
Development of a concept of mono-column platform: MONOBR

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Abstract: Over the past few years oil exploitation evolved to deep waters extraction, locations in which oil transport through pipeline systems becomes an unreasonable solution. Solutions based on ships or barges, which allow the storage of oil and its transfer to shuttle tankers, were considered as an advantageous alternative and were widely used. However, these platforms present excessive and undesirable motion for a rigid or even a flexible riser. Furthermore, the recent series of hurricanes in the Gulf of Mexico resulted in strong damages to many installed platforms. These occurrences and climate changes in several areas, all over the world, are a strong motivation for the development of new concepts and new criteria for offshore platforms. New platform concepts, with hulls similar to cylinder trunks and/or cones with shallow drafts, were proposed to the technical community, the goals of which were to respond to small motion in waves. This paper focuses on the study of the motions in waves of the Brazilian conception, MONOBR and its use exposed to severe environmental conditions. Experimental results obtained on the LabOceano (COPPE/UFRJ, Rio de Janeiro) developed in the past few years are presented.

Keywords: BUOYFORM; MONOBR; platforms.

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1 Introduction

The advance to deep waters in the exploitation and oil production leads to changes in the concepts of offshore platforms along the past few decades. In shallow waters, the fixed jacket kind of structures has been a viable solution technically and economically with the oil being transferred through pipelines to oceanic terminals or even to the continent. Even ships were already used, exploiting their storage capacity. In deep waters, ships have shown themselves as solutions, given their storage capacity. The difficulties of transfer per pipelines are overcome, using the units of production with the capacity of storing the oil produced: Floating (Production), Storage and Offloading units [F(P)SO]. However, ships also present their limitations and in particular, these are due to the possibility of having undesirable motions that would damage the risers. The question of motion on the horizontal plane can be minimised by the choice of an adequate anchorage system. For instance, systems in Spread Mooring Systems (SMS) or in Differentiated Compliance Anchoring System (DICAS) can use one side to receive the risers and the other side to receive supplies, etc. However, mooring systems based on catenary lines cannot avoid the vertical motion.

New concepts have appeared to minimise the vertical motions. These concepts point to the use of platforms with circular or polygonal decks, hulls based in circular and polygonal cylinder forms, cylinder trunk-like hulls with shallow draft, some of them provided with moonpool. One of these is the SPAR. This is an already widely used concept, with various platforms installed in the Gulf of Mexico. The SPARs managed to reduce the vertical motion at the expense of a deep draft and small diameters.

Comparing ship-shaped FPSOs with SPARs, one may recognise that the risk of the offloading operations for the SPAR would be very high and the storage of great quantities of oil produced would also be much more difficult. Therefore, it is supposed that for systems based on SPARs the oil or gas export will be done by pipelines.

Seeking for the design of floating structures that incorporate some of the qualities offered by ship shaped FPSOs, such as high capacity of oil storage, direct oil transference to shuttle tankers, with others offered by the SPARs, like small vertical motions, it seems that the use of structures based on circular cylinder trunks and cones may lead to technically viable solutions.

In a general way, all the new designs based on mono-column concept are presented by the designers as having characteristics and operational advantages that, according to each of them, reverts into benefits over the cost of the full development of the field.

Among the diverse conceptions of platforms actually proposed, PETROBRAS, collaborating with universities and research institutes, has developed a proposal that may break some paradigms and bring, from the point of view of the industry, a solution for some of the problems associated with the operation of units in very harsh seas.

This concept, called MONOBR, was designed to minimise the motions in waves. The study of the behaviour of the platform on sea was based on the analysis of experimental results of models in a reduced scale, excited by regular, transient and irregular waves.

In this work we initially present the main concepts of platforms based on trunk of cones and cylinders. After that, we present the experimental results developed in LabOceano Laboratory of Ocean Technology of the Federal University of Rio de Janeiro, developing a critical analysis of the obtained results.

2 Concepts of mono-column hull type

Many concepts of circular or polygonal-shaped hulls for production platforms have been developed and proposed for the oil industry. Among those concepts, at least, we should mention the following: SPAR, MONOBR, SSP (SEVAN MARINE), SSP (SPE), BUOYFORM (AKER) and SEMO (MPU).

We believe that all the concepts herein presented might be effective and competitive for specific applications and locations and should not be discarded *a priori*. SPAR is a concept largely utilised, with many units installed and operating in the Gulf of Mexico. The most advanced technologies were used at the time and achieved single solutions in many cases.

