Dynamic mooring lines tension of FPU operated at Madura Strait

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Abstract. An FPU operated at a gas field in Madura Strait is designed to be the main process component of the gas processing facilities for a service life 20 years. This vessel using a catenary mooring system which made up of 12 points mooring divided into 4 groups of 3 mooring lines. This vessel is necessary to be analyzed its mooring tension to ensure safety while operation. The mooring line tension is analyzed by using 3D-Diffraction Calculation. This study presents the result of the dynamic mooring line tension conducted for full load condition of FPU in extreme wave condition. The mooring analysis compliance is based on DNV GL's technical standards, as well as an international accredited registrar and classification society. Verification of computed line tension against acceptance criteria has been carried out for the current condition of the mooring system. Results of the analysis indicate that mooring line tension meets the safety factor from DNVGL OS E301 with the Maximum tension of all mooring lines value is about 159.3 t, which happened in Line 4 by heading 67.5°.

1. Introduction

One of the important ocean engineering problems is mooring system [1], which is closely related to the safety and operation performance of offshore structures [2]. Therefore, it must have sufficient strength and be able to withstand the excessive loading. Leonard et al [3], Webster [4], Skop et al [5], [6], [7] provide an overview of numerical methods for three dimensional analysis mooring line. Nakajima et al [8] provide an overview of dynamic analysis theory. The present method is used by engineers to do require procedure of numerical calculation to know dynamic behaviors of those mooring lines while its operation. Yu-Ho Rho et al [9] presented static and dynamic mooring analysis for Floating Production Storage and Offloading (FPSO) in extreme environmental conditions.

The FPU operated at Madura Strait is a spread-moored barge supporting production facilities. The FPU gas facility is designed for 175 MMSCFD produced gas. The gas streams produced by the FPU is routed gas export pipeline using flexible jumpers. At the FPU, the main process components of the gas processing facilities included: liquid separation, gas compression, gas dehydration, etc.

The FPU is moored by a spread mooring system to stay on-site in extreme conditions throughout the whole service period for a service life 20 years. Offshore operations of moored floating units perhaps stop because of excessive vessel motions while encountering harsh environments. Mooring line of floating structures, when excited dynamically at its upper end, resists the imposed displacement by increasing its tension.
The main of the study is to assess the adequacy of the mooring lines under extreme weather conditions in the field of interest along with typical operating conditions. For strength analysis, the study of mooring line tension looks into the maximum design and storm condition (100-year return period event) for the following case full load for the intact condition. Environmental conditions tend to vary considerably by region and may be accommodated in several different ways. With the environment data defined, the mooring line strength is evaluated during the mooring design. In the former case, the floating structures are simply disconnected for a severe storm condition. In the unlucky event of a storm passing close from its mooring, floating structures will move either out of the vicinity of weathering out the storm in a detached state.

Dynamic motion analysis for expected environmental conditions will indicate the mooring forces to be expected. The following items to be calculated are Response Amplitude Operators (RAO) and chain line tension. System integrity of the mooring lines will be assessed by the acceptance criteria as specified DNV Rule, i.e. “DNVGL-OS-E301, Position Mooring 2015.

2. Basic Theory

2.1. FPU

Floating Production Unit (FPU) unit is a floating vessel used by the offshore oil and gas industry. They are effective solutions in subsea, deep water, and ultra-deepwater activities. The ship-shaped hulls of FPU are the results of many experiences of design and fabrication for ship and offshore units. FPU has an excellent load-carrying capacity, more flexible, safer, and good seakeeping performance in a harsh environment. Furthermore, the operating cost of FPU is relatively low, coupled with easy reuse potential, have given these facilities the economical edge.

This paper study focuses on the adequacy of the mooring lines of FPU. The mooring layout of the FPU is shown in Figure 1. must comply with the technical standard.

