MODEL TESTS AND SIMULATIONS ON CIRCULAR SHAPED FPSO WITH DRY TREE SOLUTIONS

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ABSTRACT

New build Floating Production Storage and Offloading units (FPSOs) are traditionally shaped like a shoe box with flared bow to simplify the construction, while taking advantage of existing knowledge from sailing vessels and tankers. In harsher environments these floaters require a turret to rotate into the direction of the main environment. The need for an expensive turret can be eliminated with a circular shaped floater, which also requires less steel per storage capacity. SSP Offshore Inc developed two of these floaters, the SSP and the SSP PLUS. Both units were model tested at LabOceano in Brazil to confirm the calculated motion response and mooring loads.

This paper discusses the specific advantages of both platforms and presents the numerical and experimental models prepared for motion evaluation. The test results demonstrate the importance of second order effects for the pitch motions and confirm the ability to use the SSP PLUS with dry tree risers in Brazilian conditions.

INTRODUCTION

SSP Offshore Inc. developed a family of round floaters which combine small motions with large storage capacity and low steel weight. In this process different companies were contracted to perform specialized evaluations. The current paper discusses the studies related to the floaters motions. Both numerical and experimental models were built and will be presented.

The SSP and SSP PLUS can be classified as mono-columns. These platforms have been studied for several years, Miyagawa *et al* (1989) presented in 1989 a comparison of 4 new floating units, and concluded that the round shape was one with the biggest advantages.

Others, like Matsuura *et al* (1995), Tanabe and Matsuura (1997) and Cueva *et al* (2005), and Cueva *et al* (2006), also made contributions in this floater concept, answering several doubts usually raised by the offshore engineers.

In this paper, an overview of the unit will be presented, followed by details of the numerical model and model tests. The compared results and the conclusions are presented at the end.

SSP AND SSP PLUS OVERVIEW

Both SSP floaters are circular in shape, which makes the unit indifferent for the incidence angles of the environments. Neglecting the asymmetries in the mooring or wind loads, no excitation for yaw exist and the surge and pitch motions equal the sway and roll motions. Therefore the motion response is classified with three types of responses: vertical (heave), horizontal (surge/sway) and angular (roll/pitch).

The SSP consist of a bowl shaped hull with centre column. The roll/pitch natural period of the SSP can be moved outside the range of expected wave frequencies with the design of the weight in the bottom of the centre column. The centre column base is enclosed to bind a significant amount of water which results in added inertia for the roll/pitch motions. The added mass at the bottom of the centre column, also gives a pitch moment due to the surge loads on this segment. This effect shifts the centre of rotation further down below the waterline and couples the surge and pitch response. This results in an increase of pitch motions and available freeboard. The SSP requires approximately 29,000 tons of steel to allow storage of about 1.25 Mbbls, which is significantly more efficient than conventional new built/converted FPSOs.

To improve the heave motions of the SSP and eliminate the need for a centre column, the SSP PLUS compromises some of the steel weight storage ratio with a permanently ballasted skirt below the SSP. Combined with large bilge keels at the bottom the natural period for heave increases to 23 seconds which is well above most of the wave periods. The unit has storage capacity of 1.6 Mbbls of oil, and can support topside up to 20.000t. In wave conditions similar or smaller than Brazil's Santos basin, the unit can facilitate dry tree solutions with proven heave compensator technology.

As a general design for GoM, with 1.000m of water depth, the unit uses a 3x6 mooring arrangement, in a semi-taut layout.

The 150mm diameter chains are placed in the top and bottom of the lines, with length of 50m and 100m, respectively. The 312mm polyester line is the mid section, with 1.250m length.

Five SCR risers (varying from 16”~18”) were connected at the same elevation as the mooring systems and ran in a region between 2 mooring line groups. In an offshore application, the SCR risers and/or production risers can also be connected at the center/moonpool area of the SSP Plus keel, but the more severe option was tested to comply with earlier studies and check the feasibility of this approach for WoA conditions. The previous study contained 8 SCRs, but the value can vary according to the field characteristics.