The SPE SSP – Satellite Separation Platform – is a concept that minimises the roll and pitch motions of the unit by means of a jack-down jacket to be used as a long keel. More details can be investigated in the SPE site (www.spe.org).

The first SSP, from SEVAN-MARINE, is currently under construction and the hull has already left the Yantai Raffles Shipyard in China to the process plant deck assembling in Holland.

The SSP-300 is an FPSO with an oil storage capacity of 300,000 bbls, an oil-processing capacity of 30,000 bbls day⁻¹ and a gas injection capacity of 3.6 million m³ day⁻¹. The unit will carry upto 21 flexible risers and umbilicals. This FPSO unit will work for PETROBRAS on the Piranema field, at offshore Sergipe, Brazil, as from mid-2006. The water depth at the field is 1,000–1,600 m (www.sevanmarine.com).

Recently, SBM presented a concept project to the market, which in terms of dimensions and load capacity is very similar to the SSP-300. The most evident difference is the relative size of the external skirt. This platform presents an operational draught of 23.5 m; 65 m diameter for the body and 86 m diameter at the skirt; and, total operational displacement of 87,000 tonne, for a total weight of 6,500 tonne topside (www.mscoffshore.nl).

BUOYFORM is an innovative mono-column hull proposed by AKER KVAERNER with 300,000 bbl oil storage capacity; one variation of this concept consents oil over water (www.akerkvaerner.com).

The MPU-SEMO platform – Semi-submersible Monohull – is a concept of FPSO, developed to have dedicated drilling rig. MPU imputes its simplicity, robustness and ease of construction to the symmetry of the hull, which makes this unit quite cost-effective. The MPU-SEMO platform was also tested with a reduced scale model at MARINTEK, in Trondheim, Norway. The main focus was its behaviour in centenary conditions for the North Sea (www.mpu.no).

The FOXBOX system is another concept in floating systems that is still at concept project level and would combine drilling with production, storage and offloading. Apparently, it neither presents hydrodynamic moonpool nor presents dimension variation at the waterline. Therefore, low movements must be obtained through major displacements and increase of additional mass caused by the external skirt.

MONOBR is a platform concept developed by PETROBRAS, in cooperation with Brazilian universities and research centres. It is a mono-column structure provided with a moonpool. The project was developed with the University of Sao Paulo. Simultaneously, tests were

conducted at IPT – Technological Research Institute of Sao Paulo – and at LABOCEANO – Ocean Technology Laboratory of the Federal University of Rio de Janeiro. Simultaneously, tests results have been used to calibrate and validate numerical models. Numerical simulations were performed basically at TPN – Numerical Tests Tank of the University of São Paulo. Analytic models were also developed for better understanding of the moonpool action on the unit movements.

2.1 Main operational characteristics of mono-column hull platform

Generally speaking, all of the circular or polygonal mono-column type platforms that maintain a rotational symmetry are presented by the designers as having the same operational characteristics and advantages, which, according to each one of them, returns in benefits on the total development costs for the field. Thus, the main advantages are:

- Reducing the cost of the anchorage system due to the rotational symmetry of the hull and also for presenting the same functions as a TPL, however, with no need of tie rods and foundations designed for major vertical loads.
- Eliminating the need of turret when compared to FPSOs based in ships or barges.
- Except for the SPARs, mono-columns generally accept high loads in the deck and have a reasonable area available for process plant mounting.
- The mono-column concept may be designed for a large range of oil storage capacity, as big as 1,600,000 barrels, presenting a steel weight 20% lower than the equivalent FPSO, both under the same premises.

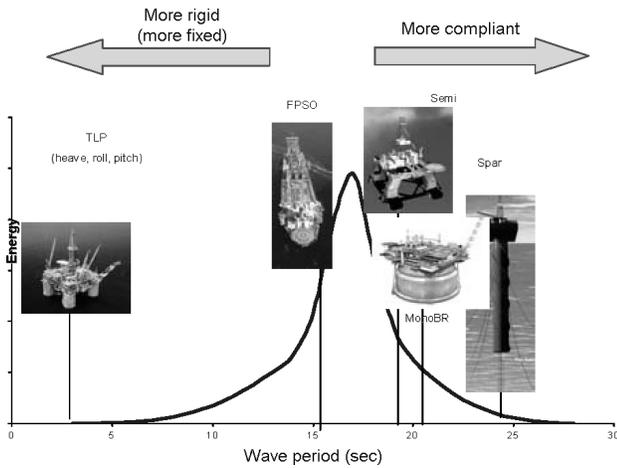
It is important to observe that the effectiveness of a platform is not merely in the structural weight and in the construction strategy. One should seek to satisfy the particular operational characteristics that might effectively add value to the concept and turn it competitive as a global solution for the development of oil fields in the sea.

