Sea Keeping Performance Investigation of Cylindrical Floating Production Storage and Offloading (FPSO) on the Indonesian Offshore Environment

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Abstract: The Natuna Islands have the largest natural gas reserves in the Asia Pacific region even in the World. To explore the hydrocarbon reserves that are scattered in many points, the FPSO is one of the alternative choices that investors are interested. The FPSO investment is more efficient than FSO, because the FPSO is a mobile system that able to carry out a reliable production processes and operation. The technological revolution in the FPSO has shown a significant improvement through the development of cylindrical shaped FPSO instead of ship shaped FPSO. In this study, the research is focused on the numerical investigations to obtain sea keeping performance of cylindrical FPSO which have an alternative bottom shape design in the Indonesia sea environment. By considering the results of the analysis of the ship's FPSO motion characteristics (Ship Shaped FPSO) and the JONSWAP wave spectrum, the operability analysis of the FPSO cylinder was performed to determine the relationship between the FPSO cylinder motion characteristics and the ability to operate at the sea, and concerning the specified operating criteria. Heave and roll motion performance will be discussed in this study.

1 INTRODUCTION

FPSO (Floating Production Storage and Offloading) is a facility on a floating building that is operated in offshore oil and gas field that functions to receive, process, store and distribute hydrocarbons that are permanently tethered to where it operates and can be moved from one place to another place. Based on the shape of the building, the FPSO is divided into two kinds of types that consist of a ship shaped and a cylindrical shaped vessel.

The first time, the barge shaped FPSO was dedicated by Arco, that is used in the Ardjuna field and it is operated at a depth of 42.7 meters in the Java Sea offshore in 1976 (D'Souza et.al, 1994). Then, it is followed by the Castellon FPSO in the offshore Spain which was using a tanker shaped design that would be operated for a 10-years field life in 1977. As the increasing demand for oil-gas and for exploration cost efficiency, nowadays the operating FPSO is designed to support the field exploration with return period of waves for the longitudinal strength design as 100 years (Paik and Thayamballi, 2007).

In 2007, the first cylindrical FPSO in the world is introduced as the Sevan Piranema FPSO. The cylindrical FPSO is developed by Sevan Marine which operated in the offshore Brazil with the design of operations in ultra-deep waters, ranging from 1000 m - 1600 m (Paik and Thayamballi, 2007)., see Fig. 1. Then it is followed by the construction of other cylindrical FPSOs, including: FPSO Hummingbird, FPSO Voyageur and FPSO Goliath.

Although the FPSO have shown good performance, however, in the last decades the performance limitations was observed for FPSO with the traditional ship shaped type and cylindrical shaped FPSO (Wang and Feng, 2011; WU, 2012). Ship shaped FPSO is significantly sensitive to the wave direction. These kind of characteristics might cause poor performance on FPSO heave and roll motion in the oblique wave condition which is FPSO usually being operated with the single point mooring system. Since ship shaped have significantly large

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longitudinal scale, the wave impact and green water load might be occurred and possible to damage the deck structure. Moreover, the turret structure also vulnerable because of the excessive yaw motion which is generated by the vane effect. The bending moment of hogging and sagging may cause fatigue failure and severe deformation in the ship shaped FPSO. In the case of cylindrical shaped, the heave motion response is significantly large because of the natural period of heave motion is centralized in the area of wave energy.

Based on the condition, this paper is focused on the investigation of sea keeping performance of cylindrical FPSO which influenced by the modification of the geometry of bottom shape design. The modification of the bottom shape geometry is conducted by adopting the disc shaped for the skirt design to improve the heave motion characteristics. Furthermore, the sea keeping characteristics of the proposed design is investigated and compared with the sevan piranema performance.

Figure 1: The cylindrical shaped FPSO developed by Sevan Marine.

