TURRET POSITIONING, DICAS HEADING AND LOADING ON CATENARY RISERS

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ABSTRACT

Riser loading, especially for the free hanging configuration, is extremely dependent on motion imposed to the top end by the floating unit. Particularly, dynamic compression on risers may occur, taking values up to critical levels. This work focus on the dynamic tension load analysis taking top-end positioning and vertical motion imposed to the riser, as parameters. The work proposes an analysis & design method by separating the tasks into two parts: (1) analysis of FPSO equilibrium position, dynamics and first-order motions induced by the waves; (2) riser design, where motion imposed to the top and installation angle are taken as parameters. An analytical approach is used for the dynamic tension analysis. Two FPSO (Floating Production Storage and Offloading) system configurations are taken as examples: a FPSO-Turret and a FPSO-DICAS (Differentiated Compliance Anchoring System) concepts. A typical flexible pipe is used in order to illustrate general trends in extreme environmental conditions under the concurrent action of waves and current.

INTRODUCTION

Riser system design is one of the most important tasks accomplished during the project of a FPSO system. Riser loading is extremely dependent on motion imposed to the suspended end by the floating unit (see, e.g., Aranha et al, 1997).

If a FPSO-Turret (Floating Production Storage and Offloading-Turret) system concept is used and if the Turret is positioned far from the mid-ship section, pitch angle response is of outmost importance. The closer to the bow the turret is located, the higher the first order excitation experienced by the riser will be. Therefore, bringing the turret aft is a desired trend. When the turret is located at mid-ship section or near it, bow and/or stern thrusters are usually installed in order to keep the vessel's heading conveniently oriented. On the other hand, it has been recently shown (Fernandes et al., 1998) and (Leite et al., 1998), that directional stability with respect to current and waves can be assured by means of special stabilizers of the rudder-type, for a wide range of Turret installation positions. As a matter of fact comparisons in extreme environmental conditions (Leite et al., 1998) showed that a rudder-type stabilizer may bring the Turret positioning from 45% length forward of mid-ship (standard practice) to 20 %.

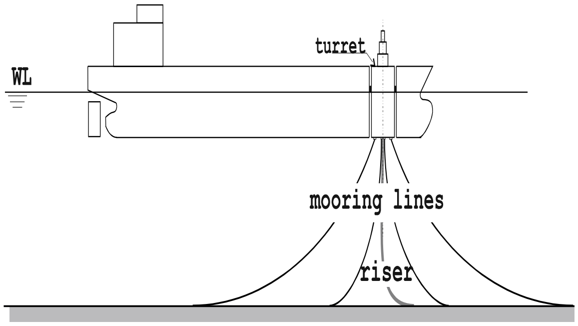

Figure 1 FPSO -Turret System

In an FPSO-DICAS (Differentiated Compliance Anchoring System, Garza-Rios et al., 1999) configuration, the mooring line system provides different rigidity concerning the yaw motions of the ship's bow and stern. Usually, the bow rigidity is higher. The system has a preferential heading direction, which is defined by its installation direction. The main differences in the FPSO horizontal plane response, whether in a turret or DICAS configuration, are briefly discussed in the following section.

This work focus on the dynamic tension load analysis taking top-end positioning and vertical motion thus imposed to the riser, as parameters. As design procedures demand expeditious analysis, an analytical approach is used, for the evaluation of dynamic tension acting on the riser. Following Aranha et al., 1993, dynamic tension can be written as a closed formula solution solely dependent on the static equilibrium configuration of the riser and to the motion imposed to its upper extremity. Results have been compared to full non-linear models, with a very good agreement. A typical flexible pipe is taken in order to illustrate general trends in real environmental conditions under the concurrent action of waves and current.

RISERS OFFSETS AND WAVE INDUCED VERTICAL MOTIONS

A rational evaluation of the dynamic tension response on risers depends on previous assessment of offsets (top ends horizontal plane excursions) and wave induced vertical loadings. Although both effects play a role on the riser's dynamic loading, the analysis shown in the next section indicate that the vertical imposed displacement is, in fact, the major restrictive effect in riser's design, for both steel catenary and free-hanging flexible risers. In the case of a typical FPSO system, such amplitude level is directly induced by the ship's first-order motions. Therefore, one of the main tasks in designing a FPSO refers to the optimum risers positioning, in order to minimize vertical motions acting upon them. Some important details regarding the risers positioning problem for two different FPSO mooring configurations, Turret and DICAS, are discussed below.

