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STRUCTURAL ANALYSIS OF HYBRID RISER SYSTEMS BY A NUMERICAL PROCEDURE

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RESUMO

Em atividades de exploração de petróleo em águas profundas e ultraprofundas, sistemas flutuantes de produção, tais como plataformas semisubmersível e unidades FPSO (Floating Production, Storage and Offloading), têm sido comumente empregados. No entanto, a utilização de *risers* flexíveis em águas ultraprofundas tem sido dificultada por razões técnicas e econômicas. Por outro lado, os movimentos de primeira ordem da unidade flutuante, devido a cargas ambientais não são favoráveis ao uso *risers* de aço em catenária livre (SCR). O objetivo deste trabalho é descrever um procedimento de solução para a análise de um sistema de elevação híbrido, constituído de uma boia de subsuperfície e SCR. Este procedimento baseia-se numa formulação analítica que é resolvida numericamente. Uma das principais características deste procedimento é o fato de levar em conta os efeitos de cargas de correnteza que atuam sobre as linhas. O perfil de correnteza pode ser considerado com direção e velocidades variando com a profundidade, portanto, configurando uma solução tridimensional.

Palavras-chave: Sistemas de *risers* hibrido. Estruturas Offshore. Correntes marinhas.

ABSTRACT

In deep and ultra-deep water petroleum exploitation activities, floating production systems such as semi submersible platforms and FPSO (Floating Production, Storage and Offloading) units have been commonly employed. However, the utilization of flexible risers in ultra-deep waters has been hindered by technical and economical reasons. On the other hand, first order motions from the floating unit due to environmental loads are not favorable to the use of Steel Catenary Risers (SCR) in a free-hanging configuration. The objective of this work is to describe a solution procedure for the analysis of such a hybrid riser system. This procedure is based on an analytical formulation that is solved numerically. One of the main features of this procedure is the fact that it takes into account the effects of current loads acting on the lines. Current profiles can be considered, with direction and velocities varying with depth, therefore configuring a full three-dimensional solution.

Keywords: hybrid riser systems; offshore structures; marine currents.

1 INTRODUÇÃO

The analytical/numerical procedure to static equilibrium of hybrid risers systems based on sub-surface buoy concept considers, both self weight and buoyancy of the segments that compose the lines and the influence of marine current. In a great number of lines design cases, the marine currents shall be considered not aligned with the lines plane, taking into a three dimensional static configuration of the lines. The obtained results, on terms of geometric configuration and tensions, are compared with those furnished by usual formulations employing Finite Element Methods (FEM).

2 STRUCTURAL MODEL ANALYSIS

In preliminary stages of the project, the complete model with several lines proposed by Fernandes (FERNANDES, 1988), *et al*, (FERNANDES, 2002), and Deepstar IIA Project (DEEPSTAR IIA PROJECT, 1995), can be substituted by a simplified equivalent model, composed by one buoy, one jumper and one Steel Catenary Riser (SCR), as shown in Figure 1.

