Experimental and Numerical Investigation on the Stability in Waves of a Mono-column Platform

Julio César Polo

COPPE/UFRJ

Claudio Rodríguez, Marcelo A S Neves

LabOceano, COPPE/UFRJ

ABSTRACT

The paper shows results from a comprehensive experimental investigation on a mono-column in regular and irregular waves. Focus is centered on improving the understanding of the occurrence of resonant motions associated with Mathieu instabilities for cylindrical floating platforms. Experimental results with the mono-column showed both roll and pitch parametric amplifications. It is concluded that the instabilities observed in the mono-column experiments were very much influenced by the mooring system. A numerical algorithm is used as a relevant tool for discriminating the role of the different nonlinear contributions to parametric amplifications arising from hydrostatics, Froude-Krylov and mooring arrangement within the observed diverse patterns of roll and pitch responses.

KEYWORDS

Mathieu instabilities; mono-column; parametric resonance; platform stability; waves.

INTRODUCTION

Mathieu instabilities are nowadays a quite well understood phenomenon which may lead to parametric rolling in ships and literature on the topic is abundant. Recent compilations may be found in Neves et al. (2011), Guedes Soares et al. (2012) and Fossen and Nijmeijer (2012). However, this may not be the case when reference is made to instabilities in waves of offshore floating platforms. Apparently, dramatic Mathieu instabilities in platforms are rare, an exceptional observation was reported in Haslum and Faltinsen (1999); this has much to do with the tendency of these vessels to have vertical walls. Yet, it is noticed from the pertinent literature that there are numerous interpretations on the probable causes of such instabilities, revealing perhaps a gap in the understanding of their main causes. As this understanding may be quite relevant for the best design of such floating artifacts, the Authors have elected this as the focusing topic to be addressed in the present paper.

An investigation on the occurrence of parametric resonance of spar platforms has been made by Haslum and Faltinsen (1999) in which the relevance of Mathieu amplifications has been assessed mainly centered on the heave/pitch coupled motions. They reported on some few test results with a 1:300 model scale, in which large angles were reached. Rho et al. (2002), Rho et al. (2003), Liu et al. (2010) have also reported on numerical and experimental simulations on spar platforms, all papers focusing on the discussion of heave and pitch instabilities. In Rho et al. (2002) a 1/400 model was tested. Hong et al. (2005) tested a set of spar platforms, models built at 1/160 scale. This last one is one of the few reports encountered in the pertinent literature discussing (albeit on a limited way) the occurrence of heave-roll-pitch instabilities in the case of vertical cylinders.

Neves et al. (2008) and Rodríguez and Neves (2012) have discussed the mechanisms of heave-roll-pitch parametric excitation for spars, based on an analytical model. They argued that parametric resonance of vertical cylinders is not related to pure hydrostatic pressure variations, but instead to the variations of the nonlinear Froude-Krylov induced pressure due to wave passage, vertical motions and the associated attenuation of wave pressure with depth (Smith effect). It was concluded that very deep structures such as spar platforms tend to be more prone to parametric resonance than small drafted platforms as is the case of the mono-column investigated in the present paper. In fact, the tests reported by Hong et al. (2005) seen to indicate stronger parametric excitation than the mono-column herein investigated.

Yet, it is still a relevant engineering problem to well ascertain the expected level of parametric resonance in mono-columns in strong seas and to better understand the associated complexities of the coupled responses. In particular, it will be interesting to understand when pitch and/or roll may find ways of manifesting themselves in high waves.

Taking into account the experimental evidence reported in the present paper on the coexistence of roll and pitch parametric amplification and the associated exchange of energy between the two modes, a time domain numerical algorithm is used as a relevant tool for discriminating on the different nonlinear contributions involved.

Another aim of the paper is to verify whether the parametric amplifications experimentally encountered in regular waves may also occur in irregular waves, in which there is not the pure tuning and regularity that may be found in regular waves.

MONO-COLUMN PARTICULARS AND TEST SET-UP

Fig. 1 illustrates the general appearance of the experimental model of the mono-column tested at LabOceano. The model was built to a 1:100 scale. Main dimensions and characteristics of the mono-column at the tested conditions are shown in Table 1 (prototype values).

As the main focus of the tests was to investigate vertical motions in longitudinal waves, a simplified horizontal soft mooring system was prescribed. However, during verification of the mono-column natural periods with decay tests, significant influence of mooring restoring was observed. To assess this influence, three different mooring lines arrangements were considered in the test programme. Mooring configuration #1 is symmetrical, mooring configuration #2 is aligned with the wave propagation and, mooring configuration #3 is normal to it. Graphical sketches of the tested mooring arrangements are shown in Fig. 2.

Fig. 1: Mono-column experimental model.

Table 1: Mono-column main particulars.