Turret Configuration

Obviously, in the case of a FPSO-Turret configuration, the risers positioning problem is actually restricted to the problem of determining the optimum turret position along the ship's center-line. This is not, however, a simple task. The best turret position depends on a balance between the ship heading stability with respect to current loading and the wave induced vertical motions on the turret point.

In order to assess an acceptable value, the horizontal plane response of the system must be analyzed for different turret positions. Analysis must take into account the whole possible set of combined current, waves and wind loading. Regarding the risers design, the main parameters to be evaluated are the turret offsets and the ship's heading angle with respect to the waves direction which, together with the ship's set of response amplitude operators, defining the hull's first-order motions for each environmental loading case.

DICAS Configuration

The analysis to be performed in order to assess offsets and vertical motions of a FPSO-DICAS configuration is very similar to the one required for a fixed turret position. The main difference in the system heading response is that for the DICAS mooring system, compared to the turret configuration, the yaw motions are now much more restricted and this implies a broader range of possible wave heading angles. Beam seas are much more likely to occur in a DICAS configuration leading to higher heave and roll induced vertical motions imposed to risers suspended far from ship center-line.

However, although the system ability to adequate its heading according to the environment is restrained, the DICAS design may take advantage of some particularities in order to minimize the vertical motions on the risers top. First of all, based on the geographic environmental statistics, the system original heading direction may be chosen in order to minimize the typical beam seas wave heights. Also, since the risers may be independently positioned along the hull, the combination of the ship's heave, roll and pitch response in different areas of the hull help to determine regions of minimum vertical displacements.

Therefore, the comparison of FPSO's Turret and DICAS configurations with respect to the risers induced vertical motions is not immediate and depends on many particular design features.

Evaluation of Riser's Offsets and Vertical Motions: Case-Example

Evaluation of risers' offsets and FPSO's possible wave heading angles depends on a series of factors such as the mooring system configuration, the local environmental statistics and particular criteria for the evaluation of design loadings but they will not be discussed herein.

Technical literature presents a series of hydrodynamic models that may be applied in order to evaluate the FPSO's horizontal plane dynamic response. A whole design methodology has been developed at University of Michigan, for instance, by Bernitsas et al (1999) and a rational comparison between the majority of such models is provided in Matsuura et al. (1999). See also (Sphaier et al., 1998).

At the University of São Paulo the evaluation of ships offsets and heading angles has been performed through direct time-domain simulations, adopting a recently developed hydrodynamic model (see Simos et al. 1998) based on a previously experimentally validated Heuristic static model (see Leite et al. 1998). The hydrodynamic model also includes wave-current interaction phenomena ('wave-drift damping') that is taken into account on the basis of a formulation presented by Aranha (1994, 1996). It should be noticed that, for some particular extreme environmental cases, the wave-drift damping effect exerts a very significant influence on the system's final heading angle (Martins et al., 1999).

Once the system's heading angle analysis is concluded, the vertical displacements imposed to the risers may be evaluated, for each one of the possible wave-heading angles. As an example, the case of an actual FPSO tanker (under development for operation at Brazil's Campos Basin) was adopted. The Tanker's particulars are presented in Table 1, below.

Table 1 Tanker's particulars

Length (L_{bpp}) (m)	320
Breadth (m)	54.5
Draft (m)	21.6
Displacement (t)	322078

Figure 2 presents a map of the turret horizontal excursions for this particular tanker. In this particular example, the turret is positioned at a distance of 64 meters forward the mid-ship section. The same tanker was analyzed in a DICAS mooring system configuration. In this latter case, the offset analysis for a particular riser is shown in Figure 3. Both maps were generated for 24 different extreme current-wave combinations, typical of Campos Basin region.

The maximum vertical displacement amplitudes are then evaluated as follows: For the turret configuration, the ship's vertical motions along its center-line (at the risers top connection vertical coordinate) are calculated for the whole set of wave heading angles (180º for head sea), for typical sea states. Figure 4 presents an example for the particular tanker considered (displacements at the bottom center-line). These results are then combined to those provided by the wave-heading analysis for different turret positions. It is then possible to assess the vertical motions induced on the turret point (and therefore on the risers top), for each of the different turret positions considered.

For the DICAS configuration the vertical displacement evaluation must be made for all the possible riser connection points. The adopted methodology in this case consists of determining the system wave heading for each particular environmental case and then the vertical displacement amplitudes for the hull at the specified vertical coordinate. Those calculations are exemplified in Figure 5, which presents a map of vertical displacement amplitudes for every point of the hull bottom (for simplicity, here represented by a region delimited by the ship's beam and length). The map presented in Figure 5 corresponds to the maximum vertical displacements that would be imposed to risers amongst a total of 24 different wave-current combination, that closely represent the most severe environmental conditions.