Mono-column hulls present a monolithic structure with high inertia in the diagonal of the cylinder, becoming not very sensitive to bending moments caused by sea waves and loading plan. Likewise, the maximum diameter and its symmetry do not provide significant torsion stresses in the structural dimensioning. These characteristics grant advantages to the mono-column hulls when compared to ship-shaped vessels of the same size used as oil production platforms.

Although some project characteristics were presented here, the focus of this paper is the hydrodynamics of the MONOBR hull, whose design shows large possibilities of tuning up to fit better the most restrictive operational requirements. Figure 1 shows different kinds of structures and indicates their period of damped oscillations for the heave motion. The oscillation period of MONOBR is about

21 sec, almost out of the range of wave excitation. The response was minimised in a wide range of period based on a hydrodynamic project of the moonpool associating theory and experiment. The main experimental results are presented in Section 3. Cueva et al. (2005) present a viability study of this conception designed for the Gulf of Mexico conditions and with storage capability.

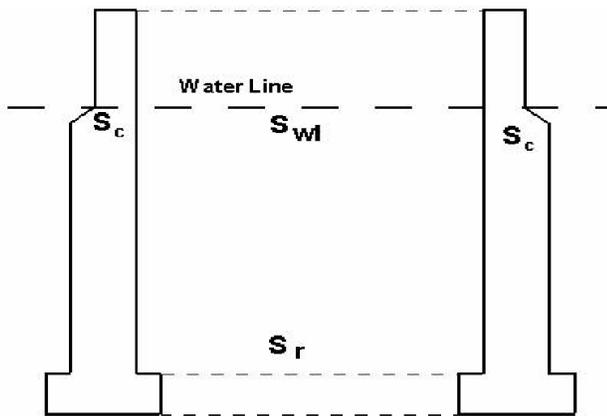
Figure 1 MONOBR behaviour at wave action compared to most common concepts



3 MONOBR concept

The design of this first hull was not focused on the storage capacity, but in the development of a structure with minimal vertical and horizontal motions. The prototype has an external diameter equal to 95 m. It is provided with an internal moonpool with diameter equal to 69 m. The depth is equal to 38 m and the free board equal to 12 m. Figure 2 presents a schematic form of the first MONOBR hull.

Figure 2 Scheme of the moonpool mono-column



3.1 Experimental analysis

Initially, some tests were developed in the channel of waves of the IPT get a basic definition of the structure. In this phase of work, a systematic study of the use of a beach with conic form immediately below the water line that would

bring a decrease in the horizontal motion of the structure, due to the second order (mean drift and slow drift) excitation, has been developed.

Later on, tests were carried out at LabOceano. In this second phase of tests, the main objective was to study an opening of the moonpool that would minimise the vertical motions of the structure. The second objective was to verify the effect of the beach and the final opening, on the planar motion of the second order.

An experimental work was developed to verify the responses of motions of the structure under the action of the sea. A reduced model was constructed in the scale of 1 : 100. Figure 3 shows a photograph of the model of the tested structure.

To analyse the responses in wave, we divide them with respect to the responses for high low frequencies. It is understood that responses in high frequencies concern the behaviour of the responses of the structure in the frequencies of the sea waves, excited by the forces of the first order. Structures anchored in great depths have very low natural frequencies for surge and at these frequencies the wave-making damping is small. Further, the pitch period of damped oscillation is out of the range of first-order wave, force and for this period the wave damping is also small. Thus, once excited by second-order forces in these frequencies, the structure can respond with great oscillations.

The tests to verify the responses in high frequencies can be carried out in regular waves, in irregular sea and transient waves. Given the low cost and the fast responses of the structure, the test in transient waves was selected to obtain the RAO (Response Amplitude Operator, amplification factor) of the high frequency motion. A procedure established by the LabOceano was utilised, as presented by Matos, Sales and Sphaier (2005). Part of the results from the transient tests was presented by Barreira et al. (2005) and Sphaier et al. (2005).

Figure 3 MONOBR’s model during tests at the LabOceano



The excitation in low frequencies happens when two waves with proximate periods are present. It is a non-linear consequence that generates forces in the frequency equal to the difference of the two frequencies of the waves (Pinkster, 1980). For this analysis, tests in irregular waves have been carried out. The irregular waves correspond to the decennial and centennial seas of Campos Basin in Brazil.