Parameter		Value
Diameter, D	[m]	110
Depth, H	[m]	70
Draught, T	[m]	43
Displacement, Δ	[t]	418 858
Metacentric height, $\overline{GM}_0$	[m]	3.82

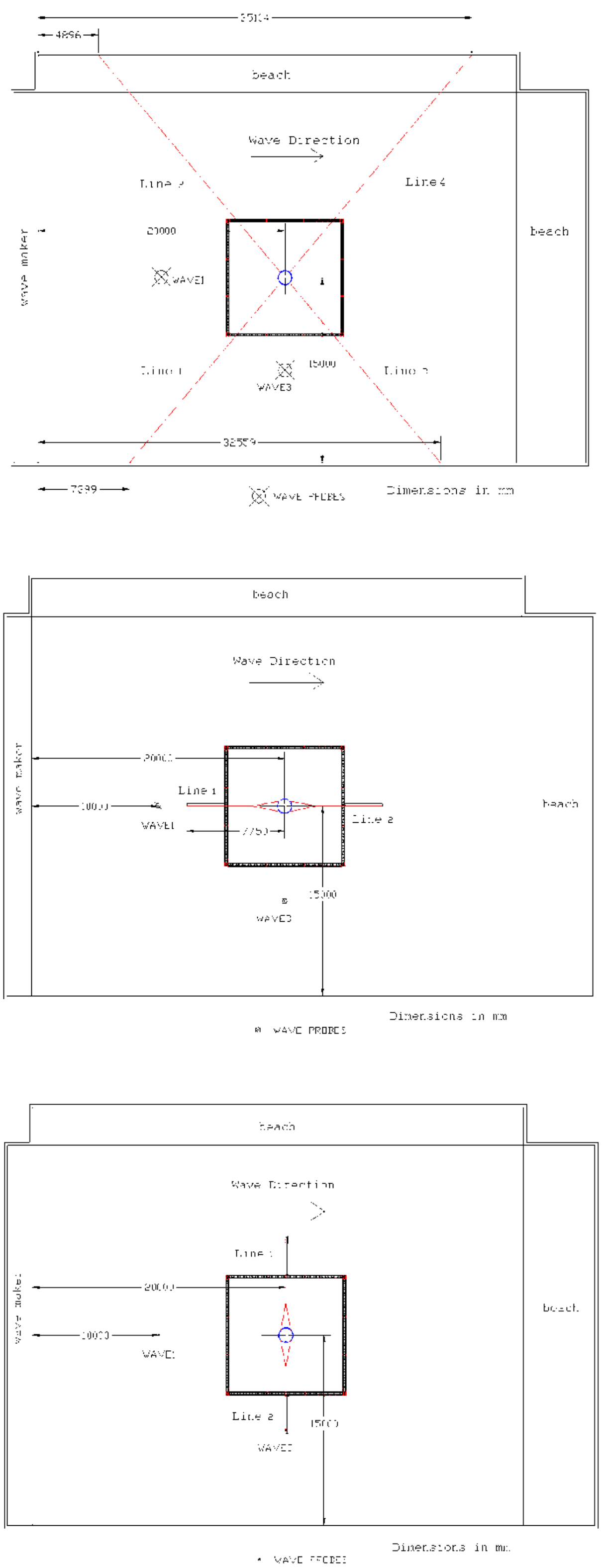

Fig. 2: Tested mooring configurations: #1 (upper), #2 (middle), #3 (lower).

For all the mooring configurations, decay tests were performed in order to obtain the heave, roll and pitch natural periods and their corresponding damping coefficients. Table 2 displays the measured natural periods, where Configuration #0 means free-floating body, i.e., no mooring system. Free-floating tests in waves are not discussed in this paper, yet it is felt that having reference to free floating natural periods is relevant to assess the mooring influence on the mono-column dynamics.

Table 2: Heave, roll and pitch natural periods for different mooring configurations

Configuration #	Heave	Roll	Pitch
0	17.0	38.3	38.3
1	17.0	32.4	32.4
2	17.0	38.0	31.8
3	17.0	32.0	37.8

From Table 2 and Fig. 2, it can be concluded that depending on the mooring arrangement, the values of the roll and pitch natural periods are affected differently by the mooring system when compared to the corresponding free floating values. In fact, Configurations #2 and #3 resulted in distinct roll and pitch natural periods: in Configuration #2 only the natural pitch period is affected, while in configuration #3 the roll natural period is affected.

Test matrix

A selected sample of experimental results covered in the LabOceano test program on stability in waves of the mono-column design is reported in the present paper. Complete details of the test procedures and a larger set of results without direct interest to the present analysis are reported in Report 007-07 (LabOceano, 2007). Table 3 summarizes the battery of tests discussed in the present paper. It corresponds to tests in longitudinal waves: nine in regular waves and three in irregular waves. Three levels of wave amplitudes (H=5m, 10m and 15m), and wave frequencies close to half the roll and pitch natural periods under the different mooring configurations were considered.