3 GLOBAL STATIC EQUILIBRIUM OF HYBRID RISER SYSTEM

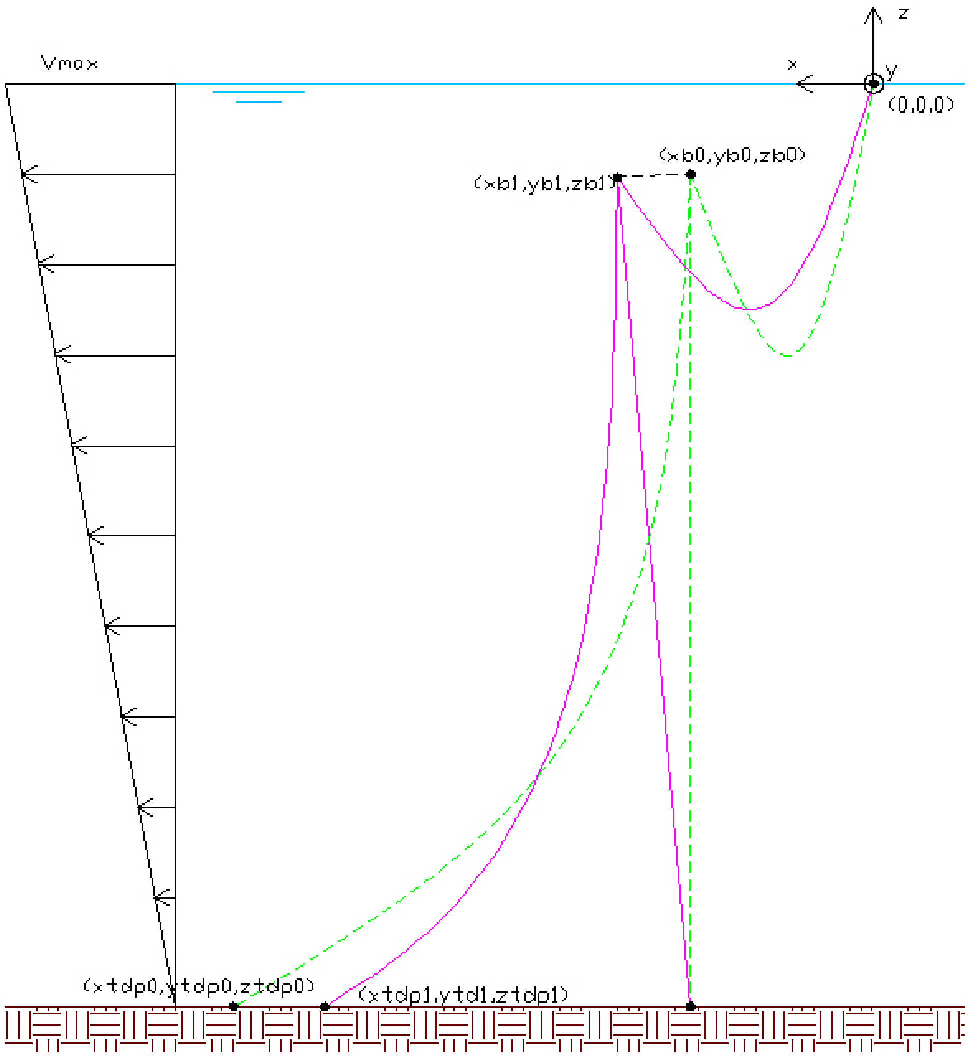
In the static equilibrium of the hybrid risers system, the segments that compose the lines (jumpers and SCRs) are considered discontinuous in a single point, where the sub-surface buoy is located.

The procedure described by Rodrigues *et al* (RODRIGUES, 2004), was applied for the structural analysis of individual lines, and an external routine was programmed to consider the global static equilibrium. The mathematical formulation is based on the simplification assumed by the consideration of inextensibility of the tether that anchors the sub-surface buoy to the seabed.

Since the tether length is considered inextensible, it can be supposed as the radius of a semi-sphere, analytically defined in Equation (1).

$$x_b^2 + y_b^2 + z_b^2 = L^2 \tag{1}$$

Figure 1 – Structural model scheme.



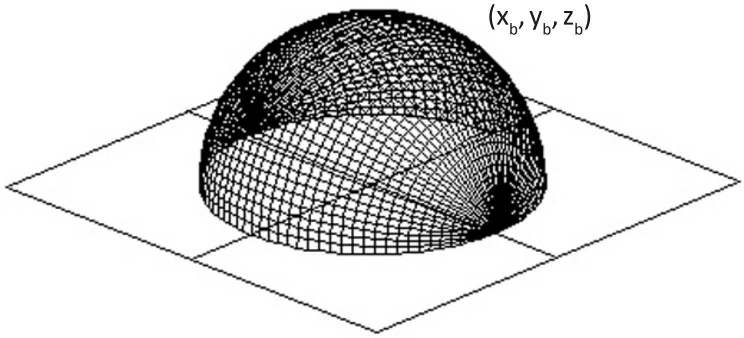
In Equation 1, the values (x_b, y_b, z_b) are the coordinates of the sub-surface buoy gravity center, and the semi-sphere radius is represented by the tether length (*L*).