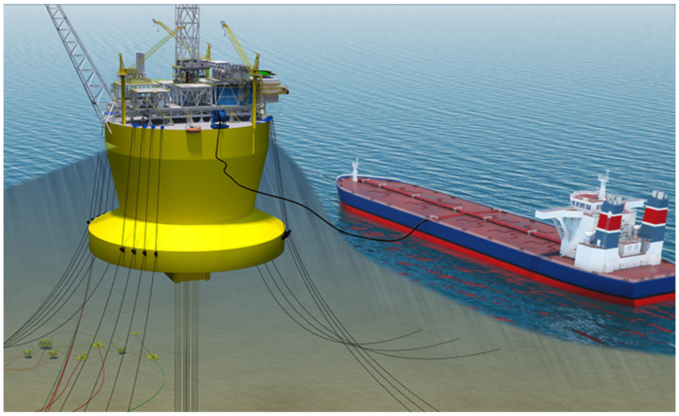

Figure 1 – Overview of the SSP Plus Concept

NUMERICAL CALCULATION

To predict the motions of the unit, a numerical model was prepared according to the same data used in the tests.

The diffraction/radiation analysis was performed with the software DIFFRAC, and the time domain coupled analysis, with mooring lines and risers included, evaluated in AnySim, both developed by MARIN.

In order to consider the viscous damping in the analysis, not calculated by potential methods, an external damping of 2% of critical damping was included on all modes of motions.

The mesh used in the diffraction method and the bird view of the complete system, is presented in Figure 2.

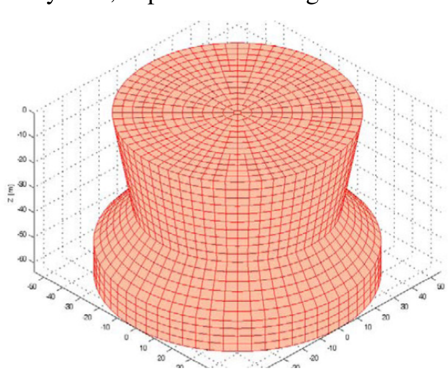

Figure 2 – Mesh for diffraction calculation

MODEL TESTS

In order to verify the motions obtained from numerical analysis, model tests were executed in the LabOceano basin, in Brazil, with specification from MARIN – Maritime Research Institute Netherlands and supervision of Oceanica Offshore, a Brazilian engineering and consulting company.

The facility is composed by a 40m long, 30m wide and 15m deep tank, with waves and wind generation capabilities. The current generation is under final phase of installation and was not generated in the tests.

The model was constructed in the scale of 1:60, with dimensions, inertia, displacement and center of gravity according to the data presented in Table 1. The model is presented in Figure 4

The differences between the specified and obtained data were maintained according to the required by ITTC, less than 1% in the displacement, less than 2% in the vertical center of gravity position and less than 3% in the radius of gyration.

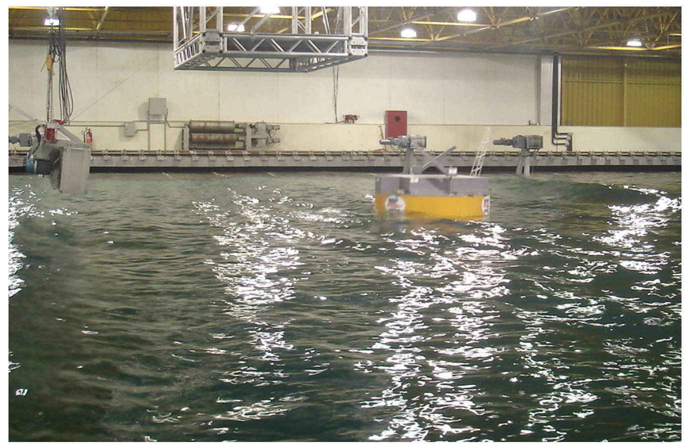

Figure 3 – LabOceano basin

Table 1 – SSP Plus Data

SSP+ CHARACTERISTICS		
Description	**Symbol**	**Value**
Diameter in waterline	Lwl (m)	96.60
Maximum diameter	Loa (m)	121.00
Moonpool diameter		17.00
Depth	H (m)	78.10
Draft	T (m)	59.40
Displacement	Δ (t)	450871.00
Logitudinal pos of CG*	XCG (m)	0.00
Transverse pos of CG*	YCG (m)	0.00
Horizontal pos of CG*	ZCG (m)	26.00
Logitudinal radius of gyration	Rxx (m)	42.00
Transversel radius of gyration	Ryy (m)	42.00
Horizontall radius of gyration	Rzz (m)	45.00
Metacentric height	Gm (m)	8.80
*from center lines and keel		