Table 3: Test matrix

Mooring Config.	Test Code	H [m]	T [s]	Wave type
1	T18-01000	5.0	17.0	Regular
	T18-01300	5.0	32.4	
	T18-01400	10.0	16.5	
	T18-01500	15.0	16.5	
	T18-01700	5.0	16.5	Irregular
2	T18-02400	10.0	18.0	Regular
	T18-02500	10.0	18.9	
	T18-02700	10.0	16.5	
	T18-02800	10.0	16.5	Irregular
3	T18-02000	10.0	18.0	Regular
	T18-02100	10.0	18.9	
	T18-02200	10.0	18.9	Irregular

EXPERIMENTAL RESULTS AND ANALYSES

Regular waves

Configuration #1

Figs. 3~6 show results in the heave, roll and pitch modes for distinct wave characteristics in the case of Configuration #1. Fig. 3 shows the responses when the wave period was tuned to the pitch/roll natural period. Because, in this case, the wave period is far lower from the heave natural period, heave motions are quite low (with amplitudes of approximately 3.1 m). Pitch motion at resonance reaches 4.3° whereas roll motions are quite small. These responses are typical of first order motions and take place at the wave period. As will be shown later, higher amplifications are attained in cases of parametric instabilities.

In order to investigate the occurrence of parametric resonance, it is required to excite the platform at wave periods close to half the roll/pitch natural period (in this case, approximately the heave natural period). Figs. 4~6 show the heave, roll and pitch coupled responses for three levels of wave amplitude, 5m, 10m and 15m, respectively. As the wave is tuned with the heave natural period, heave amplitude rises up to approximately 5.1m (see Fig. 4). Pitch motions take place at twice the exciting wave frequency, thus characterizing typical parametric resonance. Pitch amplification starts to develop after 1750s, reaching steady state amplitudes at about 2680s, with angles of approximately 4.2° (which is of the same order as the case shown in Fig. 3 – pitch linear response). It is important to observe that after 2400s, roll motion starts to develop also with twice the wave frequency (thus, characterizing also parametric motion), but with quite small amplitudes.

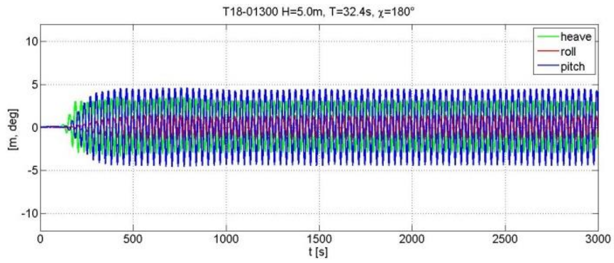

Fig. 3: Config. #1, regular wave, low wave amplitude, non-parametric resonant pitch

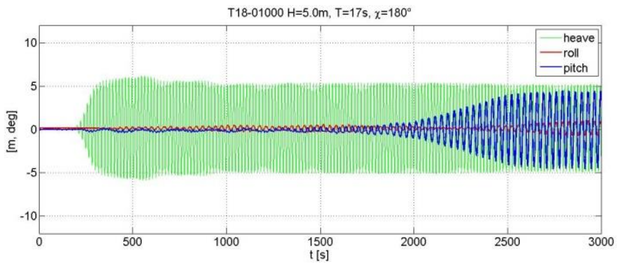

Fig. 4: Config. #1, regular wave, low wave amplitude, parametric pitch excited

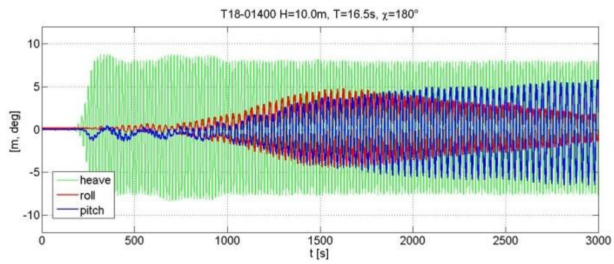

Fig. 5: Config. #1, regular wave, intermediate wave amplitude, roll and pitch are parametrically excited

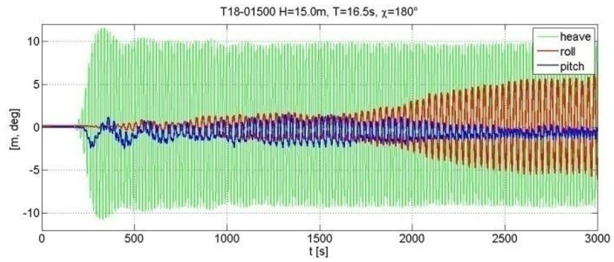

Fig. 6: Config. #1, regular wave, larger wave amplitude, roll and pitch are parametrically excited

Now, we discuss the results for the intermediate wave amplitude, H=10m (Fig. 5). With more energy being fed into the system – due to greater wave height, (parametric) roll motion amplification starts quite earlier, being stronger in intensity than (parametric) pitch amplification, up to some stage. After some time (around 1500 s), an exchange of energy between roll and pitch appears, as it is visible from the simultaneous decreasing roll and increasing pitch (which continues to grow above 7º after 3000s).