Figure 1. Mooring Layout of FPU
2.2. Response Amplitude Operator (RAO)

Response Amplitude Operator (RAO) is analyzed on a regular wave refers to the movement of a floating structure in six degrees of freedom, 3 translations (surge, sway, heave), and 3 rotations (roll, pitch, yaw), in consequence of a passing hydrodynamic wave. The function of RAOs as input data for calculations is to determine displacement, acceleration, and speed at a certain point on a turn floating structure which is used to identify the forces imposed on it [10]. For FPU or large floating structures, mean wave drift, coefficients, added mass, potential damping, and motion response amplitude operators can be obtained from a diffraction analysis [11].

Metocean wave height, water depth, and period all affect a vessel’s response. RAO contains information about the characteristics of the ship’s motion on regular waves. The RAO is defined by:

\[
RAO(\omega) = \frac{\zeta_{K0}(\omega)}{\zeta_{0}(\omega)}
\]

Where, \(\zeta_{K0}(\omega)\) is amplitude of structure (m) and \(\zeta_{0}(\omega)\) is wave amplitude (m). [12]

2.3. Catenary Theory

Mooring systems are an important means of holding floating structures against environmental forces due to wave, wind, and current. The mooring system is an essential part of the station keeping systems made of one or a number of cables that are attached to the floating structure at different points with the lower ends of the cables anchored at the sea bed with the use of appropriate anchor system. According to ISO 19901-7, the mooring system has functions to restrict the horizontal excursions of the floating structure within prescribed limits and to provide means of active or passive directional control when the structure’s orientation is important for safety or operational considerations [13].

In a spread mooring system, several pre-tensioned lines are arrayed around the structure to hold it in the desired location. Error! Reference source not found. and Figure 3 show in detail a mooring line element and the force components applied to that element.

![Figure 2. Catenary Mooring Line System](image)

![Figure 3. Force on an element of mooring line](image)

The axial tension of the mooring line segment of Figure 3, in static equilibrium condition, can be estimated by the following equations:

\[
dT - \rho GaDz = \left[ \omega \sin \omega - F(1 + \frac{T}{AE}) \right]
\]

\[Td\varphi - \rho g Az d\varphi = \omega \sin \omega + D \left( 1 + \frac{T}{AE} \right) ds
\]

The marine current effects are ignored, then the equation becomes

\[T' = T - \rho gzA\]

The segment tension of the mooring line become as follow

\[T = T_H + \omega h + (\omega + \rho gA)z\]
Horizontal force can be written as
\[ T_H = T - \omega h \]  

(6)

The vertical tension of the mooring can be written as
\[ T_z = \omega l_s \]  

(7)

When the maximum external load \( T_{\text{max}} \) is known, the minimum mooring line length, \( l_{\text{min}} \), (or suspended length for a given fairlead tension) required to ensure the whole mooring line resistance can be calculated by the following equation
\[ l_{\text{min}} = (2 T_{\text{max}} - \omega h)^2 \]  

(8)

The full projected seabed length is
\[ X = l - l_s + x \]  

(9)

\[ X = l - h \left( 1 + 2 \frac{T_H}{\omega h} \right)^{1/2} + \frac{T_H}{\omega} \cosh \left( 1 + \frac{\omega h}{T_H} \right)^{-1} \]  

(10)

The projected height of the mooring lines can be expressed as
\[ h = a \left[ \cosh \left( \frac{x}{a} \right) - 1 \right] \]  

(11)

where,
\[ a = \frac{T_H}{\omega} \]  

(12)

The maximum tension in the cable can be written as
\[ T_{\text{max}} = T_H + \omega h \]  

(13)

2.4. Mooring System Analysis

This FPU vessel is modeled by a set of points and panels. Based on the vessel geometry and mass distribution data, excitation loads can calculate using a 3D diffraction. The excitation forces could be grouped into three categories; static forces, direct wave forces, and non-wave frequency forces.

The first step of calculating the excursion of the moored vessel is to get the static equilibrium position which the sum of all external and restoring forces on the vessel equal to zero. Next step, calculating offset to the static equilibrium position however offsets relative can be calculated to any other point on the coordinates. Then, from adding the low frequency and wave frequency parts, the QTFs and RAOs are respectively used, total motions of the vessel may resulted.