2 MATERIAL AND METHODS

2.1 Literature Review

Recently, several new concepts design of the offshore structures are proposed to improve the sea worthiness and motion characteristics to support the exploration activities on the wave environment. Some literature could be found for the development of marine structure design that was made to improve the heave motion performance of the cylindrical FPSO. Goncalves, et. al., (2009) was developed the concept design of Mono column Production Storage and Offloading System (MPSO) to reduce the motion, to maintain the storage capability and have the ability to facilitate the use of rigid risers. The MPSO adopted an auxiliary apparatus which consist of moon pool, beach, skirt and spoiler plates to minimize the vertical motion. The developed MPSO design provides the best solution for the exploration field in the pre-salt area of Brazil. In the other study, Goncalves, et al., (2010), develop the new concept for MPSO by combining two functional as great oil storage capacity and dry tree production capability. The results show that the decreasing vertical motion could be achieved by implementing the appropriate appendages to the platform. The experimental comparative study on Vortex Induced Motion of a Mono column platform also investigated by Goncalvez, et. al. for the design of MPSO in the Gulf of Mexico (2012).

Besides the cylindrical FPSO of sevan technology and MPSO, a sandglass type ocean engineering floating structure is introduced by Huang et. al. (2013). The sand glass type is provided with an inversed truncated cone as the upper body, and a regular frustum or truncated cone for the lower body. Wang, et. al. was made a numerical and experimental analysis on the motion performance of the new sandglass-type floating body in waves (Wang, et.al, 2016). The study was found that the sandglass-type design able to improve the hydrodynamic performance of FPSO.

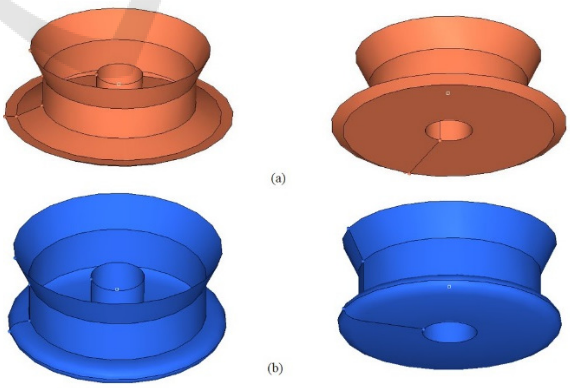

Figure 2: The geometry of cylindrical FPSO: (a) original sevan technology design; (b) modified design with the Disc Shaped skirt geometry.

2.2 Modification of the Cylindrical FPSO Hull Form

The modification of cylindrical FPSO is made by modifying the bottom design of the existing hull form design. Therefore the principal dimension was adopted from the previous hull form design data that might be seen on the Table 1. Since the principal dimension was determined, the next step is to modify the skirt design of the bottom of cylindrical FPSO. The previous skirt design of the cylindrical FPSO has the thin truncated frustum shape and the flap fin is attached at the tip of the frustum, see Fig. 2(a). The flap and the frustum shape are subjected to reduce the heave motion and vertical acceleration.

In the process of modification, the bottom shape of the FPSO was changes with the adoption of the thick disc shaped for the skirt design; see Fig 2(b). The larger volume of the thick disc shape is considered able to increase the added mass of the cylindrical FPSO. Therefore it is expected that the modification might reduce the vertical acceleration induced by wave force in the offshore environment. The influence of the design modification to the motion performance would be investigated using strip theory method for the sea keeping analysis. The sea keeping analysis is performed with the wave spectrum that is defined for the Indonesian offshore environment.

Table 1: Principal Dimension of the Cylindrical FPSO.

Parameters	Dimension
Hull Diameter	93 m
Bilge Box Diameter	124 m
Bilge Box Plate Diameter	138 m
Main Deck Diameter	103 m
Process Deck Diameter	109 m
Main Deck Diameter	42 m
Process Deck Diameter	48 m
Draft, Ballast	22 m
Draft Loaded	31 m
Constant Draft	27 m
Freeboard to Ballast	20 m
Freeboard to Loaded	11 m

2.3 Wave Spectrum and the Offshore Condition

In this study the wave spectra used are the ITTC wave spectra with 2 corresponding parameters in Eq. 1. The significant wave variations (Hs) used were 3 m, 2.5 m, 2 m, and 1.5 m with the Average Period (Tav) variation of 6.09 seconds, 5.60 seconds, 4.82 seconds and 3.70 seconds. This seawaters condition is categorized as moderate waters or sea state number 4.