Fig. 6 displays the response series for the higher wave amplitude, H=15m. Heave motion is now at its highest intensity, therefore, nonlinearities are stronger. The relevant feature is that, now parametric roll becomes dominant in the exchange of energy with parametric pitch motion: as pitch practically disappears, roll motion increases reaching angles higher than 6º.

The main conclusion to be taken from this set of tests (configuration #1) is that, at lower levels of energy (lower wave heights), pitch motion, which can be excited either internally (parametrically) and/or externally, is more prone to absorb energy from the heave motion. Whereas, the roll motion, which can ONLY be internally (parametrically) excited, requires higher levels of energy (higher waves) to develop. Depending on the level of wave excitation, an interesting interchange of energy is observed between the pitch and roll modes: at intermediate levels of wave excitation (Fig. 5), pitch motion ends up being dominant, whereas in Fig. 6 (higher level of wave excitation) roll motion prevails.

Configuration #2

This configuration is illustrated in middle diagram of Fig. 2. In this case, as indicated in Table 2, natural periods in heave, roll and pitch are, respectively, 17.0s, 38.0s and 31.8s. Tests for this configuration try to explore the pattern of responses when roll and pitch have slightly different natural periods. Fig. 7 shows responses for H=10m, T=18.9s, where it is observed that only the roll mode is excited parametrically. This situation may be explained by the fact that, the exciting period is close to half the roll natural period. On the other hand, Fig. 8 shows the responses for another test, where the same wave amplitude was used (H=10m), but with a lower wave period, T=16.5s. As observed, roll motion is insignificant while pitch is excited parametrically. In this case, the exciting period is close to half the pitch natural period.

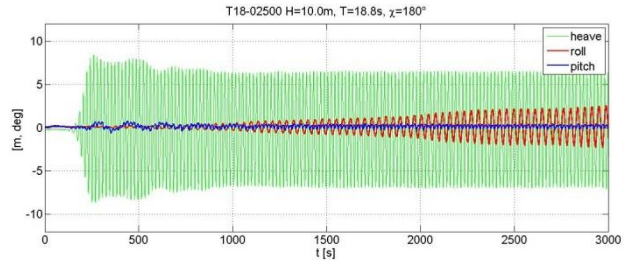

Fig. 7: Config. #2, regular wave, intermediate wave amplitude, parametric roll excited

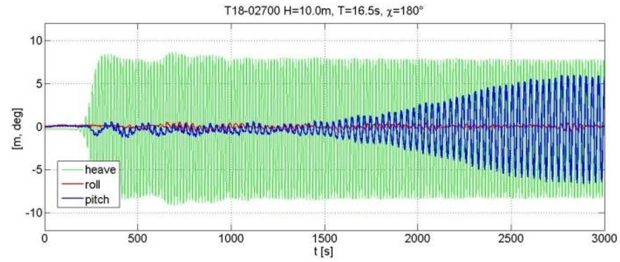

Fig. 8: Config. #2, regular wave, intermediate wave amplitude, parametric pitch excited

It is worth noting that, heave amplitudes were practically the same in the two tested conditions – around 7.0 m. However, parametric pitch reached amplitudes of 6º (see Fig. 8) and parametric roll amplitudes achieved only 2.5º. The above feature confirms the experimental evidence revealed by tests at Configuration #1 (Figs. 4~6), that is, parametric pitch motions are more likely to occur than parametric roll. This characteristic may be explained by the fact that, in longitudinal waves, pitch receives energy both from external and internal excitation, while roll only receives internal (parametric) excitation.

Configuration #3

Finally, we discuss tests with Configuration #3 - see lower sketch of Fig. 2, which correspond to 90-degree turn of Configuration #2. Under this mooring arrangement, the roll mode is affected by the mooring restoring, thus affecting the roll natural period. As indicated in Table 2, in this case natural periods in heave, roll and pitch are 17.0s, 32.0s and 37.8s, respectively. Fig. 9 shows the mono-column responses for a wave height of H=10m and a wave period of T=18s. At this condition, only parametric pitch was excited, reaching amplitudes of 4.6º.