The whole set of vertical displacement maps combined with the parametric analysis of riser dynamic tension, presented in the following section, provide the data required for a rational evaluation of the most adequate riser position and angle at top end.

RISER LOADING AND DYNAMIC TENSION

Demanded by the deep-water oil industry, the dynamic problem of a catenary riser has been addressed extensively and intensively, by many investigators, in the past few years. It is now very well known and recognized that first-order ship motions imposed to the top end is the primary dynamic loading excitation for the extreme-load analysis. Several dedicated models and computer programs have been developed worldwide in order to accomplish the analysis task (see, e.g., Larsen, 1992). Most of them include full non-linear modelling, regarding hydrodynamic loads and geometric non-linearities.

From a design-oriented point of view, however, what demands expeditious (though sufficiently accurate) evaluations, an analytical approach has been here used, instead. The dynamic tension problem had been addressed, theoretically and experimentally, by Aranha et al., 1993, dynamic tension being written as a closed formula solution solely dependent on the static equilibrium configuration of the riser and to the motion imposed to its top extremity. An analytical solution that deals with the dynamic curvature problem at the Touch Down Point (TDP) region, of the boundary-layer type, had also been developed (Aranha et al., 1997) and experimentally validated (Pesce, et al., 1998).

The present work will only treat the dynamic tension problem, one of most intriguing and not totally comprehended problem, as far as dynamic compression is concerned and since no rational criteria has been established so far in order to evaluate critical compression loads in catenary risers. It should be mentioned, however, a thorough analysis, by Bernitsas & Kokkinis, 1983, but only concerning vertical risers.

Once a critical compression load value is reached, however, dynamic curvature would then play the role.

Asymptotic Model

The present solution is, in fact, an up-graded version of an earlier analytical formula, derived by Aranha et al., 1993, for the dynamic tension acting on a catenary riser. That formulation already included the current effect but considered a restrictive assumption: tension dynamic amplitude is invariant along the line. Such a restrictive hypothesis was based on the fact that for many practical situations, amplitude tension presents a "slow" spatial variation. The whole dynamic response solution to an oscillatory motion imposed to the upper extremity was then written as function of shape coefficients, integral forms that depend solely on the static equilibrium configuration.

The present form not only incorporates the current effect that is contained in the shape coefficients, but also incorporates the dynamic tension amplitude variation along the riser. Let $\theta_0(s)$ be the angle with respect to the horizontal, at an arch-length coordinate *s*, measured from TDP, for convenience. The derivation of the present solution will not be presented here but, after some algebraic work we come up with the following analytical solution, for the dynamic tension

$$\tau_D(s) = \frac{T_D}{T_e} = \tau(s) \cdot e^{i\Phi(\omega;s)}; \tag{1}$$

with,

$$T_e = EA\frac{\sigma_U}{L + L'} \tag{2}$$

an elastic-tension scale (actually an asymptotic limit for very taught lines), where *EA* is the axial rigidity, σ_U the r.m.s. (root mean square) value for the motion imposed to the upper extremity, *L* is the suspended length and *L'* is the part of the line, supported on the soil, that is driven axially, under dry friction constraint effects. In equation (1),

$$\tau(s) =$$

$$= \left[\frac{c_2(s)\left(\sqrt{b^2 + \left(4\zeta_0^2/\Omega^4\right)a^2} - b\right)^2 + 2c_1(s)\left(\sqrt{b^2 + \left(4\zeta_0^2/\Omega^4\right)a^2} - b\right)}{\left(4\zeta_0^2/\Omega^2\right)} \right]^{1/2} \tag{3}$$

is the amplitude along the arch-length coordinate, $\Phi(\omega, s)$ is the phase lag,

$$b = \left(\frac{1-\Omega^2}{\Omega^2}\right)^2 \tag{4}$$

a frequency dependent coefficient, being

$$\Omega = \frac{\pi}{\Lambda}\left(\frac{\omega}{\omega_c}\right) \tag{5}$$

the so-called 'reduced frequency' and,

$$\Lambda = \frac{ql}{T_s} I_2^{1/2} \left(\frac{EA}{T_s}\right)^{1/2} \left(\frac{L}{L + L'}\right)^{1/2} \tag{6}$$

the non-dimensional ratio between elastic (axial) and geometric rigidities, firstly proposed by Irvine & Caughey, 1974, for the classical extensional string problem and then applied by Triantafyllou et al, 1981 and Aranha et al., 1993 for cables and risers.