The surface of this semi-sphere represents the location where one extremity of the tether may be positioned, or else, the points with three-dimensional coordinates of the sub-surface buoy. This semi-sphere is limited in its base by the seabed, considered a horizontal plane as shown in Figure 2.

The formulation considers that the discontinuity point of the lines has tension force components at the deepest extremity of the jumper and tension force components at the SCR upper extremity as shown Figure 3. The acting forces on the sub-surface buoy are its Buoyancy (E), the tension force at buoy/jumper connection (T^J), the tension force at buoy/SCR connection (T^S) and tension force component in the tether (T^T), as shown in Figure 3.

In the beginning of the static equilibrium process values for coordinates x_b and y_b, of the tether extremity are established. Starting from Equation 1 and knowing the tether length *L* which is equal to the semi-sphere radius, the buoy depth (z_b) can be determined. It can also be determined the tether projection in the horizontal plane (xy), presented in Equation 2, as well as the direction cosines (l,m,n) of the buoy position, as shown in Equations 3, 4 and 5.

Figure 2 - Coordinates of the tether extremity.



$$L_{xy} = L \cos \psi \tag{2}$$

$$l = \cos \psi \cos \varphi = \frac{x_b}{L} \tag{3}$$

$$m = \cos \psi sen \varphi = \frac{y_b}{L} \tag{4}$$

$$n = sen \psi = \frac{z_b}{L} \tag{5}$$

The resulting components of the tension in the tether (T^T) have the same direction cosines of its length, and can be written as in Equations 6, 7 and 8:

$$l = \cos \psi \cos \varphi = \frac{T_x^T}{T} \tag{6}$$

$$m = \cos \psi sen \varphi = \frac{T_y^T}{T} \tag{7}$$

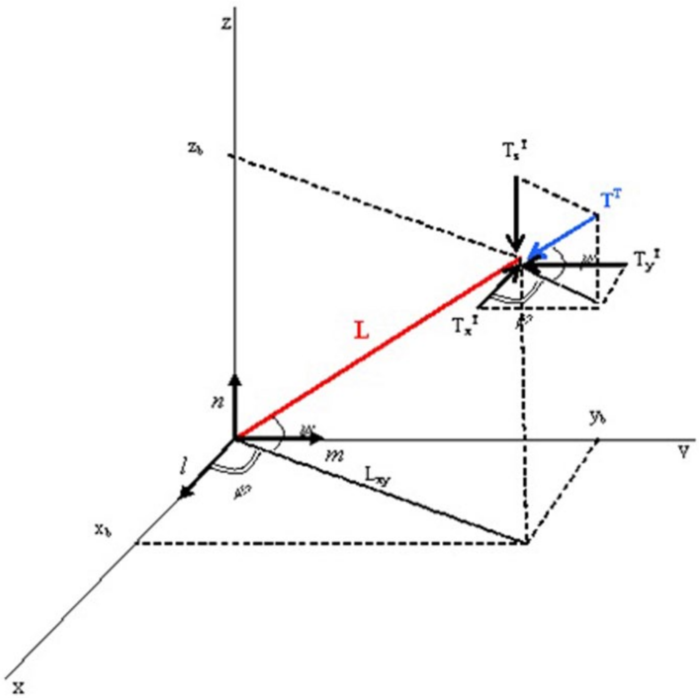
$$n = sen \psi = \frac{T_z^T}{T} \tag{8}$$

The system of Equations 9, guarantees the static equilibrium of the discontinuity point of the lines, that is, of the sub-surface buoy. The vertical component of the tension in the tether can be determined starting from Equation 10, since the vertical component forces in the lines extremities and the buoyancy of the sub-surface buoy are known.

$$\begin{cases} \sum F_x = 0 \therefore T_x^T + T_x^J + T_x^S \\ \sum F_y = 0 \therefore T_y^T + T_y^J + T_y^S \\ \sum F_z = 0 \therefore E - T_z^T - T_z^J - T_z^S = 0 \end{cases} \tag{9}$$

$$T_z^T = E - T_z^J - T_z^S \tag{10}$$

Figure 3 - Forces acting on the sub-surface buoy.