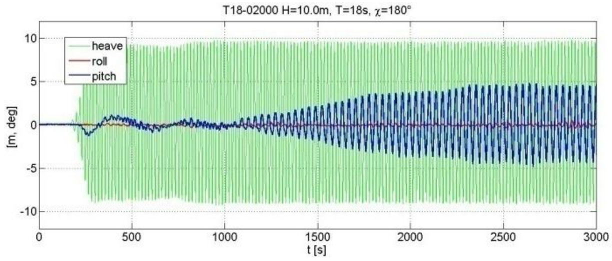

Fig. 9: Config. #3, regular wave, only parametric pitch is excited

Irregular waves

Configuration #1

Tests in irregular waves (JONSWAP spectrum) were also prescribed for each of the mooring configurations of the mono-column. The aim was to verify whether the parametric amplifications observed in regular waves could also appear under irregular waves conditions. Fig. 10 shows the heave-roll-pitch responses under a JONSWAP wave with significant wave height and peak period similar to those values defined for the regular wave in test T18_01000 (Fig. 4). It is interesting to notice that the same pattern observed for that regular wave test was also observed in the corresponding irregular wave, i.e., prevailing pitch parametric amplifications. Fig. 11 shows the spectral densities for the incident wave and for heave, roll and pitch motions.

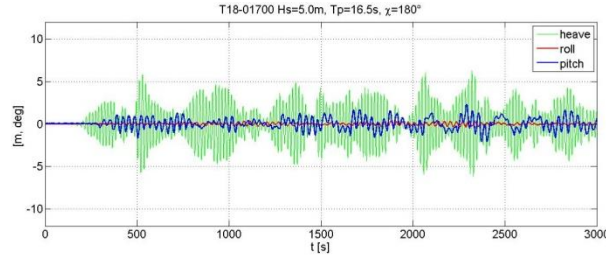

Fig. 10: Config #1, irregular waves, pitch dominant

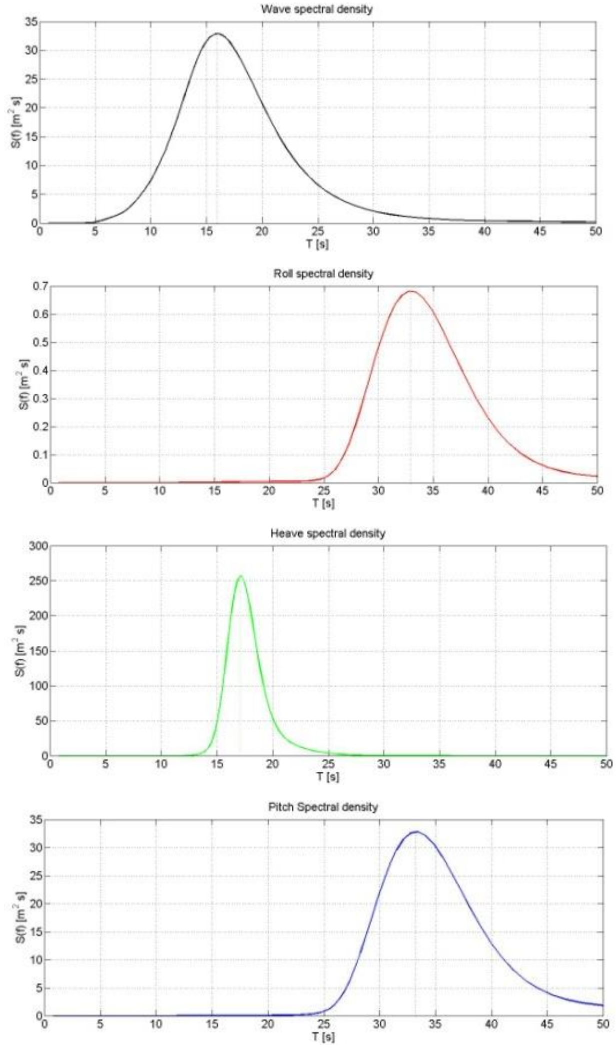

Fig. 11: Config #1, irregular waves, T=16,5s; Hs=5m. Wave, heave, roll and pitch spectra

Configuration #2

Fig. 12 shows the irregular seas responses under a JONSWAP sea with wave parameters similar to those of the regular wave reported in Fig. 8. Under this mooring configuration in regular waves, pitch motion was parametrically excited, and roll remained very small. The same pattern of results is now observed in irregular waves – see responses spectra in Fig.

13. Notice that the main energy content for roll and pitch (spectral peaks) do not occur at the same period, but at each mode's natural period, which are different due to influence of the mooring arrangement – pitch natural period being smaller than the roll natural period.