$$S_{ITTC\varsigma}(\omega) = \frac{A}{\omega^5}\exp\left(\frac{-B}{\omega^4}\right) \quad (1)$$

where:

ω = wave frequency (rad/s); $A = 172.75\frac{H_S{}^2}{T_{ave}{}^4}$; $B = \frac{691}{T_{ave}{}^4}$

The wave spectrum (Sω) generated from Eq. 1 significantly depends on the value of the wave frequency. As a result of the influence of floating body speed and the angle of attack of the wave, the frequency of the incident wave (ωw) will change to the encountering wave frequency (ωe). This encountering wave is used to make the encountering wave spectra (Se). To calculate the encountering wave frequency, Eq. 2 might be used.

$$\omega_e = \omega\left(1 - \frac{\omega V}{g}\cos\mu\right) \quad (2)$$

where:
ωe = encountering waves frequency (rad/s)
ωw = wave frequency (rad/s)
V = ship speed (m/s)
g = gravity acceleration (9.81 m/s2)

The offshore conditions in this study refer to the conditions (Sea State Code) that have been determined by WMO (World Meteorological Organization) on the review of three variations of sea conditions with different parameters covering the highest third of wave height (significant wave height), wave period, and wind speed (Sustained Wind Speed). Variations in offshore conditions are small waves (Slight), moderate waves (Moderate), and large waves (Rough), see Table 2.

North Offshore Natuna-Indonesia is identified as a sea waters with medium wave height. Based on data from the Climatology and Geophysics Meteorology Agency, North Offshore Natuna-Indonesia has an average wave height of 1.0 m - 2.0 m with a maximum wave height of 2 m - 3 m. The average wind speed in the Java Sea is 15 knots - 20 knots.

Table 2: World Meteorological Organization Sea State Code.

Sea State Code	Sustained Wave Height ($H_{1/3}$) (m)	Sustained Wind Height (knots)	Wave Period (s)	Description
	Range	Range		
3	0,5 – 1,25	11 – 16	7,5	Slight water
4	1,25 – 2,5	17 – 21	8,8	Moderate water
5	2,5 - 4	22 – 27	9,7	Rough water

3 RESULTS AND DISCUSSIONS

Evaluation of the performance of a floating body depends on the environment condition. This environment is being expressed in the form of a wave spectrum. Based on the FPSO environment condition, namely in the North Natuna Offshore Indonesia, the ITTC wave spectrum will be adopted for this research, by regarding that recently the offshore environment are considered more dangerous than 20 years ago. In the sea keeping analysis, it is consisted of three categories of problems that are included:

1. Estimation of environmental conditions which is applied to the FPSO model
2. Prediction of the response characteristics of the FPSO model
3. Specification of criteria that is used to assess the behavior of FPSO motion.

The performance assessment also can be done by comparing with the other FPSO. The comparison of the two FPSO designs or reviewing a design against the predetermined acceptance criteria depends on accurate information from the three categories.

In this study, the evaluation of motion was carried out to get varied movements from the bottom design configuration. Comparison between the two designs of the FPSO Sevan Piranema with several types of bottom variations is done to find out the advantages and disadvantages of the behavior of one another. This is needed in providing a bottom design recommendation that is better for use on cylinder FPSO. The acceptance criteria for floating body performance are determined in NORDFORSK 1987 and the operating criteria are adopted from the operability criteria for the Essar Wildcat.

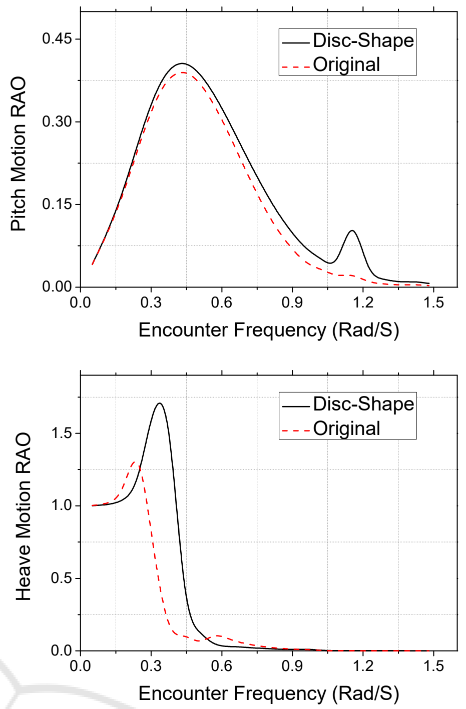

Figure 3: The FPSO Response Amplitude Operator: Heave Motion (Top); Pitch Motion (Bottom).

