Stability and Hydrodynamic Analysis of a Deepwater Spar Platformin The Gulf of Mexico

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Abstract

Global energy demand has driven the oil industry to develop floating systems with stability, low response motions, high production capacity for oil and gas in deep and ultra-deep water. Its development is an iterative process, due to the fact that it analyzes the production and safety requirements according to the bases of the project, and subsequently it will advance or go back, according to its performance, one step in the design spiral. Hernandez-Menez (2020) states that it is a meticulous process, given the high cost it represents, it requires an excellent and functional design, according to the specifications required for a safe operation. For this reason, new floating systems have been developed, such as Spar-type platforms. Hernandez-Hernandez (2020) mentions that the environmental conditions, hull shapes and weight distribution are key factors for the stability and hydrodynamic response of a floating production system which is why stability and minimal motion are sought to prevent a stoppage or failure in oil and gas production equipment. Currently there is not a floating system of this type in Mexican territory, this study analyzes a case under environmental conditions of the Gulf of Mexico, establishing the hull shape, stability criteria and loading conditions to determine the motions of the platform.

Key words: Stability, Hydrodynamics, Response Motions, Loads, Regulations.

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Introduction

OPEC expects world demand for crude oil to increase by 105.2 million barrels per day in 2025, thus, it is essential to have the means to extract and produce oil and gas to meet global energy demand and, in turn, to meet national energy demand.

New fields are continuously being discovered. Many of these fields are in more hostile environments, which is the reason why Thigpen (2020) mentions that customer demand for high-specification ultra-deepwater floating systems now equals or exceeds the number of marketable platforms currently available in many areas and this refers to the need for new systems or upgrades to existing systems in order to meet current demand.

Currently, shallow water is defined as water depths less than 500 m, deep water is defined as sites with a water depth less than 1500 m and for water depths greater than 1500 m, the term “ultra-deep water” is used.

Characteristics of Spar-type floating systems

The distinctive characteristic between fixed platforms and floating systems is that the latter are supported by buoyancy generated by the hull: the weight of the topside, the risers, the mooring lines, and, if necessary, a dynamic positioning system to keep them in their place of operation

Floating systems possess different degrees of freedom of motion in response to meteorological and oceanographic forces. Under this criterion, Barranco (2012) claims that floating platforms vibrate dynamically in six rigid body degrees of freedom, three translational motions in the direction of the X, Y and Z axes, and three rotational motions around the same axes: surge, sway, heave, pitch, roll and yaw, respectively.

Spar platforms support drilling and production operations. Their buoyancy is used to support installations above the water surface, and they are generally moored to the seabed with multiple mooring lines.

The different generations of Spar platforms have introduced technological improvements and enhanced hydrodynamic performance; the main differences between the classic Spar and truss platforms is the reduction of areas exposed to environmental loads and crude oil storage with the replacement of the middle section hull by a truss with heave plates. These changes benefit the owner, due to cost reduction and keep the same capacity.

This work has focused on Truss Spars because of its capacity to perform multiple well drilling and production activities; oil storage was not considered in the analysis; currently it does not perform this activity because the processed oil is shipped directly to land through subsea pipeline systems or by pumping it to a tanker.

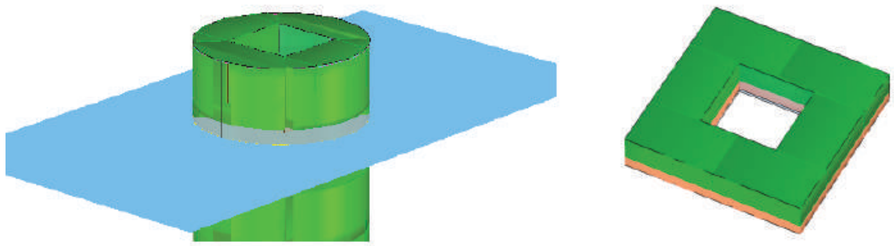
Methodology

Model

The practical recommendation API-RP-2FPS 01 mentions that the Hard Tank of Spar platforms should be divided horizontally by watertight decks and vertically by radial watertight bulkheads. These hull compartments or hard tanks are designed to support storage loads and hydrostatic pressure from the outside hull and Centrewell.

The soft tank consists of tanks located on the underside of the platform, and are primarily used to provide space to hold fixed ballast, which is necessary to lower the center of gravity. They are also used to maintain buoyancy during towing and turning at platform installation.