The mooring system tested is a 3x3 semi-taut in 875m WD, with equivalent restoring of a 3x6 system in 1.000m WD. Flexible risers were tested are in free catenary configuration. The bird view of the truncated lines arrangement is presented in Figure 5.

The horizontal restoring stiffness was adjusted with maximum difference of 6%.

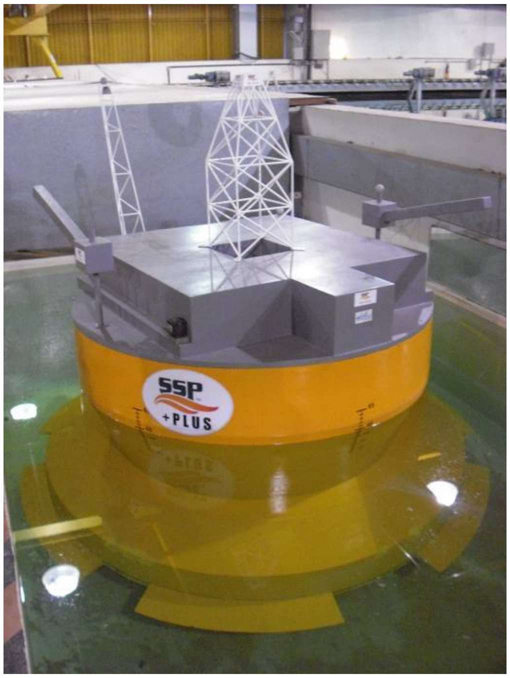

Figure 4 – Overview of the SSP Plus model

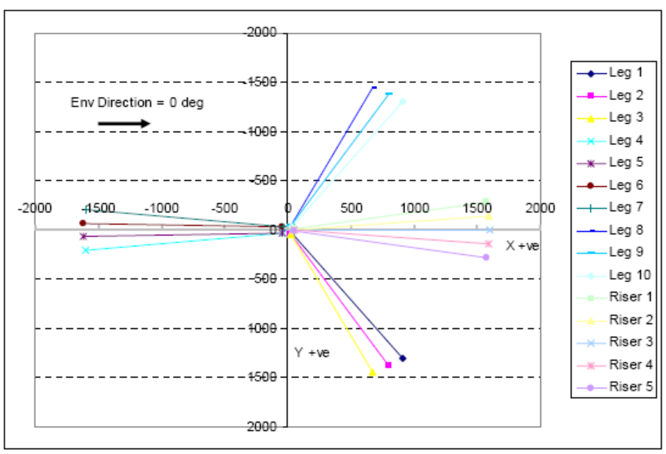

Figure 5 – Truncated mooring and riser system

The objective of the test was to verify different conditions in the main offshore areas in the world. The waves presented in Table 2 were calibrated. The environmental conditions cover a large range of wave periods and wave heights. The different wave heights show the linearity of the motion response, while the large range of periods ensures that all motion phenomena are covered in the tests.

It should also be noted that the most severe conditions for the mentioned locations are included. The 100 yr condition in the Campos basin in Brazil for instance is only 7.8m, compared to the tested 11.11m in the Santos basin. Further the latest Gulf of Mexico hurricane conditions are used for the central region and even a 1000yr wave is considered with significant wave height of 19.8m.

The system was tested in the conditions presented in Table 2, and the results analyzed both in time domain and in frequency domain.

