Safety Analysis of Mooring Hawser of FSO and SPM Buoy in Irregular Waves

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Abstract. This paper provides a method to analyze the safety factor of the hawser line between Floating Storage Offloading (FSO) and Single Point Mooring (SPM) by using motions simulation. The simulation was conducted based on irregular wave arrival for 1 year and 100 years. A case study for a mooring system of a 55,081 tons displacement of FSO tanker to a 360 tons displacement of SPM buoy was simulated with the existing hawser line length of 45 m and the new hawser line length of 70 m. The wave forces and moments are computed using Ansys AQWA based on the 3D Panel Method both in the frequency domain and time domain. The wave periods are 6 s and 8 s for the 1-year and 100-year data, respectively. The safety factor of the hawser line significantly improves by using the new hawser line.

1. Introduction

Floating Storage and Offloading (FSO) is a floating facility that is used as operational facilities for transferring petroleum products. The products are transferred from offshore drilling to the FSO through under buoy hose and floating hose connected at the Single Point Mooring (SPM) buoy. The products are transported from the FSO vessel by a shuttle tanker. The petroleum product is temporarily stored and transferred from the vessel to a shuttle tanker through another mooring line configuration between the vessels. There are some methods of the mooring system and one of them is mooring buoy. The type of buoy commonly used in petroleum transfers is Single Point Mooring (SPM). In operation, a single point is anchored to the seabed using chains or ropes or a combination connected to the anchor. The hawser is a rope made of nylon or polyester by combining a chafe chain at the ends. The top turntable of SPM can be rotated in 360° in order to stabilize the FSO from disturbance forces. The mooring has 3 types depending on the material used by the mooring namely, mooring using chains, ropes, and a combination of chains and ropes [1]. The SPM is a floating structure that functions as a mooring and interconnection for tanker loads or unloading gas or liquid products. The SPM is the connection between subsea manifold geostatic connections and tankers. One of the advantages of SPM is that it is capable of handling ships of any size, even very large oil-carrying vessels where there are no alternative facilities available [2].

According to Chakrabarti [3], single point mooring consists of floating structures connected to the seabed. The most common SPM system is a floating buoy that is connected to the seabed by the catenary anchor chain. Other SPM system consists of articulated towers that have a large buoyancy section on the free surface and ballast tanks at the bottom. Articulated towers are connected to the base by universal joints which allow articulated towers to move freely in all directions. In both types of SPM, oil flows through the SPM to the surface, where the shuttle tanker is moored by the SPM by synthetic mooring hawser and the oil is transferred to the tanker with a floating hose. Around 300
SPM mooring systems have been operating in the world today. The SPM has several types according to its function. As an example, some of these SPMs are used for combustion of gas, while others are used to distribute oil where tankers are moored to SPM with a single mooring line. According to Kantharia [4], SPM is divided into several different parts that have special functions. Some of these special functions namely tethering and anchoring systems, buoys and product transfer systems are the main parts of SPM. SPM is tethered to the seabed using mooring equipment which includes anchors, anchor chains, chain stopper, etc. Mooring equipment is arranged in such a way as to allow the buoy to move freely within the specified limits, taking into account the wind, wave, current and tanker conditions. The buoys are tethered to the seabed using anchor chains attached to anchor points based on gravity on the seabed. The chain stopper is used to connect the chain to the buoy. Tension analysis of SPM mooring to the seabed considering extreme wave was developed by Eghbali [5]. In this study the tension analysis is developed for the mooring hawser between FSO and SPM. The part of the buoy body of the single point mooring system that floats on the water has a rotating part, turntable connected to the FSO. The rotating part allows the FSO to be stable at the desired position around the buoy. Tankers are usually moored to the buoy by adjusting the hawser arrangement, which consists of nylon or polyester straps fastened to an integrated hook on the buoy deck. Chafe chains are connected at the end of the hawser tanker to prevent damage from the fairlead tanker. The mooring system used for offshore operations follows the standards proposed by the Oil Companies International Marine Forum (OCIMF). The transfer system from SPM transfers products to FSO from Pipeline End and Manifold (PLEM), geostatic locations located on the seabed. Flexible hoses known as risers connect subsea pipelines to the buoy product transfer system. The SPM system uses a rotary system that connects PLEM to the buoy. The product rotary system provides flexibility for movement to tankers during product transfer. This movable pipe connection system prevents premature hose failures due to pressure or bending.