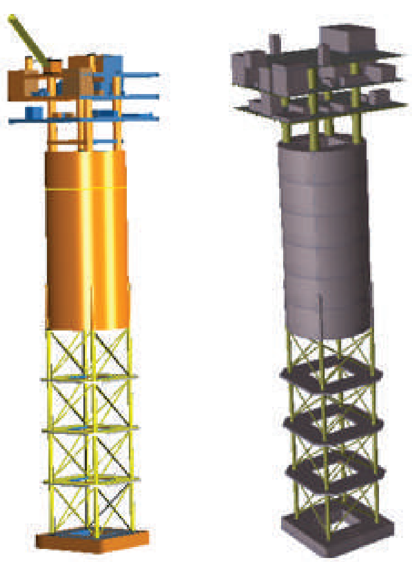
Fig. 1. Hard Tank and Soft Tank of the Spar platform.



The hull model of the platform was developed using two software tools. To perform the stability analysis it was required to create a NURBS surface model, in which all the surfaces of the hull structure, Topside and deck equipment were incorporated.

The hydrodynamic analysis was performed by finite element analysis with the hull panel model, which uses plate and slender tube elements to which surface and structural properties can be assigned.

Fig. 2. Truss Spar platform hull models.



Dimensions

The analyzed platform is a truss Spar platform, which has the followings characteristics:

Table 1. Dimensions and displacement of the Spar platform.

Spar platform dimensions		
Operating draft (Maximum draft)	164.6	m
Depth (L.B. to Spar Deck)	181.3	m
Freeboard	16.7	m
Displacement	67127	T
Hard Tank Diameter	37.2	m
Centrewell	16x16	m
Hard Tank Depth	80.8	m
Soft Tank Dimensions	37.2x37.2	m
Soft Tank Depth	6.1	m
Heave Plates Number	3	m
Heave Plates Depth	1	m
Heave Plates Dimensions	37.2x37.2	m
Main Truss Depth	94.5	m
Main Truss Diameter	2	m
X Truss Diameter	0.8	m
Distance between main trusses	18.6	m

Identification of the stability standards applicable to Spar platforms

In Mexico the National Maritime Authority is the Secretaria de Marina, which verifies that the floating systems that are registered and/or operating in Mexican territory comply with the Mexican Official Standards (NOM), but there are no regulations for Spar type platforms. Internationally, there are standards and recommendations about stability and operation, but the criteria most commonly applied are those issued by the IMO. Classification societies such as DNV give more demanding stability parameters and requirements including wind and wave parameters.

IMO has two important codes, the 2008 IS Code and the 2009 MODU Code, but both do not give criteria and recommendations directly applicable to Spar platforms. On the other hand, in the standard "DNVGL-OS-C301 Stability and Watertight Integrity" defines Spar platforms as "Deep Draught Floating Unit" type units, where in section 2.1.1.6 it mentions:

"2.1.1.6 Deep draught floating installations (e.g. SPARs), cylindrical units, and tension leg units are not directly covered by the IMO MODU Code. Criteria identical to those of a column stabilized unit or installations have been adopted, with some additional criteria for SPARs."

The platform must pass the stability criteria without the need for anti-roll systems, mooring lines or stability increasing elements. According to Mexican regulations, IMO codes and classification societies, the criteria applicable to Spar type platforms are as shown in Table 2.

Floating system loads identification

Wind

The loads that impact the stability of the platform were analyzed in accordance with the regulations and the displacement in lightship, the weight of equipment on deck and the force of the wind were obtained.

Wind acts as a disturbing force, causing the platform to heel. According to the 2009 MODU Code the wind forces can be determined:

$$F = 0.5*C_s*C_h*P*V^2*A \quad (1)$$

Where: "F" is the wind force, "Cs" is the shape coefficient of the structural member exposed to the wind, "Ch" is the height coefficient depending on the height above sea level of the structural member exposed to the wind, "P" is the air mass density, "V" is the wind speed and "A" is the projected area of all exposed surfaces, either upright or heeling.

Typically, a wind speed of 36 m/s (70 knots) is used for normal offshore operations, and

Table 2. Stability criteria for the Spar platform.

Standard	Chapter	Criteria
MODU	3.3.1.2	The area under the righting moment curve to the angle of downflooding shall be not less than 30% in excess of the area under the wind heeling moment curve to the same limiting angle.
MODU	3.3.1.3	The righting moment curve shall be positive over the entire range of angles from upright to the second intercept.
OS-C301	4.3.3	During temporary conditions the metacentric height (GM) shall be at least 0.3 m.
OS-C301	4.5.2	The righting moment curve shall be positive over the entire range of angles from upright to the second intercept.
OS-C301	4.5.4	Intact inclination angle is limited to 6° and 12° for normal operating conditions and survival conditions, respectively.