In equation (6) the shape or integral form coefficients are defined as,

$$\begin{aligned} I_n &= \frac{1}{L}\int_0^L \left|\chi_1(s)\right|^n ds; \qquad n = 1,2,3,\ldots \\ I_c &= \frac{1}{L}\int_0^L \left|\chi_c(s) \cdot (z(s) \cdot sen\,\theta(s)\right| \;\; \chi_1^2(s)\Big)ds \end{aligned} \tag{7},$$

where $\chi_1(s) = \frac{T_L}{qL}\frac{1}{\cos\theta_L}\frac{d\theta_0}{ds}$ is a re-scaled curvature function, and the subscript L indicates upper end extremity. $\chi_c(s) = V_c(s)/V$ is the normalized current profile along the arch-length coordinate *s*. Also,

$$\omega_c = \frac{\pi}{L}\left(\frac{T_A}{m+m_a}\right)^{\frac{1}{2}} \tag{8}$$

is a 'catenary frequency-scale', with m_a the added mass, and

$$\omega_e = \frac{\pi}{l}\left(\frac{EA}{m}\right)^{\frac{1}{2}} \tag{9}$$

is an 'elastic frequency scale'. Finally, frequency and damping dependent functions $c_1(s)$ and $c_2(s)$, are given by

$$c_1(s) = \left(1+\zeta_c^2\right) - 2\left(\zeta_c^2 - \frac{1-\Omega^2}{\Omega^2}\right)\left(\frac{L+L'}{L}\pi^2\left(\frac{\omega}{\omega_e}\right)^2\right)\frac{s}{L} +$$

$$+ b\left(\frac{L+L'}{L}\pi^2\left(\frac{\omega}{\omega_e}\right)^2\right)^2\left(\frac{s}{L}\right)^2; \qquad (10),$$

$$c_2(s) = \left(1 - \frac{L+L'}{L}\pi^2\left(\frac{\omega}{\omega_e}\right)^2\frac{s}{L}\right)^2$$

being,

$$\begin{aligned}\zeta_c &= \frac{1}{L}\int_0^L C_D(s)\left|\chi_c(s)\sin\theta(s)\right|\chi_1{}^2(s)ds \\ \zeta_0 &= \frac{8}{3\pi}\frac{2C_D}{\pi}\frac{m_a}{m+m_a}\frac{1}{\sin\theta(s)}\frac{I_3}{I_2{}^2}\frac{U_0}{D}\end{aligned} \tag{11}$$

the linearized damping coefficients, determined from standard energy equivalence considerations over a whole cycle of motion. The first coefficient takes into account the current effect, while the second one corresponds to the dissipated energy in the absence of ocean current. U_0 is the amplitude of motion imposed to the upper extremity, such that the coefficient

$$a = \frac{U_0}{\sigma_U} \tag{12}$$

takes the value $\sqrt{2}$ for purely harmonic excitation.

Flexible Riser Example

A 6 inches internal diameter flexible riser has been taken as an example for the present analysis. Table 2 shows riser data and depth.

Figure 6 shows a comparison between the asymptotic formula for the dynamic tension amplitude and results from a fully non-linear numerical solution[1]. Tension is calculated at TDP. As no current is considered in this case, asymptotic solution is, as matter of fact, analytical, since catenary curvature function is known and integrals $I_n(\theta_L)$ can be easily determined. Two curves have been plotted, as a function of angle with respect to the horizontal at the upper extremity, for two different amplitude values of imposed motion. Agreement is considered satisfactory, as far as a parametric analysis and design-oriented procedures are concerned.

Table 2 Flexible riser's data

External diameter (m)	0.216
Internal diameter (m)	0.152
Mass per unit length (kg/m)	67
Axial Rigidity (EA) (kN)	192000
Flexural Rigidity (EJ) (kNm^2)	9.84
T_r (kN)	98
C$_D$	1.1
C$_m$	1
Friction coefficient	0.4
Total length (m)	5000
Axial damping (% of critical value)	10
Depth (m)	1030
Riser Top (m) at	1008.4

Dynamic tension amplitude is normalized with respect to $T_0 + T_r$, being T_0 the tension at TDP and T_r a 'compression limit', experimentally determined by the supplier industry, taking this case, the value 98kN. So, whenever $T_D/(T_0 + T_r) = 1$, the compression limit would be reached.