On 6 April 2006, due to extreme weather the single hawser of an FSO, Dampier Spirit failed causing the breakaway coupling on the import hose and releasing oil into the sea [6]. The mooring system between SPM and FSO has the interaction of movement in 6 degrees of freedom including surging, heaving, swaying, rolling, pitching, and yawing. The movements yield tension force in the hawser line. The safety factor of the hawser will increase if the tension decreases. This paper is intended to predict the tension of the hawser line and identify the effect of the hawser line length on the tension. The probability of breaking of the hawser line is analysed in order to identify the safety level. The motions of FSO and SPM configuration were simulated using Ansys Aqwa in irregular waves. The program is based on a 3D Panel Method to compute wave forces and moments both in the frequency domain and time domain [7]. The research is intended to analyze the maximum tension of the hawser due to the wave forces and moments.

2. Methodology
The 4 motions of FSO and SPM were considered in the safety analysis to determine the tension of the mooring hawser.

![Figure 1. The six degrees of ship motions.](image-url)
The motions are heaving, surging, pitching, and rolling. The swaying and yawing motions were not considered due to the vertical rotation ability of the SPM. The 6 motions are shown in figure 1. The motions experienced by FSO and SPM configuration were simulated using Ansys Aqwa in irregular wave based on the 1-year and 100-year data. The configuration is shown in figure 2 and the program is based on 3D Panel Method to compute wave forces and moments both in frequency domain and time domain [7]. The JONSWAP wave spectrum [8] as shown in equation 1 is used in this analysis.

\[
S(\omega) = \alpha g^2 \omega^{-\gamma} \exp \left[ -1.25 \left( \frac{\omega}{\omega_0} \right)^{-4} \right] \gamma \exp \left[ \frac{(\omega - \omega_0)^2}{1.375 \omega_0^2} \right].
\]

(1)

where,
\[
\gamma \quad \text{is peakedness parameter} = 3.3
\]
\[
\tau \quad \text{is shape parameter} = 0.07, \text{if } \omega \leq \omega_z
\]
\[
= 0.09, \text{if } \omega > \omega_z
\]
\[
\alpha = 0.076 (x_0)^{0.22}
\]
\[
= 0.00819 \text{ (when } x \text{ is unknown)}
\]
\[
\omega_0 = 2 \pi (g / U_0) (x_0)^{0.33}
\]
\[
x_0 = gx/U_0^2
\]
\[
\omega_0^2 = 0.161g/\text{HS}
\]

![Figure 2. The FSO and SPM configuration.](image)

The environment data was taken from the Andaman waters data, Myanmar. The data consists of significant wave height and significant wave period, with a period of 1-year and 100-years. The data are presented in table 1 and table 2. The key plan and main dimensions of FSO vessel and the SPM were required as a reference in modeling the shape of the hull. The models of FSO and SPM were developed using Maxsurf software. The main dimensions were needed for validation of the size of the models. The actual dimensions are shown in table 3 and table 4. The data of mooring hawser and chafe chain connecting between the FSO and SPM is shown in table 5 and table 6 [9].

| Table 1. The 1 year wave data. |
|-------------------------------|
| 1-Year                        |
| N | NE | E | W | NW |
|--------------------------------|
| Significant wave height, Hs (m) | 2.5 | 3.1 | 3.3 | 0.6 | 0.8 |
| Significant wave period, Tz (s) | 6   | 6   | 6   | 10  | 10  |

| Table 2. The 100 years wave data. |
|-------------------------------|
| 100-Year                      |
| N | NE | E | W | NW |
|--------------------------------|
| Significant wave height, Hs (m) | 4.8 | 5.9 | 6.3 | 1.0 | 1.5 |
| Significant wave period, Tz (s) | 8   | 8   | 8   | 10  | 6   |

![enter image description here](image)
Table 3. FSO’s main dimension.

| Principal Dimensions          | Quantity | Unit |
|-------------------------------|----------|------|
| Displacement                  | 55081    | ton  |
| Length Of Overall (LOA)       | 179.80   | m    |
| Breadth Moulded (B)           | 32.30    | m    |
| Depth Moulded (H)             | 18.80    | m    |
| Draft (T)                     | 12.116   | m    |
| Cb                            | 0.805    |      |
| Cp                            | 0.808    |      |
| Cm                            | 0.996    |      |
| Cwp                           | 0.896    |      |
| LCB from Midship              | -0.266   | m    |
| LCF from Midship              | -2.684   | m    |