In this study, mooring line tensions are calculated using a dynamic mooring line analysis in the time domain. For basic theories regarding hydrodynamic calculations the authors refer to Baltrop, 1998. [16]

According to DNVGL OS E301, 2015, significant and maximum low-frequency excursion are defined as:
\[ X_{\text{LF-sig}} = 2 \sigma_{x_{-\text{LF}}} \]  

(14)

\[ X_{\text{LF-max}} = \sigma_{x_{-\text{LF}}} \sqrt{2 \ln N_{\text{LF}}} \]  

(15)

Where \( N_{\text{LF}} \) is the number of low-frequency platform oscillating during 3 hours of the environmental state. Significant and maximum wave-frequency excursion are defined as:
\[ X_{\text{WF-sig}} = 2 \sigma_{x_{-\text{WF}}} \]  

(16)

\[ X_{\text{WF-max}} = \sigma_{x_{-\text{WF}}} \sqrt{2 \ln N_{\text{WF}}} \]  

(17)
Where $W_{LF}$ is the number of wave-frequency platform oscillating during the duration of the environmental state. The LF and WF, components of low frequency and wave frequency, are interacting with each other.

When dynamic mooring line analysis is calculated, the maximum wave frequency tension is defined by:

$$T_{WF-MAX} = \sigma_{WF}[X_C - X_{WF-MAX}]\sqrt{2\ln N_{WF}} \quad (18)$$

Where $T_{QS}[X_C - X_{WF-max}]$ is quasi-static tension calculated with the upper terminal point in position $X_C - X_{WF-MAX}$.

The partial safety factors are used to check mooring line design in DNVGL OS E301 [17], which is given by:

$$S_c - T_{c-mean} \gamma_{mean} - T_{c-dyn} \gamma_{dyn} \geq 0$$

Where $S_c$ is the characteristic strength of mooring line, $T_{c-mean}$ is the characteristic mean mooring line tension, $T_{c-dyn}$ is the characteristic dynamic line tension, $\gamma_{mean}$ is the partial safety factor for the characteristic mean tension, $\gamma_{dyn}$ is the partial safety factor for the characteristic dynamic tension.

And the characteristic dynamic tension $T_{c-dyn}$ is defined by:

$$T_{c-dyn} = T_{QS}[X_C - X_{WF-max}] - T_{c-mean} + T_{WF-max} \quad (19)$$

For time domain analysis the following equation is used

$$T_{c-dyn} = T_{MPM} - T_{c-mean} \quad (20)$$

Where, $T_{c-mean}$ is mean tension of the times series, $T_{MPM}$ is most probable max of the time series. For Ultimate Limit State (ULS) design criteria equation is calculated as

$$u = \frac{S_c}{T_{c-mean} \gamma_{mean} + T_{c-dyn} \gamma_{dyn}} \quad (21)$$

Where $S_c$ is 0.95 of minimum breaking load (MBL) and $u$ should not be less than 1.0 [17]

2.5. Environmental Condition

Environmental loads acting on floating structures could be categorized as steady loads (wind, current, and mean drift force) which is push the floating structure to an offset, wave frequency cyclic loads which giving loads result in wave frequency motions and low-frequency cyclic loads that excite the entire floating system at its natural period [18]. Present the effect of wave directionality on the loads and motions experienced by the floating structure in directional characteristics of the sea.

The mooring system should be evaluated for load cases which include the most severe directional combinations of wind, wave, and current directions.