Figure 7 shows a parametric analysis according to the amplitude of motion imposed to the top. Notice that the dynamic tension does not reach the critical value $T_0 + T_r$, for $A < 4.0\text{m}$, irrespective the angle with horizontal at the top, θ_L . On the other hand, looking at Figure 4, we see that we should set $\theta_L \approx 87^o$, for an FPSO-Turret configuration, if the Turret position were placed at 20% (64 m) forward mid-ship and if no wave heading restrictions were imposed. Otherwise, for this particular Turret position, and taking $\theta_L \approx 85^o$, wave heading would be restricted to ranges around 150º ≤ α ≤ 210º (head-seas, ± 30º) and around -30º ≤ α ≤ 30º (following–seas, ± 30º).

Nevertheless, if no compression were allowed, what turns to be a safe and usual hypothesis, the maximum permissible amplitude motion would be $A \approx 2.5\text{m}$, irrespective θ_L , as shown in Figure 8. Looking at Figure 4 again, we easily see that for this extreme environmental condition there would be no wave heading under which compression could be avoided, irrespective the Turret position. However, under such no-compression criterion, some feasibility would last by taking a small value for the horizontal angle, say $\theta_L \approx 65^o$, restricting the amplitude motion to the range $A \le 3.5\text{m}$ and placing the Turret system some few 25 meters forward mid-ship. As this simple examples show, an imperative research topic is to determine, through a rational methodology, the compression limits for a catenary riser.

If we take a FPSO-DICAS system, instead, allowing again for a 98kN compression value, and for a typical flexible riser angle installation $\theta_L \approx 85^o$ such that, from Figure 7, amplitude motion limit is around $A \approx 6\text{m}$, Figure 5 shows that the riser should not be installed 70 meters or farther from mid-ship.

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[1] ORCAFLEX; see Larsen, 1992.

Finally, to exemplify the current effect problem, we took a strong profile, typical for Campos Basin, as given in table 3, surface current forcing the riser to a‘ Far’ equilibrium configuration. Figure 9 shows dynamic tension amplitude at TDP, normalized with respect to $T_0 + T_r$, $T_r = 98\text{kN}$. As it should be expected, as current effect increases static tension at TDP region in this particular case, dynamic tension amplitude decreases, for the same motion imposed to riser’s upper extremity, as compared to the no-current case. Notice that now, for this ‘far’ static equilibrium configuration, horizontal top angle θ_L can reach values greater than 90 degrees.

Table 3 Current Profile

Depth (m)	Vel. (m/s)
0	1.7
50	1.54
100	1.39
140	1.18
230	0.72
340	0.78
415	0.01
545	-0.28
640	-0.36
785	-0.53
1030	0

CONCLUSIONS

This work focused on the dynamic tension loading analysis taking top-end positioning and vertical motion imposed to the riser, as parameters. By combining recent developments in either FPSO-mooring system dynamics and risers dynamics, a rather general and expeditious method was constructed and exemplified. FPSO’s dynamics in the horizontal plane were assessed through time-domain simulations, using a hydrodynamic model that takes into account wave-current interaction effects. An analytical approach was used for the riser’s dynamic tension analysis, dynamic tension being written in a closed form solution, for a given static equilibrium configuration. Two FPSO (Floating Production Storage and Offloading) system configurations were taken as examples: a FPSO-Turret and a FPSO-DICAS (Differentiated Compliance Anchoring System) concepts. Horizontal FPSO’s dynamics was addressed, for a representative set of environmental conditions, and a standard first-order seakeeping analysis was performed, in order to construct a map for the vertical motion that would be imposed to riser’s upper extremity. A typical flexible pipe was chosen in order to illustrate general trends in extreme environmental conditions. Current effect on the riser has been exemplified as well. As far as dynamic compression is concerned , the results indicate that the installation angle at top, (pre-tensioning) is the most important parameter affecting feasibility in extreme environmental conditions. The particular but typical example shows that, for usual installation angles, around 85 degrees with respect to horinzontal, feasibility would arise for a free-hanging flexible catenary riser, only if some level of dynamic compression were allowed, either for Turret or DICAS concepts. Therefore, as previously mentioned, an imperative research topic turns to be to construct a rational methodology in order to determine the compression limits for a catenary riser.

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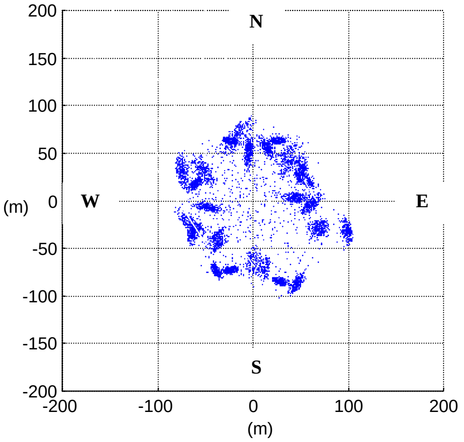


Figure 2 Turret Point Horizontal Excursions. Hydrodynamic model with wave-current interaction effect.