Table 4. SPM’s main dimension.

| Dimensions                     | Quantity | Unit |
|--------------------------------|----------|------|
| Displacement                   | 360.167  | ton  |
| Skirt Diameter                 | 17.885   | m    |
| Inside Centre Well Dia.        | 3.65     | m    |
| Buoy Body Breadth              | 12       | m    |
| Hexagonal Dia.                 | 13.9     | m    |
| Tonnage                        | 280      | ton  |
| Buoy Hull Height (mld.)        | 5.5      | m    |
| Max Draft                      | 2.8      | m    |

Table 5. Double braided nylon mooring hawser 45 m length.

| Parameter                       | Quantity | Unit |
|---------------------------------|----------|------|
| Length                          | 47.5     | m    |
| Circular                        | 16       | inch |
| Diameter                        | 128      | mm   |
| Maximum Breaking Load, MBL      | 595      | ton  |

Table 6. OCIMF Gr.4 chafe chain.

| Parameter                       | Quantity | Unit |
|---------------------------------|----------|------|
| Special End Link Dia.           | 95       | mm   |
| Special End Link Length         | 560      | mm   |
| End Link Dia.                   | 84       | mm   |
| End Link Length                 | 504      | mm   |
| Common Link Dia.                | 76       | mm   |
| Common Link Length              | 456      | mm   |
| HD Shackle 200 T Dia.           | 105      | mm   |
| HD Shackle 200 T Length         | 779      | mm   |
| Tensile Strength                | 860      | MPa  |
| Yield Strength                  | 580      | MPa  |
3. Results and discussion
The precision of the models were achieved by maintaining the main dimensions. The difference between the FSO main dimensions and the model should not be more than 2% [10]. The difference of displacement between the model and the FSO is 1.1%. The models have been developed as shown in figures 3 and 4.

Figure 3. The FSO model.

Figure 4. The SPM model.

The displacement of SPM model is 0.04% less than displacement of the SPM. The configurations of mooring between the SPM and FSO were developed with the hawser length of 45 m and 70 m as shown in figures 5 and 6.

Figure 5. Configuration of mooring hawser 45 m length.
Once the 3D geometry of FSO and SPM are modelled, the next step is conducted the meshing process where the surface mesh is generated using quadrilateral elements. Figure 7 shows the meshed model of FSO with approximately 3000 panels.

Wave spectrum analysis was carried out on the variations of wave height and period with 2 types of wave arrival period, 1-year and 100-years. The wave data can be seen in Table 1 to Table 2. The maximum wave heights for 1-year and 100-years arrival are 1.68 m and 8.10 m, respectively. The response spectrum analysis was carried out with 5 variations of wave direction namely heading sea (180°), heading quartering sea (135°), beam sea (90°), following quartering sea (45°) and following sea (0°). The maximum responses generated from the calculation of the wave spectrum at each motion of the ship and the buoy in accordance with the time of arrival of the waves that is 1 year and 100 years at mooring hawser lengths of 45 m and 70 m are presented in table 7 and table 8.

**Table 7.** The maximum motion responses to the 1 year wave spectrum.

| Motions    | 45 m Hawser FSO (m²/rad/s) | 45 m Hawser SPM | 70 m Hawser FSO | 70 m Hawser SPM |
|------------|----------------------------|-----------------|-----------------|-----------------|
| Heave,     | 0.01323                    | 0.35456         | 0.01310         | 0.37703         |
| Surge,     | 0.00191                    | 0.10676         | 0.00192         | 0.14510         |
| Roll,      | 0.00274                    | 1.56061         | 0.00274         | 0.16813         |
| Pitch,     | 0.04242                    | 0.71353         | 0.04118         | 0.29240         |

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|------------|-----------------------------|-----------------|-----------------|-----------------|
| Heave,     | 0.86922                     | 1.65761         | 0.40488         | 1.75422         |
| Surge,     | 0.01003                     | 0.69317         | 0.00250         | 0.61463         |
| Roll,      | 0.03772                     | 1.84755         | 0.04311         | 0.25779         |
| Pitch,     | 0.64236                     | 1.54718         | 0.63719         | 0.65273         |

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The force acting on the mooring hawser is the tension force due to the movement of the FSO and SPM resulting from the waves disturbance. In the connection configuration of the FSO and SPM there are 2 mooring hawser, line A and line B. Time domain simulations are performed in the Ansys-Aqwa program to simulate the response in irregular waves. The required description is transferred directly from the output result of the analysis done in previous section. The results of this simulation is the spectrum of hawser tension. Figure 8 and figure 9 present the response of hawser tension for 70 m length in head sea condition, both in 1-year and 100-year wave spectrum, respectively.