3.2 Responses in transient waves

The mono-column was tested with seven different openings of the moonpool in the base. The total inner diameter has 69 m and this case corresponds to the moonpool without any constraint. From this case on, smooth horizontal plates were installed at the bottom opening, with small thickness and circular holes of minor diameters: 64, 58, 47, 33 and 23 m. Diameter equal to 0 corresponds to the inexistence of the moonpool. The tests were carried out with a system of horizontal anchorage to simply maintain the structure stationary.

The following measurements were carried out:

- motions of the water column inside the moonpool with the structure kept fixed
- motions of the water column inside the moonpool with the structure left free to oscillate in waves
- motions of the six degrees of freedom of the structure in waves.

Figure 4 shows the amplification of the vertical motion of the water column inside the moonpool for different frequencies of the wave external to the structure, for the diverse openings of the moonpool. It can be observed that in the case of the opening without constraint, the period of damped oscillation is around 15.5 sec. As the opening constraint increases (smaller diameters), the amplification of the vertical motion decreases significantly, the damped period of oscillation increases and the case of a system with supercritical damping is attained. Thus we have: resonant period of 15.7 sec for the opening with the diameter equal to 64 m and resonant period of 16.8 sec for the diameter equal to 58 m. For opening with diameter equal to 47 m, the period of damped oscillation is between 18.0 and 20.0 sec. For smaller openings, diameters equal to 33 and to 23 m, there is not a peak of amplification and, therefore, one cannot estimate a resonant period. With the increase of the wave period, the amplitude of the vertical motion in the moonpool becomes close to 1, that is, moves in phase and with the same amplitude of the exciting wave.

Figure 5 shows the amplification of the vertical motion when the structure is free to oscillate in waves, for the different entry diameters at the bottom of the moonpool. In this figure we observe that the structure with the moonpool, without constraint at the opening, shows two resonant periods. One of them corresponds to the period of damped oscillation in the moonpool mode, around 15.1 sec and the other around 21.6 sec corresponding to the structure mode. The completely closed structure has the period of damped

oscillation around 19.3 sec. Although it is possible to observe the influence of the coupled motion, structure and moonpool on the period of the moonpool mode, one cannot estimate the degree of influence on the mode of the structure, for it is not possible to isolate the phenomenon neutralising the effect of the moonpool, as it was done previously when we fixed the structure and observed the motion of the moonpool in waves. Another question to be observed is that there is a cancellation period in the motion of the structure without moonpool very close to the period of damped oscillation of the moonpool. We can also see that the amplification of the vertical motion of the mono-column is strongly affected by the entry diameter at the bottom of the moonpool. The period of damped oscillation of the moonpool mode increases, although not much. On the other hand, the period of the mode of the structure is more affected.

Figure 4 Vertical motion of the water surface inside the moonpool

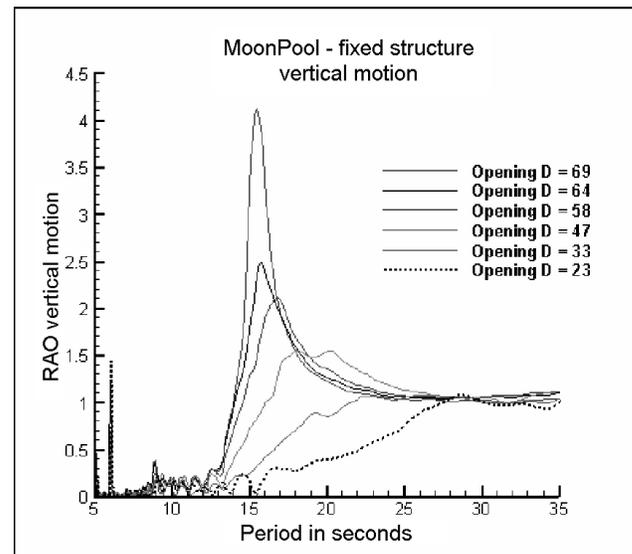
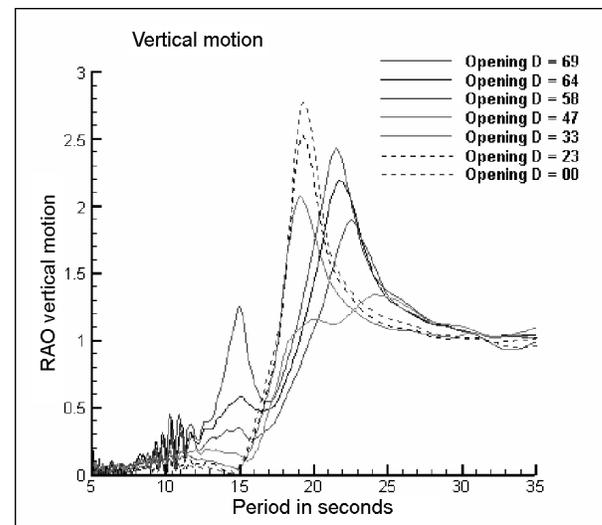