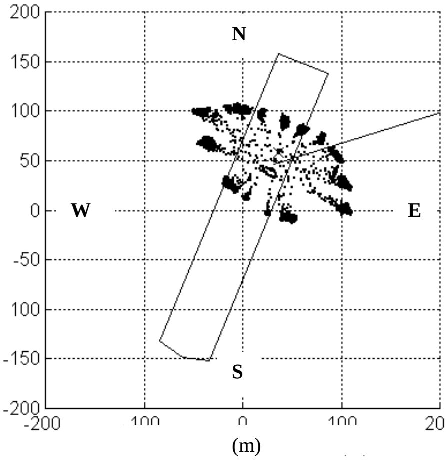


Figure 3 Riser Horizontal Excursions in a DICAS Mooring System. Hydrodynamic model with wave-current interaction effect.

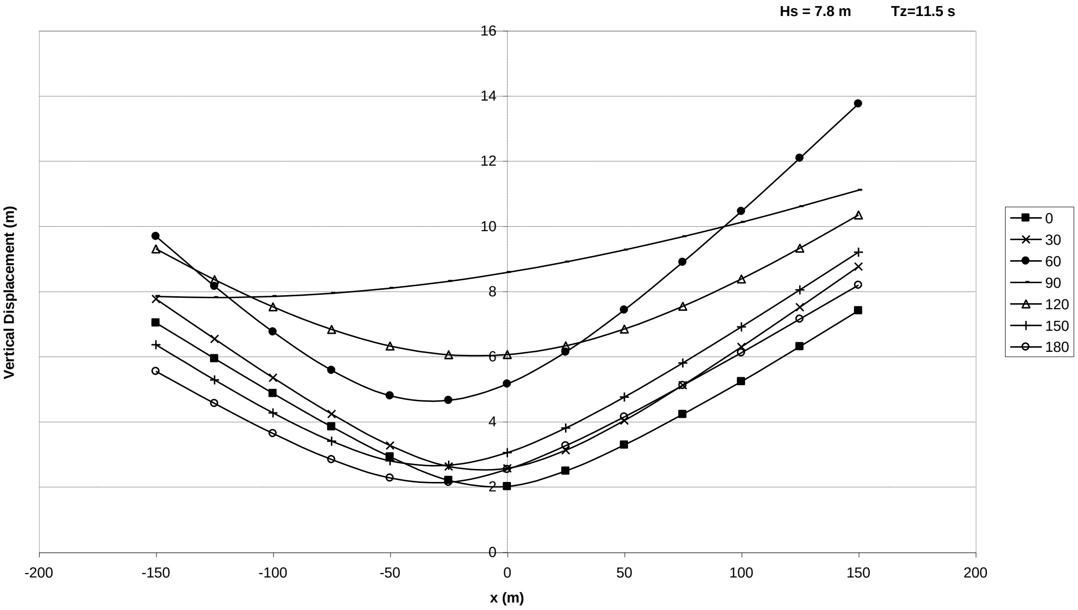
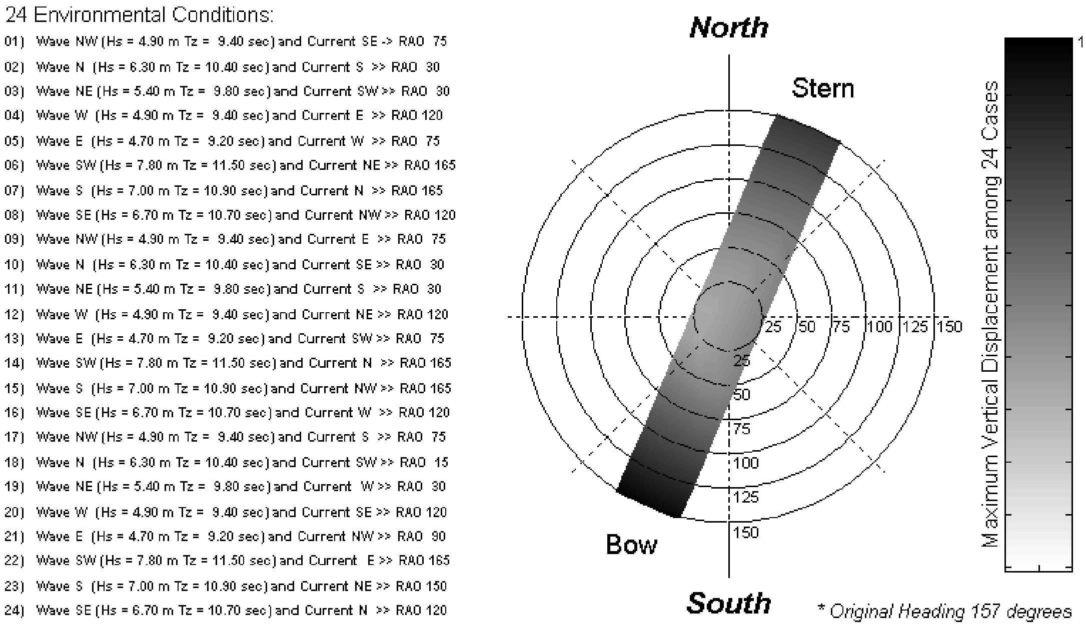