Table 2 – Environmental conditions calibrated

	WAVE		WIND
CONDITION	Hs(m)	Tp (s)	Vw (m/s)
Brazil 1yr	5.70	13.70	19.00
Brazil 100ya	9.87	11.00	30.00
Brazil 100yb	10.79	13.50	30.00
Brazil 100yc	11.11	16.00	30.00
Brazil 100yd	10.35	18.50	30.00
WoA 1y	2.70	15.00	19.00
WoA1oy	3.40	17.00	25.00
WoA 100y	3.80	18.00	31.00
GoM 1y	4.90	11.10	14.50
GoM 100y	15.8	15.40	48.00
GoM 1000y	19.8	17.20	60.00

In addition to motion response tests in operational and survival conditions, offloading simulations were carried out in the operational conditions and in squalls. The squalls were simulated with increasing wind perpendicular to the waves, so that the tanker was forced to rotate around the SSP. To facilitate this rotation a special reel system was included, shown in Figure 6. Some fishtailing occurred in the collinear conditions, which was suppressed with stern thrust on the tanker, simulating a tug pulling controlling the vessel at the stern. The response to the squall condition showed promising results and will be further studied with tug master and marine specialist with several operations in a Joint Industry Project (JIP). The results are not further discussed in this paper, but will be shared in this JIP.

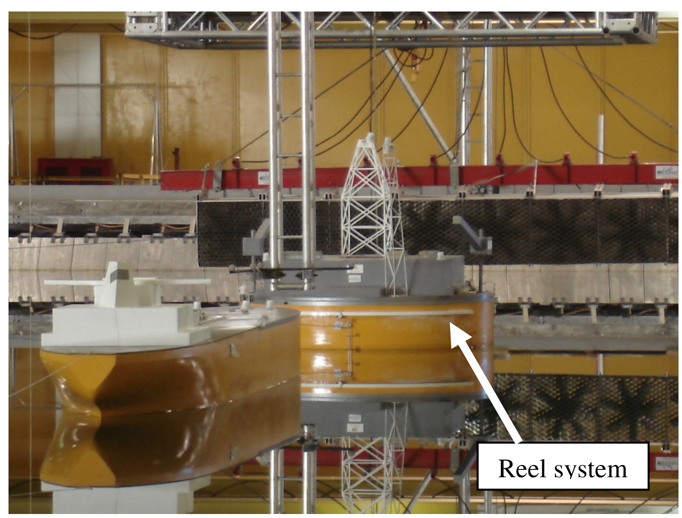

Figure 6 – Reel system which allows the shuttle tanker to weathervane around the SSP+

RESULTS

The results for both numerical and experimental evaluations are presented in terms of RAOs, for the heave and pitch/roll motions, and in terms of standard deviation and most probable maxima in three hour simulations.

First Figure 7 presents the RAOs for pitch derived from all the tests, showing a good agreement between numerical and experimental for the first order response. In the large range of environmental conditions tested, the response is relatively linear (all colored lines coincide).

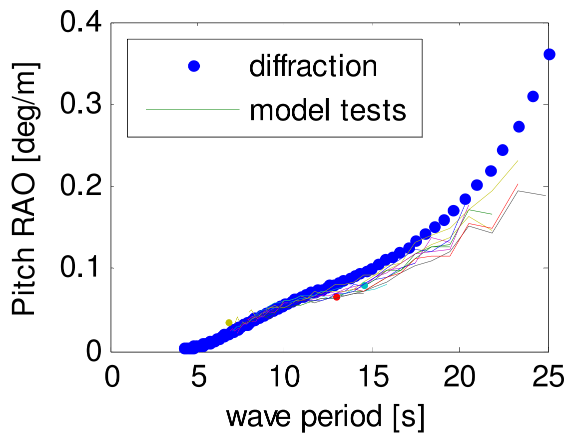

Figure 7 – Pitch RAO: Numerical x Experimental

The pitch response in the model test is slightly smaller than predicted by the simulations. The decay tests (Figure 8) shows that the damping is much larger than in the initial simulations and is mainly quadratic. The dotted line is the same in both graphs and represents the measurement. The solid line is the numerical result in the upper plot and the best quadratic fit on the model tests in the lower plot.