2.6. Standard of Mooring System

In order to ensure the safety of design mooring system while operation at sea, Det Norske Veritas in DNVGL-OS-E301, Position mooring, set minimum criteria especially for mooring systems. Then, the safety factors specified by DNVGL-OS-E301 are commonly used for design of mooring systems. The required minimum safety factors are as shown in Table 1 [17].
### Table 1. DNV Safety factor of Mooring Lines Design

| Consequence Class | Type of analysis of wave frequency tension | Partial safety factor on mean tension ($\gamma_{\text{mean}}$) | Partial safety factor on dynamic tension ($\gamma_{\text{dyn}}$) |
|------------------|-------------------------------------------|-------------------------------------------------------------|---------------------------------------------------------------|
| 1                | Dynamic                                   | 1.10                                                        | 1.50                                                          |
| 2                | Dynamic                                   | 1.40                                                        | 2.10                                                          |
| 1                | Quasi-static                              |                                                             | 1.70                                                          |
| 2                | Quasi-static                              |                                                             | 2.50                                                          |

The safety factor of quasi-static mooring analysis is used higher than the safety factor of dynamic mooring analysis. The effects due to added mass, damping, fluid acceleration, and the relative velocity between the mooring system and the fluid are considered in dynamic analysis.

### 3. Method of the Study

#### 3.1. Literature Study

This stage the authors to search the source of information and references as supporting materials in this study. The source of reference and information that the authors get from various national and international journals, books, course materials, codes, and various references from the internet.

#### 3.2. Procedure of Evaluation

At this stage, mooring analysis is performed by numerical modeling.

#### 3.3. Data Collection

Data to support the work of this study will be collected to facilitate and increase the accuracy of the study results. The ship data of FPU used for this study are presented in Table 2.

### Table 2. Main dimensions of the FPU

| Description                | Value | Unit  |
|----------------------------|-------|-------|
| Length Over All (LOA)      | 162.5 | meter |
| Breadth (B)                | 36.00 | meter |
| Depth (H)                  | 12.00 | meter |
| Design Draught (T)         | 8.00  | meter |
| Displacement               | 45727 | ton   |

All mooring lines of the FPU have the same specification included sectional and strength properties as presented in Table 3.

### Table 3. Mooring lines properties

| Properties                  | Value      | Unit     |
|------------------------------|------------|----------|
| Type                         | R4 Studless| [-]      |
| Diameter                     | 4          | [inch]   |
| Length @825                  |            | [m]      |
| Mass/Unit Length             | 0.208      | [t/m]    |
| Minimum Breaking Load (MBL)  | 1021.7     | [ton]    |
The raw environmental data is obtained from BMKG for the area of interest, as indicated by corresponding geographical coordinate. The raw data consist of sea wave height, significant wave height, wind intensity, and current. The raw data is then processed to derive the specific necessary data for current study. The environment data that will be used for this research are presented in Table 4.

Table 4. 100 Years Return Period Environment

| 100yr Load cases (Sea no.) | Heading (deg.) | Sig Wave Height (m) | Wave Peak Period (s) | 1-hr Wind Speed (knots) | Current Speed (m/s) |
|----------------------------|----------------|---------------------|----------------------|------------------------|---------------------|
| 1                          | 180            | 2.01                | 5.9                  | 18.8                   | 1.01                |
| 2                          | 157.5          | 2.8                 | 7.3                  | 22.2                   | 0.94                |
| 3                          | 135            | 2.71                | 7.1                  | 25.6                   | 0.79                |
| 4                          | 112.5          | 2.59                | 5.8                  | 23.2                   | 0.82                |
| 5                          | 90             | 2.19                | 5.3                  | 20.8                   | 0.27                |
| 6                          | 67.5           | 3.41                | 6.9                  | 27.4                   | 0.24                |
| 7                          | 45             | 3.51                | 7                    | 34                     | 0.27                |
| 8                          | 22.5           | 6                   | 10.3                 | 34                     | 0.37                |
| 9                          | 0              | 3.2                 | 6.6                  | 24.4                   | 0.4                 |

4. Result and Discussions

4.1. Modeling and Meshing of FPU
Based on the data that has been collected then ship modeling is performed in the form of 3-dimension drawings using Maxsurf software. Modeling of the ship consists of images of the ship hull viewed from a three-dimensional face. The FPU modeling and meshing is presented in Figure 4.