Figure 4 Set of Amplitude of Vertical Displacement at the Ship's Bottom along Center-Line for various wave heading angles. An extreme environmental condition is considered $H_s = 7.8\text{m}; T_z = 11.5\text{s}$.



24 Environmental Conditions:

01) Wave NW (Hs = 4.90 m Tz = 9.40 sec) and Current SE -> RAO 75
02) Wave N (Hs = 6.30 m Tz = 10.40 sec) and Current S >> RAO 30
03) Wave NE (Hs = 5.40 m Tz = 9.80 sec) and Current SW >> RAO 30
04) Wave W (Hs = 4.90 m Tz = 9.40 sec) and Current E >> RAO 120
05) Wave E (Hs = 4.70 m Tz = 9.20 sec) and Current W >> RAO 75
06) Wave SW (Hs = 7.80 m Tz = 11.50 sec) and Current NE >> RAO 165
07) Wave S (Hs = 7.00 m Tz = 10.90 sec) and Current N >> RAO 165
08) Wave SE (Hs = 6.70 m Tz = 10.70 sec) and Current NW >> RAO 120
09) Wave NW (Hs = 4.90 m Tz = 9.40 sec) and Current E >> RAO 75
10) Wave N (Hs = 6.30 m Tz = 10.40 sec) and Current SE >> RAO 30
11) Wave NE (Hs = 5.40 m Tz = 9.80 sec) and Current S >> RAO 30
12) Wave W (Hs = 4.90 m Tz = 9.40 sec) and Current NE >> RAO 120
13) Wave E (Hs = 4.70 m Tz = 9.20 sec) and Current SW >> RAO 75
14) Wave SW (Hs = 7.80 m Tz = 11.50 sec) and Current N >> RAO 165
15) Wave S (Hs = 7.00 m Tz = 10.90 sec) and Current NW >> RAO 165
16) Wave SE (Hs = 6.70 m Tz = 10.70 sec) and Current W >> RAO 120
17) Wave NW (Hs = 4.90 m Tz = 9.40 sec) and Current S >> RAO 75
18) Wave N (Hs = 6.30 m Tz = 10.40 sec) and Current SW >> RAO 15
19) Wave NE (Hs = 5.40 m Tz = 9.80 sec) and Current W >> RAO 30
20) Wave W (Hs = 4.90 m Tz = 9.40 sec) and Current SE >> RAO 120
21) Wave E (Hs = 4.70 m Tz = 9.20 sec) and Current NW >> RAO 90
22) Wave SW (Hs = 7.80 m Tz = 11.50 sec) and Current E >> RAO 165
23) Wave S (Hs = 7.00 m Tz = 10.90 sec) and Current NE >> RAO 150
24) Wave SE (Hs = 6.70 m Tz = 10.70 sec) and Current N >> RAO 120

* Original Heading 157 degrees

Figure 5 FPSO-DICAS system. Map of vertical displacement amplitudes for every point of the hull bottom (for simplicity, here represented by a region delimited by the ship's beam and length). Amplitudes correspond to the maximum vertical displacements that would be imposed to risers amongst a total of 24 different wave-current combinations, which closely represent the most severe environmental conditions at Campos Basin.

