk of operational failure which could reduce operational life. This is caused by one of the reasons that the mass of the rope used is not proportional to the mass of the rope used displacement ship so that additional mass or number of ropes is required. And also in the numerical analysis simulation carried out it only reaches the initial movement (transient) namely at a time of 100 seconds where the ship's condition has not yet reached a stable condition (steady) which should. It is hoped that the simulation will then be carried out until the ship is truly in a stable condition in order to obtain more detailed results.

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