51.5 m/s (100 knots) for severe weather conditions.

Wave

The wave characteristics are obtained from data collected at the site where the platform will operate and from an analysis of extreme values for the design return periods. In this study, the platform is considered will be located in the Lucius field in Keathley Canyon 874, 875, 918 and 919 (Tule, 2015). The Spar platform will be analyzed with a 100-year return wave in storm condition, with the parameters shown in Table 3.

Wave Spectrum

The knowledge of wave generation is very extensive and is not sufficiently advanced to allow a complete prediction of waves by theoretical considerations Nevertheless, several empirical formulas exist that are derived from the observed properties of ocean waves.

Different spectrum models for the same energy content distribute the energy differently in the frequency band. Therefore, the response of the structure for the same random wave energy (or equivalently, significant wave height) will be different if different spectrum models are used *(Chakrabarti, 2005)*.

The wave spectrum used is the JONSWAP spectrum, as it is applicable for fetch-limited developed sea states. The shape of this spectrum has been demonstrated by a wave observation program known as the Joint North Sea Wave Project (JONSWAP) and depends on the significant height and peak periods.

$$S_J(\omega) = A_\gamma S_{PM}(\omega)\gamma^{\exp\left(-0..5\left(\frac{\omega-\omega_p}{\sigma\omega_p}\right)^2\right)} \qquad (2)$$

Where:

- Y is the shape parameter of the spectrum peak.
- σ is the spectrum breadth parameter.
- A_γ is the normalization parameter and equals 1-0.287 ln (Y).
- Response spectrum

It is important to predict the response of the platform in a specific sea condition, due to the evaluation of its effects on its performance and its damaging effects, such as, for example, water loading, slamming and excessive vertical accelerations.

Table 3. Wave conditions.

Methoceanic Criteria	1000-year hurricane		100-year hurricane	
	Max. wave	Max. wind	Max. wave	Max. wind
Hs (m.)	18.745	17.831	13.503	12.832
Tp (seg)	15.600	15.400	14.000	13.800
Tz (Tp/1.1049) (seg)	11.104	10.962	9.965	9.823
Gamma	2.200	2.200	2.200	2.200
Maximum crest (m.)	21.366	20.300	15.392	14.630
Wind speed (knots) (1 hour at 33 ft.)	92.500	92.500	92.500	92.500
Surface current velocity (ft/sec.)	7.000	7.000	7.000	7.000

This performance is obtained by the response spectrum, whose procedure consists of the product of the square of the RAO of a specific movement by the wave spectrum used to represent a given sea condition:

$$S_R = \left| RAO^2 \right| \cdot S_J \quad (3)$$

Analysis and results

Stability analysis

The platform's stability was analyzed under two operating conditions: wind at 70 knots and 100 knots.

It was also analyzed under three loading conditions: maximum draft, 90% and 75% of fixed ballast, the last one with the objective of comparing the response motions.

The results of the stability analysis are shown below. It is shown that the Spar type platforms have great stability under all weather conditions, even with the variation of the fixed ballast weight that caused a decrease in metacentric GM height.

In the third case, 10% of the fixed ballast was decreased, reducing the VCG of the platform, causing a 49.12% decrease in GMt with respect to the second case.

In the fourth case, 25% of the fixed ballast was decreased, causing a 92.66% decrease in GMt with respect to the second case; even with this loss of GMt, the platform is in a stable equilibrium condition.

The stability criteria were approved for the conditions analyzed, which supports the results of the analysis and confirms the operational safety of the platform.

Hydrodynamic analysis

The heave, roll and pitch motionss of the platform were analyzed with the wave height (Hs), period (Tz) and spectrum (JONSWAP)

Table 4. Comparative stability analysis of the platform in intact condition.