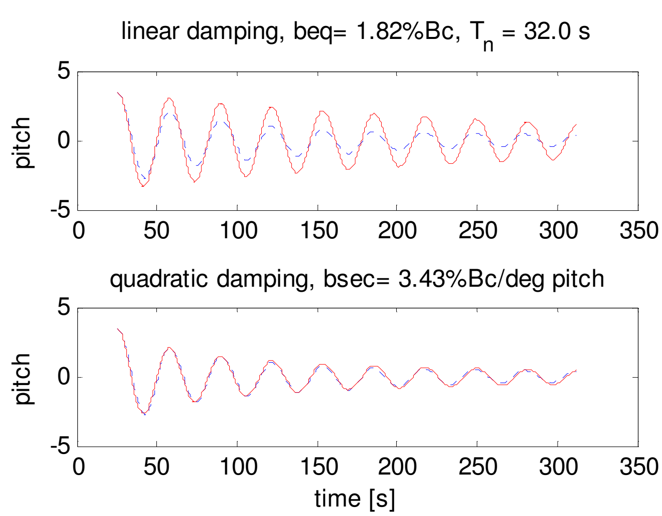

Figure 8 – Pitch Decay

The natural periods are high: 23s for heave and 32s for pitch, resulting in small response in to the first order waves, helping the riser design both in extreme and fatigue criteria.

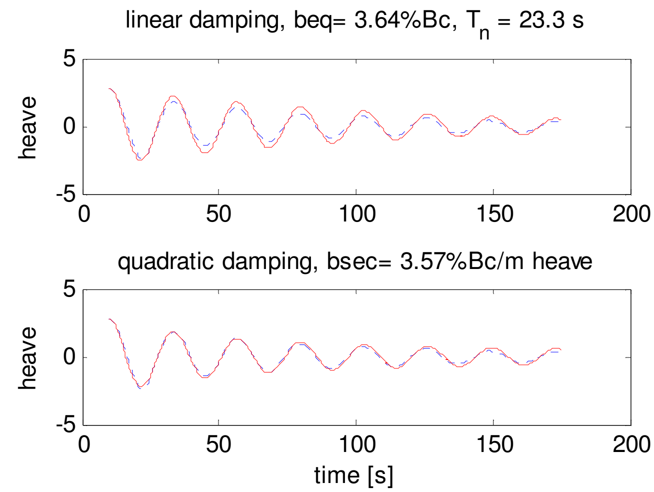

Figure 9 – Heave Decay

The heave RAO is also fairly linear for wave periods shorter than the natural period. Figure 10 shows the RAO derived from the waves with peak period above 16 seconds. The response at the natural frequency is dependent on the wave height. This is induced by the viscous damping (see decay test in Figure 9), resulting in a smaller heave response for larger waves due to vortices shedding of the bilge keels. As a result the diffraction analysis shows good comparison for the operational sea states, but overestimates the motions in storm conditions.

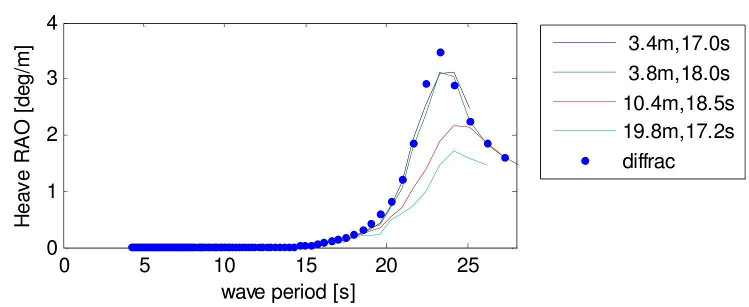

Figure 10 – Heave RAO

Figure 11 compares the heave response at the centre of gravity in beam seas with other production floaters, showing a significant improvement of the response compared to traditional ship shaped FPSOs.