![Figure 8](image1.png)  
**Figure 8.** The 1-year tension response spectrum.

![Figure 9](image2.png)  
**Figure 9.** The 100-year tension response spectrum.

| Wave Attack Angle | Tension Force (N) | 45 m Hawser | 70 m Hawser |
|-------------------|-------------------|-------------|-------------|
|                   | Line A | Line B | Line A | Line B |
| 0°                | 3,748  | 3,748  | 6,984  | 6,985  |
| 45°               | 6,176  | 6,792  | 7,467  | 7,576  |
| 90°               | 4,580  | 58,679 | 9,111  | 9,379  |
| 135°              | 3,739  | 3,413  | 7,726  | 15,191 |
| 180°              | 9,601  | 10,308 | 14,240 | 14,386 |
Identical procedure has been performed to obtain the result of maximum tension for other loading variation, such as variation of hawser length and wave direction. For practice purpose, recapitulation of the maximum tensions are presented in table 9 and table 10. An interesting result is found in the tables, especially in the beam sea condition. In this condition, the tension of the 45 m length hawser is significantly increasing but it does not occur in the 70 m hawser. This phenomenon is rational considering that the maximum hull force is resulted due to the maximum area of the hull facing the wave pressure from aside. The hull force yields two possibilities of force vector direction configurations. The first configuration is the swaying force and astern surging force leading to the highest hawser tension. The second one is the swaying force and the forward surging force reducing the hawser tension. The usage of the longer hawser increases the probability of the second configuration.

### Table 10. The maximum hawser tension for 100 years wave spectrum.

| Wave Attack Angle | 45 m Hawser | 70 m Hawser |
|-------------------|-------------|-------------|
|                   | Line A | Line B | Line A | Line B |
| 0°                | 13,903 | 14,234 | 7,665 | 7,666 |
| 45°               | 9,654  | 11,323 | 8,267 | 10,839 |
| 90°               | 376,434 | 668,847 | 8,726 | 8,527 |
| 135°              | 7,560  | 11,687 | 14,253 | 8,760 |
| 180°              | 120,869 | 121,004 | 29,173 | 35,394 |

The maximum tension of the 45 m mooring hawser is 668,847 N and the maximum braking load is 559 tonnes or about 5,590,000 N. Accordingly, the safety factor of the hawser is 8.20 meaning that the braking load is 8.2 times higher than the actual maximum tension. Stress analysis of the chafe chain was conducted using the finite element method as shown in figure 10. The maximum stress of the chafe chain of the 45 m mooring hawser is 317.16 MPa, yield strength of the chafe chain is 580 MPa and the safety factor of the chain is 1.83. This tension satisfy the minimum safety factor as required by codes or standars for mooring line strength such as GL Guidelines for Mooring and API RP 2SK which is 1.67 for the dynamic analysis method of intact condition [11,12]. This study shows that the safety factor of the chafe chain is lower than the hawser line. Table 10 shows the tension force of 45 m hawser is significantly higher than the tension of 70 m hawser. The safety factor of the hawser and chafe chain can be improved by increasing the length of the hawser line to be 70 m. The fatigue life of chains depends on the tension and its corrosion rate. An experiment by Fernandez [13] found that the failure cycle in seawater at the stress of 340 MPa is 319,863.
4. Conclusions
This study confirms that the probability of breaking the mooring hawser disturbed by the 100 years wave arrival is zero if the tensile strength of the chafe chain of the mooring hawser is properly maintained. The safety factor of the 45 m hawser is 8.2 and the safety factor of the chafe chain is 1.83 based on the yield strength of the chain. The improvement of the safety factor can be achieved by increasing the length of the hawser line to be 70 m.

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