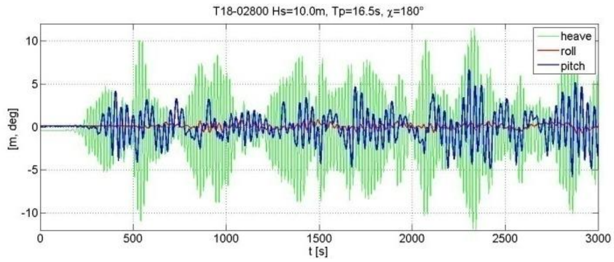

Fig. 12: Config #2, irregular waves, pitch dominant

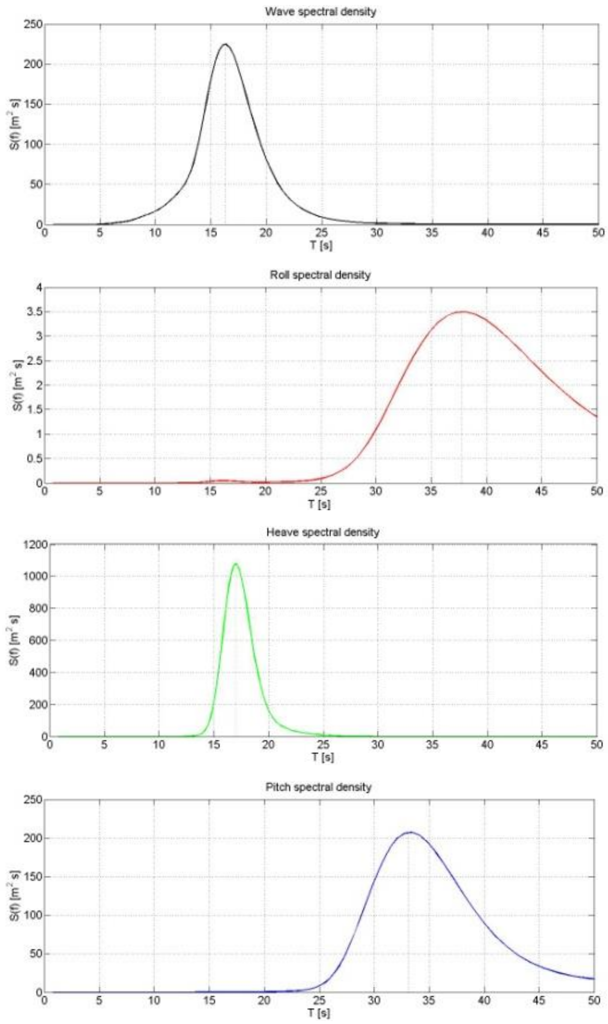

Fig. 13: Config #2, irregular waves, T=16,5s; H=10m. Wave, heave, roll and pitch spectra

Configuration #3

Fig. 14 shows the response time series for a JONSWAP wave with Hs=10 m, and Tp =18.9 s, similar to the regular test wave shown in Fig. 9.

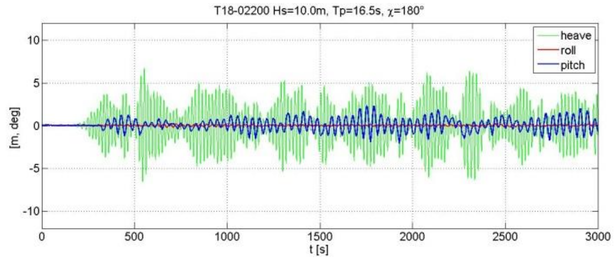

Fig. 14: Config #3, irregular waves, pitch dominant

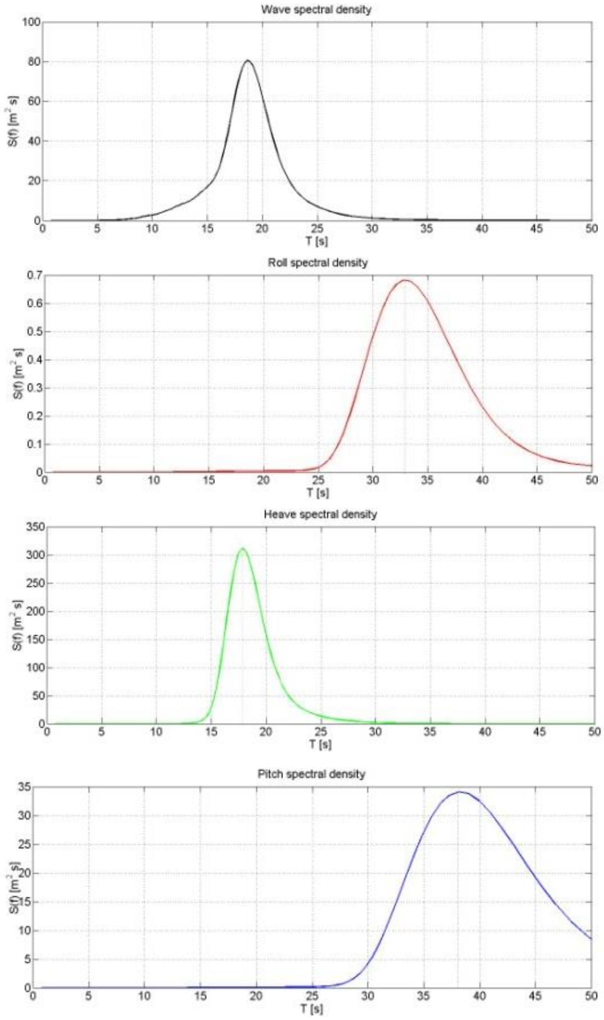

Fig. 15: T02200, Irregular waves, Config #3, T=18,9s; H=10m. Wave, heave, roll and pitch spectra

Again, parametric pitch amplifications are displayed – similar to what was already observed for the regular test. The spectral densities for the irregular wave responses are shown in Fig. 15. Again, it is clear that, the spectral peaks for roll and pitch motions do not occur at the same period, but at each mode's natural period – now, the roll natural period being smaller than the pitch natural period. As stated before, roll and pitch response periods are affected by the kind of mooring arrangement.