Figure 5 Amplification (RAO) of the heave motion of the structure



The result that we are more interested in observing is the result obtained for the opening equal to 47 m. In this case, the amplification of the vertical motion is small for periods around 15–16 sec. The resonant periods increase and the amplification of the motion is also reduced near the oscillation period of the moonpool mode. For periods in the range of 15–20 sec, the amplification is almost constant and small in comparison with the other cases. It is possible to draw an analogy between the system and the damped absorber of Den Hartog (1956), where the right choice of the coefficients of the damping coefficient leads to the minimisation of the motion in a large range of periods. In the presented case, this damping coefficient corresponds to the damping imposed by the opening of the moonpool.

Figures 6 and 7 present the results of the RAO of the surge and pitch motions. The amplification is not affected by the opening of the moonpool and is also very small.

Figure 6 Amplification (RAO) of the surge motion of the structure

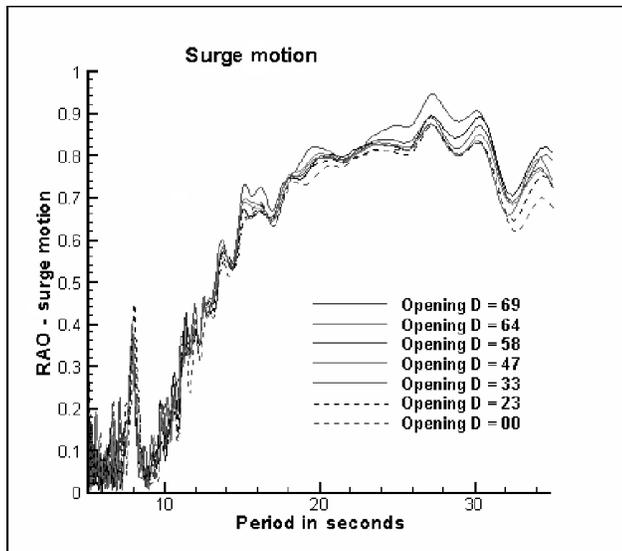
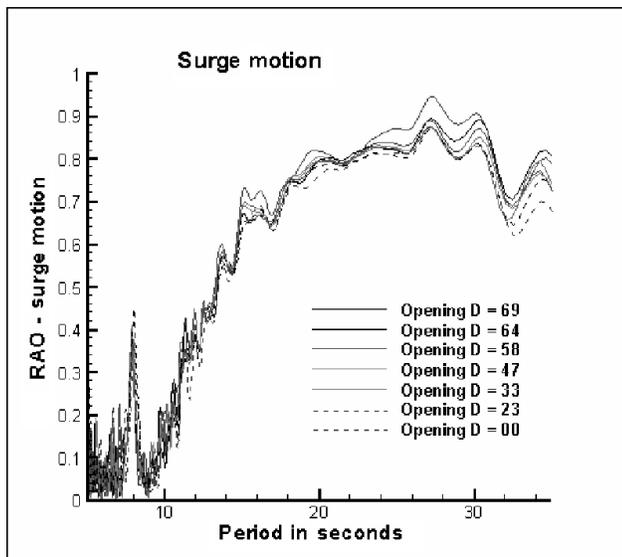


Figure 7 Amplification (RAO) of the pitch motion of the structure



3.3 Behaviour in centenary irregular sea

The last analyses carried out are the ones of the structure response to irregular sea. We shall concentrate here on the surge and pitch motions, since their natural periods are out of the range of the sea wave frequency and can be excited by non-linear effects. Our objective is to verify if the usage of conic beach may result in small responses of low frequency. To evaluate the behaviour of the structure, we shall observe the responses of surge and pitch in a 3-hours centenary storm with the Jonswap spectrum with significant height $H_s = 7.9$ m and a period of the peak $T_p = 12.8$ sec.

The analysis of the motions consists of considering the wave and responses signals, conducting a Fourier analysis, separating the mean value, the contribution of low frequency and the contribution of high frequency. With the response signals at high and low frequency, we select the extreme values, maxima and minima and present them in the form of histograms. The results are presented in the scale of the prototype so that the surge and heave motions are presented in meters. The time is given in seconds on the prototype scale.