Motion analysis is calculated using hydrodynamic diffraction method. The results of the analysis of the ship motion are divided into several parts, namely:

1. Response Amplitude Operator (RAO) from heave and pitch motion
2. Wave spectra of the North Natuna Offshore Indonesia
3. Vertical acceleration of the two FPSO design

The results of this motion analysis that are represented in the form of Response Amplitude Operator graphics for heave and pitch can be seen in Fig. 3.

It can be observed that the motion characteristics of the two cylinder FPSO model have a fairly small rotational motion (pitch). The Disc Shape Skirt design has a larger rotational motion compared with the original FPSO model. This is caused by differences in geometry configuration, and bottom dimension size, that gives a difference in the cross-sectional area of the structure that might be influenced by sea waves, which in turn gives different characteristics of motion. In heave motion RAO, it can be seen that Original Model has the higher maximum value of 3.84 m/m, at the encounter frequency of 0.31 rad/s. In pitch motion RAO, the higher maximum value is obtained in the

Disc Shape Model with the magnitude of RAO is 0.41 deg./m, at the encounter frequency of 0.44 rad/s.

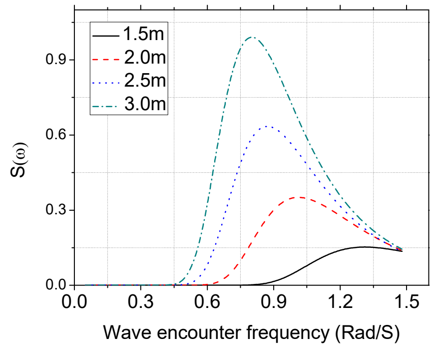

Figure 4: The wave spectrum of the North Natuna Offshore Indonesia.

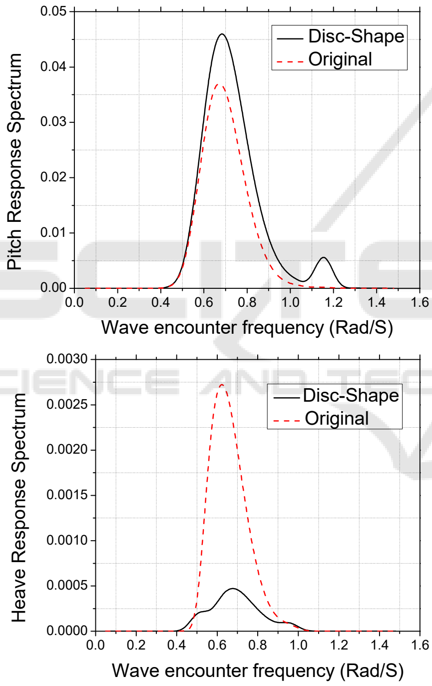

Figure 5: The FPSO Motion Response Spectrum: Heave Motion (Top); Pitch Motion (Bottom).

The spectral peak period distribution in the North Natuna Offshore Indonesia has a range between 3.70 s - 6.09 s and the range of significant wave height (Hs) is between 1.5 m - 3 m. Each peak period consists of certain variations (Hs). Fig. 4 shows the wave energy spectrum of the North Natuna Offshore Indonesia in each period using the ITTC formula.
Response spectra were obtained after multiplying the wave spectra with RAO. In this response spectra computation, it is only conducted on the fluctuation of heave and pitch motion modes that are conformed to the operating criteria requirements. The response spectra of the heave and pitch motion of the two FPSO is shown in Fig. 5.

Table 3: Heave and Pitch Motion of the two FPSO.