	Comparison with heel to zero degrees			
	Operation in wind at 70 knots	Storm with 100 knots wind	Storm in wind at 100 knot with 90% fixed ballast	Storm in wind at 100 knot with 75% fixed ballast
GZ m	-0.045	-0.045	0.066	0.069
Area under GZ curve from zero angle m.rad	-0.0014	-0.0014	0.0021	0.0022
Displacement t	65545	65545	63865	61338
Draft on FP m	164.754	164.754	162.711	159.134
Draft on AP m	164.648	164.648	162.622	160.031
Trim (+ve to FP) m	-0.106	-0.106	-0.089	0.897
VCB m	111.488	111.488	110.115	108.013
BMt m	1.332	1.332	1.367	1.424
GMt corrected m	14.399	14.399	7.326	1.057

Table 5. Comparative stability analysis of the platform in intact condition.

Standard	Chapter	Criteria	Operation in wind at 70 knots	Storm with 100 knots wind	Storm in wind at 100 knot with 90% fixed ballast	Storm in wind at 100 knot with 75% fixed ballast
MODU	3.3.1.2	Ratio of Areas	Ok	Ok	Ok	Ok
OS-C301	4.3.3	GM>0.3 m	Ok	Ok	Ok	Ok
OS-C301	4.5.2	Range of positive stability	Ok	Ok	Ok	Ok
OS-C301	4.5.4	Intact inclination angle<6°	Ok	Ok	Ok	Ok

previously mentioned. A wave incidence at 0, 45 and 90 degrees was analyzed, looking for the wave incidence angles that generated the most motion on the platform. The platform's motions at maximum draft are summarized below:

Table 6. Results of platform motions at maximum draft operation.

Motion	0 degrees		45 degrees		90 degrees	
	Amplitude	Units	Amplitude	Units	Amplitude	Units
Heave	1.645	m	1.672	m	1.704	m
Roll	0.00059	deg	1.03132	deg	1.43239	deg
Pitch	1.43239	deg	1.03132	deg	0.00056	deg

Table 7. Results of platform motions at a draft of 160.7 m and a wave angle of 90°.

Motion	90 degrees	
	Amplitude	Units
Heave	1.931	m
Roll	0.97403	deg
Pitch	0.00104	deg

The maximum heave motion was observed at a wave incidence angle of 90°, while roll and pitch amplitudes were symmetric at 0° and 90° due to the platform’s hull geometry.

The motions obtained from the platform at a draft of 160.7 meters and at a wave angle of 90° were studied to obtain the maximum heave value; for this draft the weight of the fixed ballast was decreased by 20% and an increase in the VCG was obtained and, consequently, a 77.82% decrease of the GMt (3.193 meters) with respect to the maximum operating draft.

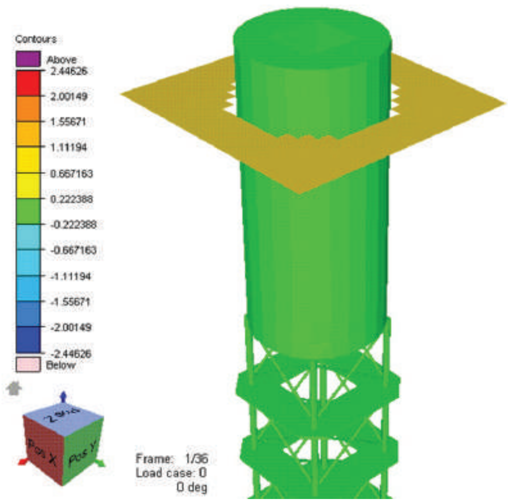
Conclusions

The stability analysis showed the importance of maintaining the iron mineral ballast in the Soft Tank, since it is located in the lowest position of the platform and its weight changes affect the position of the center of gravity, the transverse metacentric height (GMt) for a correct equilibrium condition.

The longitudinal and transverse center of gravity is also sought to be located in the center of the platform and with the help of the ballast tanks at the bottom of the Hard Tank, the possible settling of the platform is corrected.

The hydrodynamic analysis of the platform was conducted under free-floating conditions at maximum draft. The motions in heave, pitch, and roll were studied, as they are the most critical among the six degrees of freedom of a floating rigid body. These motions have the greatest impact on accelerations affecting the platform and its appendages. Values exceeding recommended limits would compromise the safety of onboard equipment and installations.

Fig. 3. Spar platform roll motion.



With the free-floating hydrodynamic analysis, it was detected that the maximum movements of the platform were obtained at 90 degrees:

Table 8. Maximum response motions of the Spar platform.

Motion	Max. Draft		Draft of 160.7 m.	
	90 degrees			
	Amplitude	Units	Amplitude	Units
Heave	1.704	m	1.931	m
Roll	1.4323945	deg	0.97403	deg
Pitch	0.000557	deg	0.00104	deg

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