Figures 8–10 present a part of the register of the surge motion and the statistics of the maximal and minimal (peaks) values of displacement during the 180 min. The time series has been separated in mean drift, slow drift and the response in high frequencies. It can be observed that if we superpose the maximum displacements, a maximum displacement around 12 m can be reached. Oscillations of low frequency about 200 until 300 sec can be observed.

The pitch motion is shown in Figures 11–13. A small angle of mean pitch can be observed. The peak values of slow motion and high-frequency motion are small. Adding up the peak values, it can be stated that the structure presents in the centenary sea maximum angles of the order of 3° . The oscillations of low frequencies have periods of the same order as the periods of low frequency of surge.

Figure 8 Surge motion in time domain

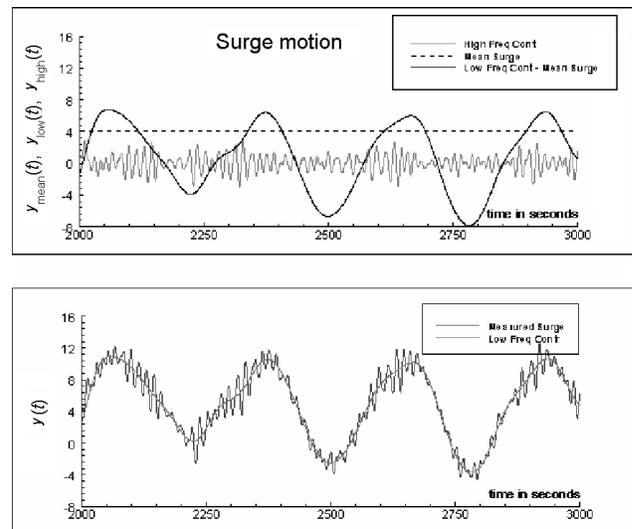


Figure 9 Surge: peak values for low modes

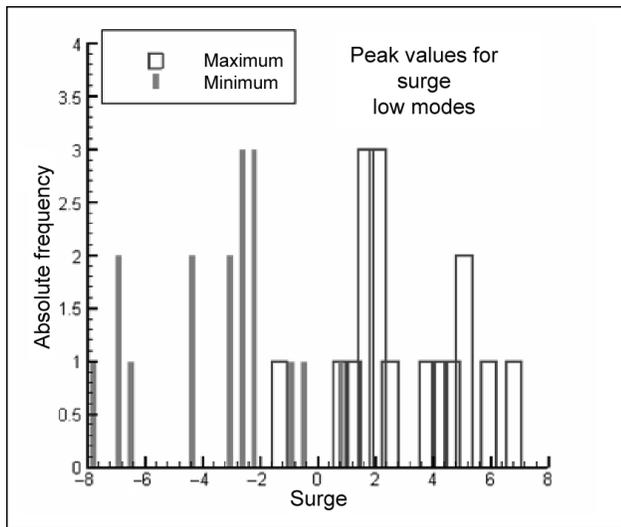


Figure 12 Pitch: peak values for low modes

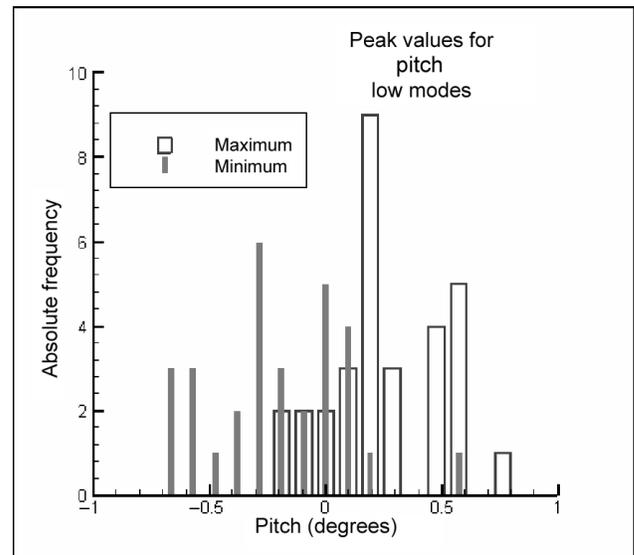


Figure 10 Surge: peak values for high modes