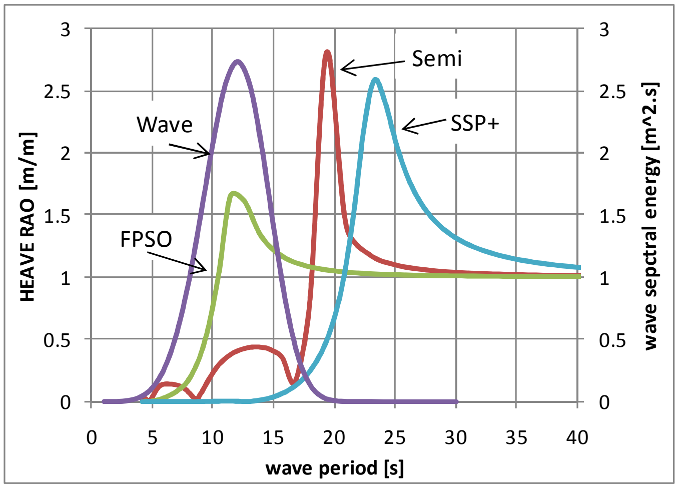

Figure 11 – Heave RAO compared to other floaters

In Table 3 the standard deviations are presented for heave and pitch. The comparison with numerical simulations shows that the numerical simulations are conservative for the heave motions in storm conditions, in line with the observation for the RAO. However the pitch motions are underestimated in the calculations, although the damping in the tests was larger than assumed in the calculations.

Table 3 – Motions statistical values

St. dev.	numerical results		model tests values	
Condition	Heave [m]	Pitch [deg]	Heave [m]	Pitch [deg]
Brazil 1yr	***0.26***	0.13	0.16	***0.30***
Brazil 100ya	0.06	0.31	***0.19***	***0.73***
Brazil 100yb	***0.43***	0.28	0.33	***0.90***
Brazil 100yc	***1.89***	0.36	0.71	***1.04***
Brazil 100yd	***3.41***	0.48	1.45	***0.90***
WoA 1yr	***0.23***	0.07	0.12	***0.09***
WoA 10yr	***0.64***	0.12	0.36	***0.14***
WoA 100yr	***0.95***	0.15	0.51	***0.17***
GoM 1yr	0.02	0.09	0.09	***0.25***
GoM 100yr	***2.03***	0.51	0.73	***1.71***
GoM 1000y	***4.66***	0.80	1.46	***2.68***

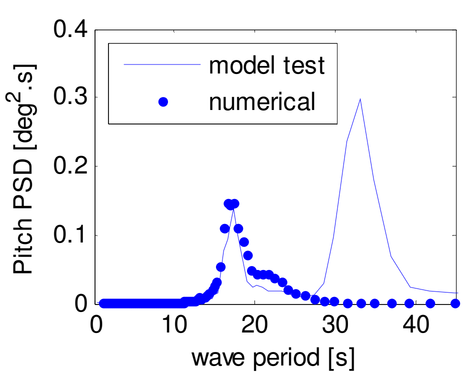

Figure 12 – Pitch spectra for 10yr WoA condition

The spectral content of the pitch motions (see Figure 12) shows that significant motions occur around the natural frequency. Comparison with the numerical model which only includes first order motions, shows an under prediction of the second order response.

This second order roll and pitch phenomena is observed before on drilling semi submersibles with low metacentric height (see Voogt (2002). Due to the underwater hull shape second order excitation exists and with the very small pitch response at the wave frequencies, these forces dominate the response spectrum. The study on semi submersibles shows, motions are smaller for shorter natural periods. The pitch natural period can be reduced by relocating the permanent ballast further towards the centre. This can further reduce the pitch motions in the GoM conditions, but for the generic unit this was not an option since it would increase the first order response in long period swells West of Africa.

A weibull analysis is used to analyze the extremes and determine the most probable maxima in a 3 hour storm. The resulting values are shown in Table 4.

Table 4 – Most probable maximum motions

Tests	Heave [m]		Pitch [deg]	
Condition	MPM-	MPM+	MPM-	MPM+
Brazil 1yr	-0.56	0.53	-0.95	1.32
Brazil 100ya	-0.57	0.62	-2.82	2.10
Brazil 100yb	-1.13	1.09	-3.22	3.39
Brazil 100yc	-2.36	2.38	-3.92	4.25
Brazil 100yd	-4.68	4.71	-3.18	4.07
WoA 1yr	-0.36	0.35	-0.38	0.26
WoA 10yr	-1.22	1.24	-0.59	0.39
WoA 100yr	-1.65	1.65	-0.67	0.60
GoM 1yr	-0.29	0.31	-0.91	0.76
GoM 100yr	-2.36	2.35	-6.89	7.48
GoM 1000y	-4.88	5.19	-10.14	11.05

The largest heave motions are observed in the 1000 yr Hurricane condition and are comparable to the heave response in the 100yr Brazil condition with the 18s wave period. It should be noted that even though these conditions are extremely severe, dry tree production is possible with 20m stroke heave compensators, which are available.