In Equation 10, T_z^T is the vertical component of the tension in the tether, T_z^J is the vertical component of the tension in the jumper, T_z^S is the vertical component of tension in SCR and E the buoyancy of the sub-surface buoy. The tension components in the jumper (T_z^J) and in SCR (T_z^S) are obtained through the solution procedure for an isolated line described by Rodrigues *et al* in Rodrigues (2004).

Equations 5 and 8 are matched and substituted into Equation 10, allowing the determination of the resulting tension in the tether (T^T) and, consequently, the other tension components of the tether, as shows Equations 11, 12 and 13:

$$T^T = \frac{T_z^T L}{z_b} \tag{11}$$

$$T_x^T = T^T \frac{x_b}{L} \tag{12}$$

$$T_y^T = T^T \frac{y_b}{L} \tag{13}$$

Components T_X^T and T_Y^T of the tension in the tether and components T_X^J, T_Y^J, T_X^S and T_Y^S are then obtained verifying if the static equilibrium is satisfied (Equations 14 and 15).

This procedure is repeated until these static equilibrium equations are satisfied, configuring an iterative process. This iterative process was implemented on the graphic computational tool and constitutes the solver for the structural analysis of the hybrid riser system called HIB3DGRAF.

$$T_x^T - T_x^J - T_x^S = 0 \qquad (14)$$

$$T_y^T - T_y^J - T_y^S = 0 \qquad (15)$$

At the end of the iterative process, the components of the acting forces at sub-surface buoy will be known and consequently, the coordinates of the point that allow the static equilibrium. As consequence, the inclination angle of the tether is determined, as shown in Figure 3. A flowchart of the process is shown in Figure 4.

Figure 4 - Flowchart of iterative process to obtain the static equilibrium.

4 NUMERICAL EXAMPLES

Identical models of the hybrid system were generated, submitted to variable current profiles acting in East direction (0° with the plane of the lines) and North direction (90° with the plane of the lines). The current values presented for each direction, corresponds to a maximum velocity that occurs in the surface of a triangular current profile and has null intensity at the seabed.

Although the following examples refer to triangular current profiles, the formulation herein proposed, makes possible current profiles with velocities and assigned directions, in such a way to allow the most several current profiles, as for instance, reverse current profiles.

The jumper horizontal projection is defined by the FPSO coordinates and the tether anchor. The coordinates of the tether anchor and the SCR extremity at sea bead define the SCR horizontal projection.

In this comparative study, jumper, SCR, buoy and tether with the following characteristics modeled composes a hybrid system:

• Depth of the sheet of water	1020 m
• Horizontal projection of jumper	200 m
• Horizontal projection of SCR	3000 m
• Length of the tether	920 m
• Buoyancy of the buoy	2563,1 kN
• Jumper length	800 m
• Jumper axial stiffness	416666,7 kN
• Jumper external diameter	0,324 m (10 “)
• Jumper linear weight	0,5567 kN/m
• Jumper normal drag coefficient	1,1
• Jumper tangential drag coefficient	0,0
• SCR length	3500 m
• SRC axial stiffness	3353000 kN
• SCR external diameter	0,2731 m (10”)
• SCR linear weight	0.6614 kN/m
• SCR normal drag	1,1
• SCR tangential drag coefficient	0,0
• Each segment length	1,0 m

In order to assure that the HIB3DGRAF tool supplies reliable results, it was made a comparison of the same model whose characteristics was previously described, with a computational program based on the Finite Element Method (JACOB, 2006) .

The surface current speed was varied in the marine surface in the values 0, 0.5, 0.8, 1.0, 1.3, 1.5 and 2.0 m/s, staying constant in 0 m/s at the seabed, characterizing a triangular current profile.

As comparison, the following parameters were chosen:

- Resulting force tension at the connection between the jumper and FPSO (Top);
- Resulting force tension at the connection between the jumper and the buoy (JumperBuoy);
- Resulting force tension in the connection between SCR and the buoy (SCRBuoy);
- Force tension in the tether (Tether);
- Longitudinal displacement of the buoy - Surge (xf);
- Traverse displacement of the buoy - Sway (yf);
- Vertical displacement of the buoy - Heave (zf).