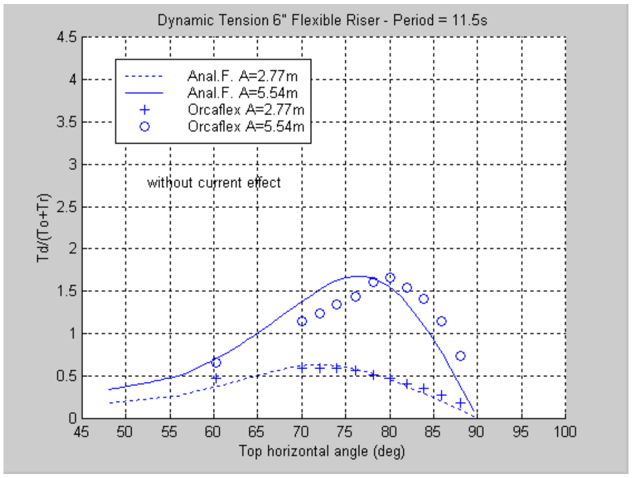


Figure 6 Analytical Solution compared to fully non-linear model results, for a 6 inches internal diameter flexible riser (Table 2). T_0 is the tension at TDP. $T_r = 98\text{kN}$ is an experimentally determined compression limit value

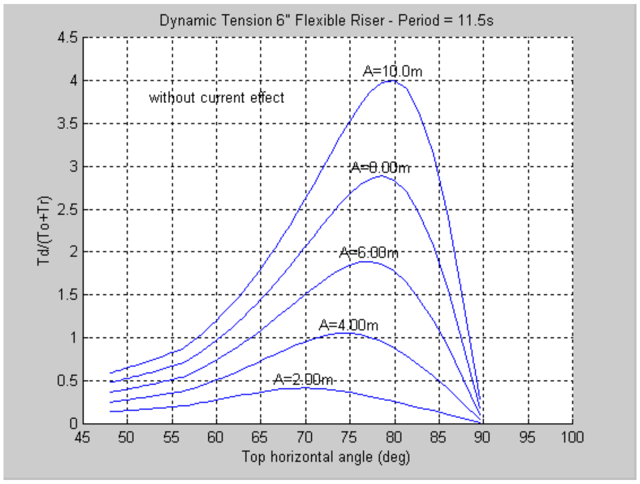


Figure 7 Analytical solution's parametric analysis for a 6 inches internal diameter flexible riser (Table 2). *A* is the amplitude of motion imposed to the upper extremity. T_0 is the tension at TDP. $T_r = 98\text{kN}$ is an experimentally determined compression limit value.

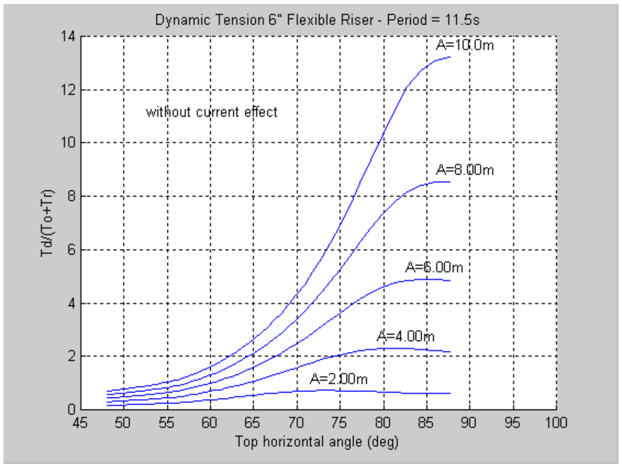


Figure 8 Analytical solution's parametric analysis for a 6 inches internal diameter flexible riser (Table 2). *A* is the amplitude of motion imposed to the upper extremity. T_0 is the tension at TDP. Here $T_r = 0.0\text{kN}$ is taken.

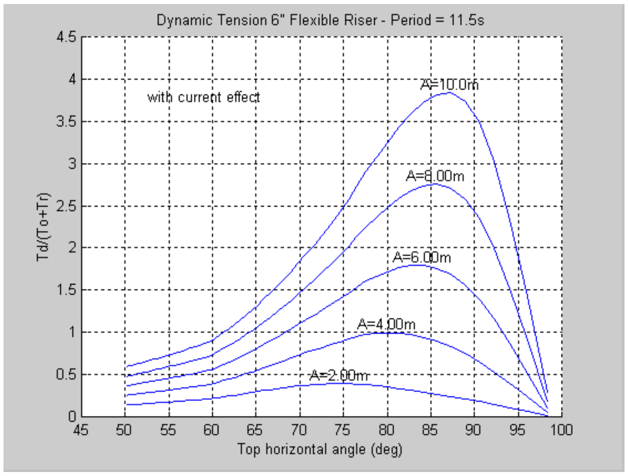


Figure 9 Analytical solution's parametric analysis for a 6 inches internal diameter flexible riser (Table 2). Current effect is now included. *A* is the amplitude of motion imposed to the upper extremity. T_0 is the tension at TDP. Here $T_r = 98\text{kN}$ is an experimentally determined compression limit value.