The pitch motions are largest in the hurricane conditions. As discussed these motions are dominated by second order effects and are comparable to the response of drilling semi submersibles in these conditions. To further study the measured pitch response, Figure 13 compares the most probable maximum pitch with the significant wave height in each condition. The tests with wave peak periods between 15s and 17s are marked with green triangles, while the remaining test results are marked as diamonds. The effect of the wave period seems limited in the tested range, indicating that the pitch response is not driven by resonance at twice the wave period, but by the drift forces resulting in a quadratic increasing pitch response with increasing wave height (the red line indicating a fit equal to MPM=0.28.Hs^2) .

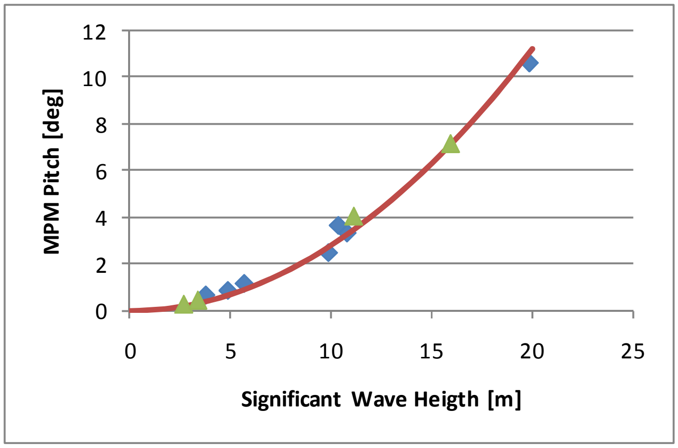

Figure 13 – MPM Pitch as function of the significant wave height

When the risers are connected at the outside of the unit, the fatigue live will be influenced by the pitch motions, but this can be prevented by running the SCR's through the centre column. The pitch motions also reduce the available freeboard, resulting in possible green water on deck which needs to be deflected or prevented by raising the freeboard.

Overall the motions are very limited for almost all conditions, and the environmental conditions with larger motions are extreme, and should be analyzed considering this fact.

Table 5 – Mooring lines tension and offsets

	Numerical Values		Experimental values	
CONDITION	Surge St.Dev [m]	Max ML Load [kN]	Surge St.Dev [m]	Max ML Load [kN]
Brazil 1yr	1.58	2549	2.00	3214
Brazil 100ya	10.85	7928	8.57	6340
Brazil 100yb	6.02	5604	6.83	5523
Brazil 100yc	4.97	5162	5.97	5093
Brazil 100yd	5.78	5765	4.64	5060
WoA 1y	0.46	2073	0.77	2734
WoA10y	0.61	2337	0.86	2889
WoA 100y	0.82	2617	1.41	3083
GoM 1y	1.87	2486	2.30	3218
GoM 100y	9.86	9403	9.87	8191
GoM 1000y	14.2	14576	10.00	12239

The extreme mooring tensions are presented in Table 5, with the standard deviation of the surge motions. Each model test line is equivalent to two mooring lines in real scale and the maximum top tensions observed are below the required limit by API. Further, the standard deviation of the surge motions is less than 1.5% of the tested water depth.

CONCLUSIONS

The SSP+ was tested in a very broad range of waves, which can possible represent almost all conditions that can occur offshore. Special attention was dedicated to the harsh conditions.

The model tests confirmed the large natural periods and showed motion characteristics similar to a SPAR. The heave motions are significantly reduced compared to conventional FPSOs, allowing dry tree applications in a broad range of environments.

The vertical motions are limited to motions around the natural frequencies. Decay tests show that a significant amount of viscous damping exists which is quadratic in nature. The influence of the tested mooring system on the heave and pitch decays is limited.

The heave motion RAO show a reduction of the amplification at the natural frequency for increasing motions. This phenomenon is induced by the second order damping and results in a less than linear increase of the heave motions with the wave height.

Due to second order excitation the pitch extremes increase with the wave height squared. In all non-hurricane conditions the extreme pitch motions are less than 4 degrees.

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