Figure 4. 3-D model of the FPU Vessel

4.2. Response Amplitude Operator (RAO) of FPU Vessel
Motions of the FPU are calculated over regular wave in stationary condition. This computation results have been done by varying nine directions of waves heading, consist of 180°, 157.5°, 135°, 112.5°, 90°, 67.5°, 45°, 22.5°, and 0°. Where 180° means that waves come from bow to stern of FPU or usually called as head seas. The 90° wave heading means the waves come from side of FPU or usually called as beam seas. Meanwhile for heading 0° is named as following seas which wave crest pass the FPU through the stern to bow. RAOS calculations have been carried out from wave frequency 0.1 rad/s to 2.0 rad/s or when viewed from wave period, these RAOS have been calculated at 3.1 sec to 62.5 sec wave period. RAO’s results can be seen in the following graph for each movement surge, sway, heave, roll, pitch, and yaw as presented in Error! Reference source not found.
From Figure 5, the highest value of RAOs surge obtained when the ship suffered head seas and following seas. While highest sway RAOs, heave RAOs, and roll RAOs occurs when the ship experienced a beam sea. RAOs of the FPU represents the vessel characteristic response in a regular wave when free-floating. These results will be used to predict FPU motions on irregular wave to find mooring lines tension.
4.3. Dynamic Tension of Mooring Line

After the modeling, meshing, and we got the RAOs of the FPU as presented above, the next step perform FPU’s mooring lines tension calculation and analysis. The configuration of mooring lines for tension calculation is arranged as shown in Figure 6.

![Figure 6. FPU mooring lines configuration](image)

In this study, dynamic mooring analysis was conducted with variations of nine different loading conditions or wave heading (see Table 4). The dynamic tension of mooring lines analysis was calculated based on time domain method, where the FPU’s mooring system was simulated for 3 hours as recommended by DNV standard. From the dynamic mooring tension simulations, we obtain results of tension data as represented, shown in the graphic of Figure 7, one of all mooring line tension curves based on the time-domain calculation. Figure 7 is an example of tension data result of mooring line 4 (group 2) which simulated for 10800 seconds or 3 hours. Simulations have been done for all of the mooring lines to all of the loading conditions.

After obtained these all mooring lines tension results, then we continue analyzing the tension data to get tension ratio by the line properties especially the MBL value 403.44 t. This analysis has been done by calculate tension based on equation

\[
\frac{\Delta}{\gamma_c} = \frac{T_{c\text{-mean}} \cdot \gamma_{\text{mean}} + T_{c\text{-dyn}} \cdot \gamma_{\text{dyn}}}{\gamma_c}
\]

and using safety factor from Table 1. Most probable maxima (MPM) tension of time series are gotten from maximum tension of time series multiplied by \( F_{nx} \), where \( F_{nx} \) is a factor to convert maximum value to MPM value. The \( F_{nx} \) used number is 1.28 for simulation more than 60 minutes, where estimation of non-exceedance values is 5% [19]. The smallest ratio value should be greater than the safety factor that has been given by DNV standard as explained at page 5. Mooring lines tension and the analysis based on DNVGL-OS-E301 standard are summarized in Table 5.