NUMERICAL ANALYSIS

A nonlinear algorithm has been used to verify the different roll/pitch contributions to the parametric amplifications. Fig. 16 shows the numerical model of the mono-column with mooring lines and wave. Numerical code DSStab, a 6-DOF panel method with pressure integration assessed at the instantaneous wet surface, is employed. For more details on the algorithm, see Pasquetti et al. (2012). Test case reported in Fig. 5 is chosen for the present limited numerical analysis.

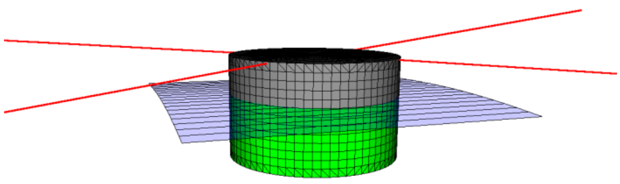

Fig. 16: Mono-column numerical model incorporating lines.

Fig. 17 indicates that, despite the decaying transients at the beginning of the experimental tests, the numerical simulation captures well the mean surge offset of the body by taking into account the coupling of lines with body responses in waves.

Prior to the numerical simulations in waves, calibration of damping coefficients in heave, roll and pitch was performed in the numerical model by comparison of decay tests results between experiments and simulations. After this calibration, the numerical code was capable of reproducing roll and pitch responses in waves very close to the observed ones during the experiments – see, for example, Fig. 18, which should be compared to Fig. 5.

One of the main capabilities of the numerical model used here is that it permits to assess the different force and moment instantaneous contributions coming from a) hydrostatics; b) wave field and c) mooring lines. Typical spectra of these effects are shown in Figs. 19~22. Quadratic (2nd order) wave pressures have in general a very small contribution for this hull, for this reason these are not examined further. As the objective here is to assess contributions to parametric excitation, linear restoring moments in roll and pitch ($\Delta\overline{GM}\,\phi$ and $\Delta\overline{GM}$, respectively) have been excluded from the total hydrostatic moments. The non-linear parts of roll and pitch hydrostatic moments are then obtained – spectra being plotted in Fig. 19. It is observed that both moments take place as parametric actions (double wave period), pitch moment being higher. Less relevant super-harmonic contributions are observed at the 1/3 and 1/5 frequency tunings.

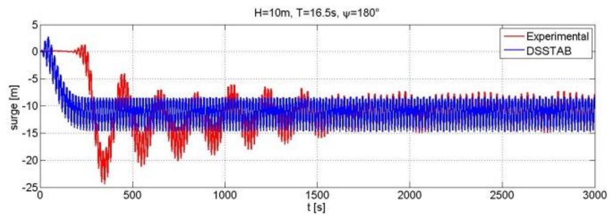

Fig. 17: Surge motion, T=16.5s; H=10m.

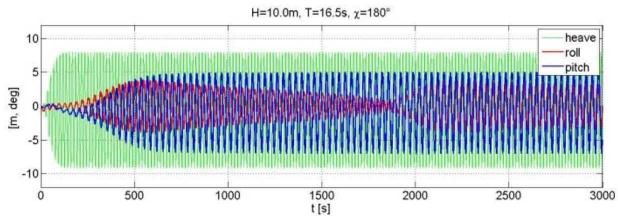

Fig. 18: Heave, roll and pitch motions, numerical simulations, T=16.5s; H=10m.

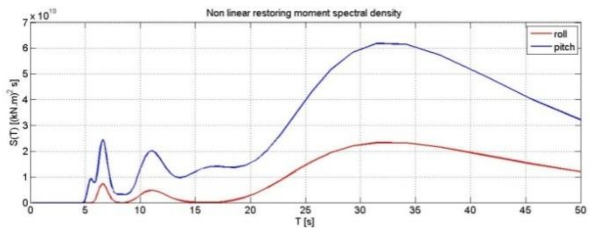

Fig. 19: Nonlinear restoring moment spectral density, T=16,5s; H=10m.

It is interesting to observe the qualitative distinct aspects of the Froude-Krylov contributions in the pitch and roll modes: Fig. 20 shows that the instantaneous pitch Froude-Krylov effect takes place at the wave period, whereas Fig. 21 shows that roll Froude-Krylov moment has its main contribution close to twice the wave period. Then, it may be concluded that, in the pitch mode the wave field does not "notice" the pitch (parametric) motion, which exists as sub-harmonic at twice the wave period, whereas for the roll mode, which is not externally excited, the wave field does contribute to parametric amplification.