There were created tables with the absolute and relative errors for comparison of the results. They were also generated graphs for evaluation of these results, in which it can be noticed the non linearity of this system and the coherence between the two kinds of analysis procedures (HIB3DGRAF and PROSIM).

5 MODEL SUBMITTED TO THE ACTION OF CURRENT PROFILES IN EAST DIRECTION

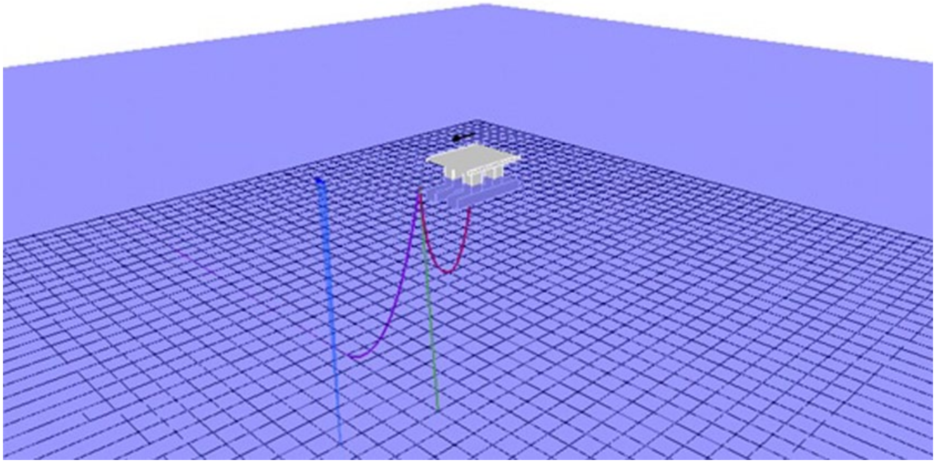
The model was submitted to several triangular current profiles aligned with the North direction.

As observed in Table 1, Ttop represents the tension force at the connection between jumper and FPSO, JumperBuoy corresponds to the tension force at the connection between jumper and buoy, SCRBuoy corresponds to the tension force between the SCR and buoy, and Tether, the tension force that acts on the tether of the hybrid system. The lines named x, y and z, are related to the static displacements of the sub surface buoy. The numeric differences obtained and treated as numeric error, can be considered despicable. The Figure 5 shows a three-dimensional configuration of the structural behavior based on the action of the current applied.

Table 1 – Aligned current with East direction.

Direction 0º (E)	Surface Vel.(m/s)	0,0	0,5	0,8	1,0	1,3	1,5	2,0
Top (KN)	PROSIM	257,55	257,42	257,06	256,42	254,49	252,31	243,15
	HIB3DGRAF	258,01	257,93	257,58	256,87	254,95	252,31	244,84
	relactive error (%)	0,18	0,20	0,20	0,18	0,18	0,00	0,70
	absolute error (KN)	0,46	0,51	0,52	0,45	0,46	0,00	1,69
JumperBuoy (KN)	PROSIM	199,91	199,53	198,80	197,90	195,35	192,82	183,64
	HIB3DGRAF	199,86	199,53	198,77	197,81	195,22	193,48	182,15
	relactive error (%)	0,03	0,00	0,02	0,05	0,07	0,34	0,81
	absolute error (KN)	0,05	0,00	0,03	0,09	0,13	0,66	1,49
SCRBuoy (KN)	PROSIM	771,77	763,92	751,97	741,22	721,61	706,75	668,04
	HIB3DGRAF	772,63	764,74	751,24	741,76	722,14	709,68	666,97
	relactive error (%)	0,11	0,11	0,10	0,07	0,07	0,41	0,16
	absolute error (KN)	0,86	0,82	0,73	0,54	0,53	2,93	1,07
Tether (KN)	PROSIM	1614,70	1626,80	1636,70	1650,10	1677,50	1701,10	1777,20
	HIB3DGRAF	1617,67	1626,17	1641,50	1653,72	1681,29	1696,43	1783,43
	relactive error (%)	0,18	0,04	0,29	0,22	0,23	0,27	0,35
	absolute error (KN)	2,97	0,63	4,80	3,62	3,79	4,67	6,23
x (m) (surge)	PROSIM	280,55	284,77	291,50	297,72	309,59	319,00	346,00
	HIB3DGRAF	279,78	284,09	292,00	296,98	308,47	319,31	345,00
	relactive error (%)	0,27	0,24	0,17	0,25	0,36	0,10	0,29
	absolute error (KN)	0,77	0,68	0,50	0,74	1,12	0,31	1,00
y (m) (sway)	PROSIM	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	HIB3DGRAF	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	relactive error (%)	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	absolute error (KN)	0,00	0,00	0,00	0,00	0,00	0,00	0,00
z (m) (heave)	PROSIM	-103,54	-103,91	-104,56	-105,20	-106,55	-107,72	-111,65
	HIB3DGRAF	-103,47	-103,85	-104,61	-105,13	-106,42	-107,61	-111,54
	relactive error (%)	-0,07	-0,06	-0,05	-0,07	-0,12	-0,10	-0,10
	absolute error (KN)	0,07	0,06	0,05	0,07	0,13	0,11	0,11