\[ (21) \]
Figure 7. Tension of mooring line 4 FPU heading 22.5°

Table 5. Line Tension of FPU

| Load case  | Line Tension (ton) | Group-2 | Group-3 |
|------------|--------------------|---------|---------|
| 100-yr     |                    |         |         |
| Full       | a                  | b       | c       |
| 0°         | 142.99             | 144.10  | 145.62  |
| 22.5°      | 182.26             | 188.49  | 195.50  |
| 45°        | 200.64             | 210.39  | 220.87  |
| 67.5°      | 234.37             | 251.34  | 273.25  |
| 90°        | 142.23             | 141.64  | 143.85  |
| 112.5°     | 143.05             | 144.18  | 145.85  |
| 135°       | 143.30             | 143.28  | 143.44  |
| 157.5°     | 145.54             | 145.31  | 145.36  |
| 180°       | 141.98             | 141.89  | 142.06  |
|            |                    |         |         |
|            | d                  | e       | f       | g       | h       | i       |
|            | 96.11              | 76.59   | 66.71   | 150.29  | 150.22  | 149.75  |
|            | 283.09             | 263.43  | 282.55  | 176.26  | 177.73  | 180.26  |
|            | 234.61             | 166.56  | 124.43  | 158.33  | 156.66  | 155.71  |
|            | 403.44             | 216.82  | 185.87  | 157.44  | 159.11  | 158.06  |
|            | 93.24              | 74.66   | 62.86   | 140.70  | 138.91  | 138.18  |
|            | 92.09              | 72.26   | 60.80   | 140.26  | 139.49  | 139.08  |
|            | 74.11              | 61.17   | 53.29   | 136.84  | 136.64  | 136.56  |
|            | 74.30              | 61.33   | 54.30   | 148.92  | 136.64  | 135.95  | 135.77  |
|            | 51.94              | 46.67   | 43.54   | 134.80  | 134.08  | 133.57  |
|            |                    |         |         |

| Load case  | Line Tension (ton) | Max Tension (ton) | Break Tens/Max tens | DNV Cons. Class 2 Criteria |
|------------|--------------------|-------------------|---------------------|---------------------------|
| 100-yr     |                    |                   |                     |                           |
| Full       | L10                | L11               | L12                 | m                        | n                        |
| 0°         | 69.54              | 58.65             | 68.89               | 150.29                   | 6.48                     | passed                   |
| 22.5°      | 227.58             | 220.18            | 221.01              | 283.09                   | 3.44                     | passed                   |
| 45°        | 166.85             | 165.98            | 174.31              | 234.61                   | 4.15                     | passed                   |
| 67.5°      | 169.02             | 169.70            | 167.26              | 403.44                   | 2.41                     | passed                   |
| 90°        | 74.71              | 61.48             | 57.38               | 143.85                   | 6.77                     | passed                   |
| 112.5°     | 56.09              | 49.86             | 66.23               | 145.85                   | 6.68                     | passed                   |
| 135°       | 62.45              | 53.87             | 48.35               | 143.44                   | 6.79                     | passed                   |
| 157.5°     | 73.25              | 61.46             | 53.49               | 145.54                   | 6.69                     | passed                   |
| 180°       | 86.64              | 69.43             | 58.33               | 142.06                   | 6.86                     | passed                   |
In Table 5, column a to l are summarized of all mooring lines tension which are gotten from 10800 seconds simulation based on time-domain. Maximum tension of line 1 to line 12 for each heading angle attack shown in m column of Table 5, then the maximum tension is divided by MBL value of mooring lines properties (see Table 3). Then the ratio value was represented in n column. Maximum tension of all mooring lines value is about 159.3 t. which happened in Line 4 by heading 67.5°. The maximum tension according to DNV OS E301 standard still has 6.5 tension ratio (safety factor). It means that the mooring lines system of FPU complies with the DNV requirement.

5. Conclusions and Suggestions
5.1. Conclusions
The results of the study of dynamic mooring line tension of FPU operated at Madura Strait based on numerical modeling has been conducted produced a number of conclusions as follows:

- Verification of computed chains tension against acceptance criteria has been carried out for the designed mooring system.
- The analysis as summarized in this paper shows that the maximum chains tension occurred at the mooring line still under the permissible value as given by DNVGL OS E301.
- It is concluded that the existing mooring system facility is acceptable to hold an FPU for 8 m full draft as per Rules and Regulations for the Classification of a Floating Offshore Installation at a Fixed Location.

5.2. Suggestions
Based on the findings of the current study, there are two points need to be pursued further in relation to the safety evaluation of the FPU operated at Madura Strait mooring system as follows:

- It is important to conduct Accidental Limit State analysis at FPU operated at Madura Strait mooring lines.
- This FPU is permanently moored at a fixed location, so it is necessary to do fatigue analysis to ensure the mooring lines can work properly due to FPU’s lifetime.

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