Finally, Fig. 22 shows that both roll and pitch moments due to mooring lines act at double the wave period, pitch moment being higher.

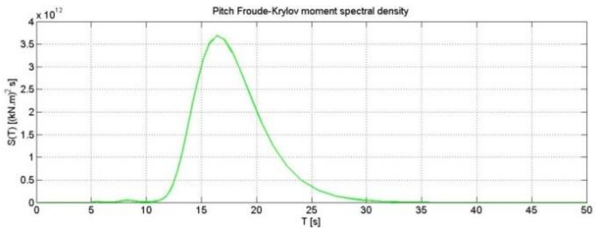

Fig. 20: Pitch Froude-Krylov moment spectral density, T=16,5s; H=10m.

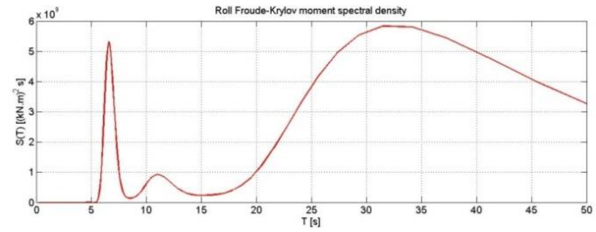

Fig.21: Roll Froude-Krylov moment spectral density, T=16,5s; H=10m.

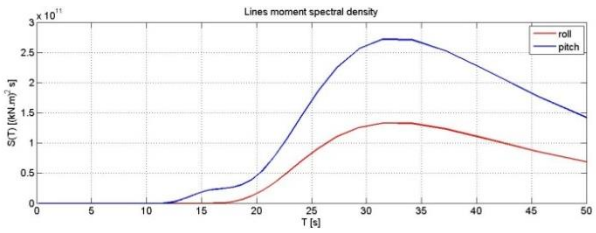

Fig. 22: Lines resultant moment spectral density, T=16,5s; H=10m.

A summary of parametric excitation results in Figs. 19-22 indicate: in pitch the largest moment is exercised by the lines; nonlinear hydrostatic contributions comes second (one order of magnitude lower) and there is no Froude-Krylov contribution. Lines moments are again the largest actions in roll, second comes hydrostatic (also one order of magnitude lower) and there exists a Froude-Krylov moment, which is a smaller contribution. In this context it is important to register (not shown in this paper for lack of space) that without mooring lines, no parametric amplification was observed, either in pitch or roll, neither in experiments nor in numerical simulations.

CONCLUSIONS

Tests performed with a mono-column hull under different mooring arrangements in longitudinal regular and irregular waves have been presented and discussed. Tests showed physical evidence on the occurrence of undesirable parametric amplifications not only in pitch but also in roll.

Different patterns of coupled responses have been identified, depending on the mooring arrangement. In the case of the symmetrical mooring configuration, dependence of angular responses on wave amplitude has been identified. In particular, it has been observed that roll parametric resonance requires higher levels of energy to build up than pitch parametric resonance. Interesting nonlinear exchanges of energy between roll and pitch have been observed.

When the mooring lines are arranged such that roll and pitch natural periods become different (configurations #2 and #3), it is observed that for the same wave height, pitch motion (when tuned, Fig. 9) becomes stronger than roll motion at its respective tuning (Fig. 7). Again, this result reinforces the conclusion that pitch motion is more prone to parametric amplification than roll.

The practical relevance of parametric resonance for mono-column structures may be assessed by noting that parametric pitch amplitudes are of the same order of those resulting from direct excitation at its natural period (classical resonance).

Experimental results for the three tested mooring configurations also showed that parametric resonance (pitch and roll) occurs in irregular waves displaying the same patterns observed at the corresponding regular tests counterparts.

Numerical analyses of Configuration #1 for H=10m showed that mooring lines moments are predominant in establishing the resulting parametrically excited roll and pitch motions. An interesting aspect of the different roles of roll and pitch in the coupled process arises from the Froude-Krylov moments analyses: pitch moment is not internally excited by the waves, its sub-harmonic motion being dependent in this case mainly on the mooring actions.

Mooring influence was evident in the different arrangements considered in the experiments. It was also shown to be relevant in the limited numerical analysis of the symmetrical configuration. A general, yet pertinent conclusion is that the mooring arrangement should be considered as integral part of a testing programme on parametric resonance of cylindrical floating platforms.

ACKNOWLEDMENTS

The Authors acknowledge the contributions of LabOceano technical staff, especially Prof. Sergio Sphaier and Mr. Joel Sena Sales, for their participation in the planning and execution of the tests reported in the present paper. The Authors also acknowledge financial support from CNPq, ANP, PETROBRAS and LabOceano.

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