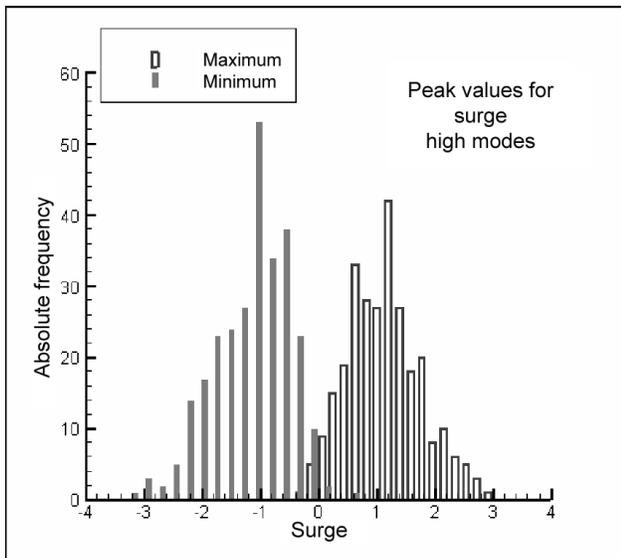


Figure 13 Pitch: peak values for high modes

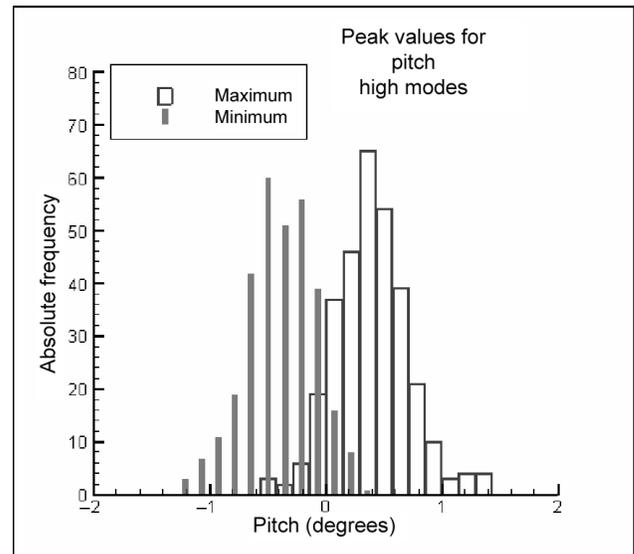
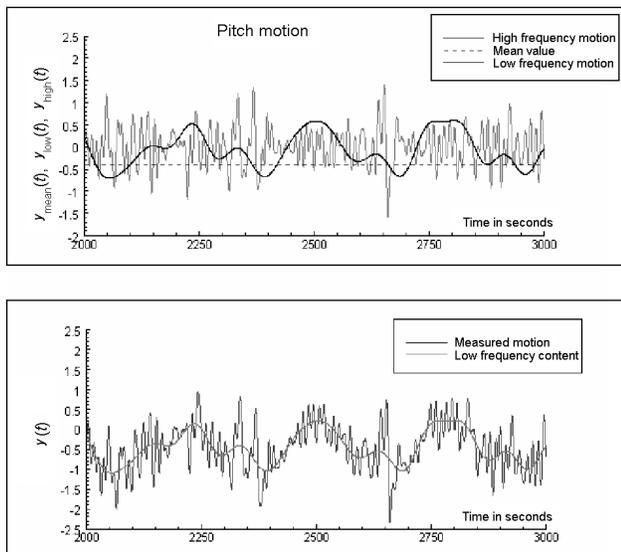


Figure 11 Pitch motion in time domain



Figures 14–16 show the responses of heave motion. The mean value of displacement is negative, which is due to the variation of the water line area. The motion of high frequency presents the beating behaviour. The motion of low frequency is very small.

Estimation of critical values can be obtained from the time series for surge, heave and pitch when the model is exposed to the centenary sea state. We assume that the extreme values for both the high frequency and the low frequency follow the Rayleigh probability density. We determine the variance for the responses in high and in low frequency. The critical value (value with the probability of 0.001 to be exceeded) is estimated multiplying the variance by 3.72. We add both estimations for high and for low frequency. To this result we add the mean drift. With this procedure we obtain 18.88 m, 3.1° and 3.77 m for the critical motion in surge, pitch and heave, respectively.