Motion Parameters	Significant Wave Height	Original Cylindrical FPSO	Disc-Shaped Skirt FPSO
Heave Amplitude	3.0 m	0.023856	0.011821
	2.5 m	0.013845	0.007178
	2.0 m	0.005046	0.003330
	1.5 m	0.000638	0.000647
Heave Velocity	3.0 m	0.015973	0.008199
	2.5 m	0.009775	0.005449
	2.0 m	0.003996	0.002821
	1.5 m	0.000596	0.000630
Heave Acceleration	3.0 m	0.011035	0.006039
	2.5 m	0.007131	0.004315
	2.0 m	0.003249	0.002458
	1.5 m	0.000564	0.000624
Pitch Amplitude	3.0 m	0.094705	0.112535
	2.5 m	0.059676	0.075440
	2.0 m	0.025725	0.040202
	1.5 m	0.004886	0.016221
Pitch Velocity	3.0 m	0.066637	0.084585
	2.5 m	0.044356	0.061391
	2.0 m	0.021307	0.038427
	1.5 m	0.005086	0.018422
Pitch Acceleration	3.0 m	0.048786	0.069121
	2.5 m	0.034267	0.054329
	2.0 m	0.018336	0.039073
	1.5 m	0.005449	0.021085

The area under the response spectra curve for each motion needs to be obtained, since it would be used to find the statistical value of each movement as the next procedure. Furthermore, significant amplitude values and average amplitude can be obtained for each FPSO design. The calculation results can be seen in Table 3. The value of the amplitude of the average movement response in each movement is correlated with the operating criteria, to obtain operability in each period and significant wave height.

From the analysis results, it is show that the Disc-Shape Cylindrical FPSO model has a different motion acceleration compare with the original model. The Disc-Shape model has a 45.27% lower heave motion acceleration compare with the original model. However the pitch acceleration of Disc-Shape model is 41.68% higher than the Original Model. It is indicated that the Disc Shape model is an effective damper for the translation acceleration, otherwise the original model have a better rotational damper. It might be explained that the original model have the flap skirt that is able to reduce the rotational motion.

According to the acceptance criteria for the operational requirement of the two FPSO, it can be seen that the motion amplitude of both FPSO variation models, for heave and pitch, up to the highest significant wave height, are comply with the NORDFORSK 1987 and the Essar Wildcat criteria, see Table 4 and Table 5. Although in the Disc Shape FPSO model have larger maximum RAO than original model, the Disc Shape model generally shows better heave motion response than the original model, because of the wave spectrum have a small value at the range of encounter frequency of 0.5-0.8 rad/s.

Table 4: NORDFORSK 1987 operability criteria.

Description	RMS Vertical Acceleration
Light Manual Work	0.20 g
Heavy Manual Work	0.15 g
Intellectual Work	0.10 g
Transit Passengers	0.05 g
Cruise Liner	0.02 g

Table 5: Essar Wildcat operability criteria.

Operation	Heave	Pitch/Roll Single Amplitude
Operability	0,2 g (m/s^2)	-
Land BOP on Wellhead	2.4 m	2.5 deg
Running BOP	4.6 m	2.5 deg
Running Casing	4.6 m	2.5 deg
Disconnect Riser	5.5 m	2.5 deg
Drilling or Tripping	4.6 m	2.5 deg
Hang-off	2.2 m	2.5 deg
Cementing	2.2 m	2.5 deg
Crane Operation	5.5 m	3 deg
End of Self Propelled Transit	-	3 deg
Helicopter	5.5 m	-

4 CONCLUSIONS

From the overall analysis results, it is obtained that the heave and pitch motion characteristics of the two FPSO design on the highest significant wave height is comply with the operability criteria. It is indicated that all of the design is reliable to be adopted for the offshore exploration activities at the North Natuna offshore Indonesia.

The Disc Shape design have larger heave motion RAO than original design, however the Disc Shape shows better heave motion response. It might be explained that the maximum RAO of the two FPSO design is occurred on the frequency which the wave spectrum have very small magnitude. Since the Disc Shape has shown larger RAO, the application of the Disc Design should be thoroughly assessed by considering the experimental studies. In the case of pitch motion, the original design shows better motion response characteristics than the Disc-Shape design. It is indicated that the flap of the skirt was effectively able to reduce the pitch acceleration of the FPSO

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