Figure 14 Heave motion in time domain

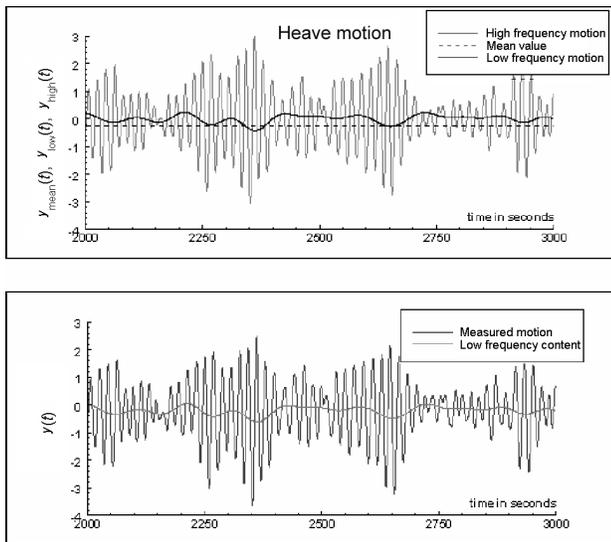


Figure 15 Heave: peak values for low modes

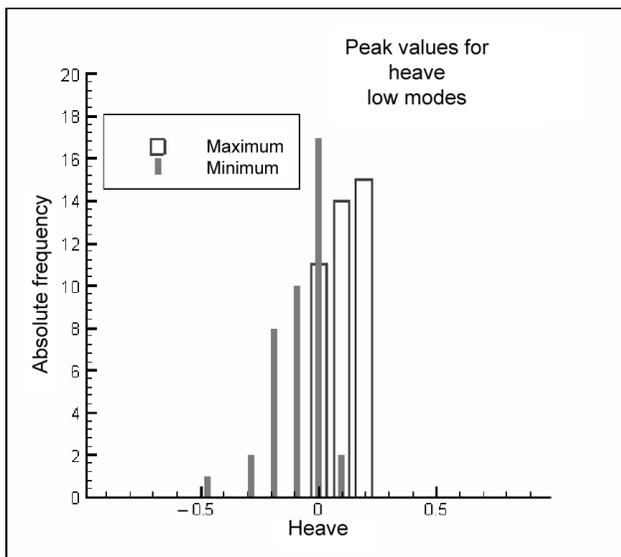
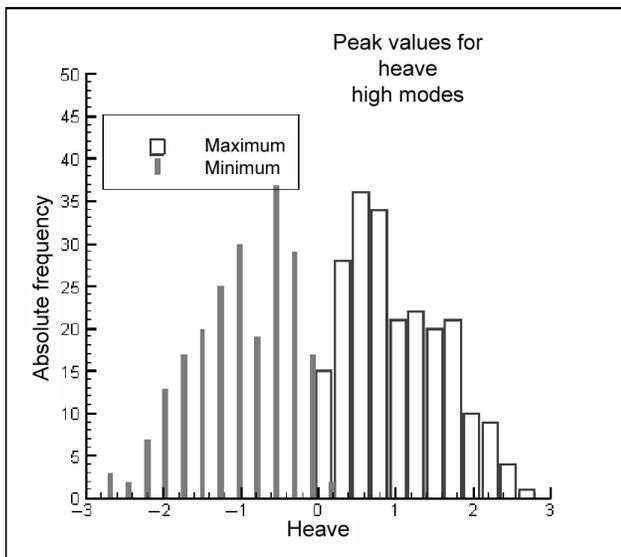


Figure 16 Heave: peak values for high modes



4 Conclusions and future developments

One fundamental aspect of the MONOBR concept development was the minimisation work of the motions based on theoretical and experimental studies of the hull shape. The vertical movement was minimised based on the hydrodynamic project of the moonpool. The restriction adopted for the moonpool led to a low vertical response.

The MONOBR concept enlarges the strategic horizons of PETROBRAS, enabling the application of consolidated technologies in ultra deep waters, guarantying a low-risk operation.

Among the most attractive scenarios, we can mention:

- Wet completion, with storage, making use of Steel Catenary Risers (SCRs) for oil and gas or even PIP for very heavy oil that needs isolation and heating. The wells and the production lines set-up will determine the type of riser to be used. *A priori* the MONOBR project can fulfil the motion requirements of any of them.
- Single scenario, when dry completion and oil storage are required, in any water depth.
- Wet completion scenario, with dedicated drill and storage.
- Platform scenario for anticipated production with oil storage capacity, with wet completion and dedicated workover rig.

In any scenario where the use of free water tanks for oil-water separation by the action of gravity is advantageous, the MONOBR presents fewer movements as further advantages, as well as a geometry that favours the separation, in addition to having bulkhead walls without secondary structural stiffeners. The volumes available in the tanks grant a reasonable permanence time.

The MONOBR design is still under development and accepts several levels of optimisation very easily to get to better configurations much more costly and operationally attractive.

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