Figure 5 – A 3D View of the system (V=0,5m/s - East).



6 MODEL SUBMITTED TO THE ACTION OF CURRENT PROFILES IN NORTH DIRECTION

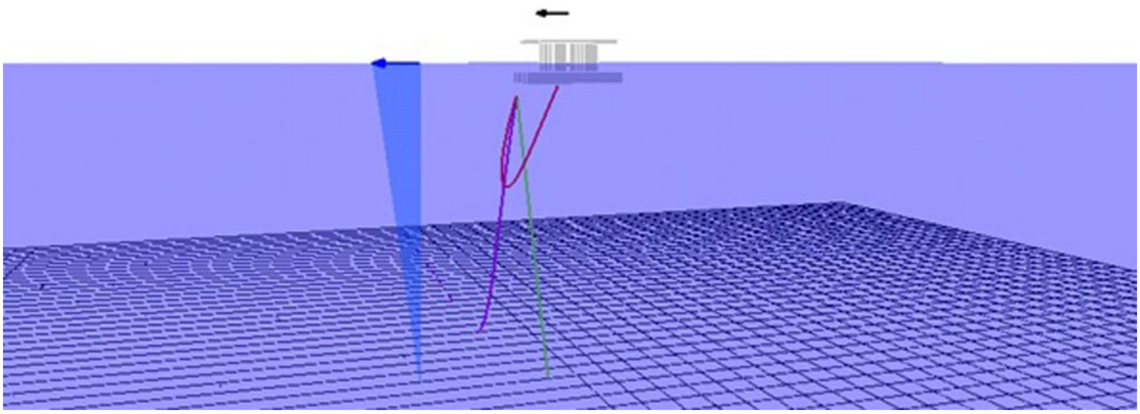
Once again the model was submitted to several triangular current profiles. At this time, current is aligned with North direction. The analysis results can be observed in Table 2.

Table 2 – Aligned current with North direction.

Direction 90º (N)	Surface Vel.(m/s)	0,0	0,5	0,8	1,0	1,3	1,5	2,0
Top (KN)	PROSIM	257,55	259,99	257,33	255,93	252,90	248,91	237,02
	HIB3DGRAF	258,01	257,91	256,88	256,35	253,42	250,15	238,98
	relactive error (%)	0,18	0,80	0,17	0,16	0,21	0,50	0,83
	absolute error (KN)	0,46	2,08	0,45	0,42	0,52	1,24	1,96
JumperBuoy (KN)	PROSIM	199,91	199,81	198,98	198,04	194,74	192,04	180,34
	HIB3DGRAF	199,86	199,73	199,05	197,74	194,06	190,05	175,81
	relactive error (%)	0,03	0,04	0,04	0,15	0,35	1,04	2,51
	absolute error (KN)	0,05	0,08	0,07	0,30	0,68	1,99	4,53
SCRBuoy (KN)	PROSIM	771,77	771,72	772,52	772,12	772,66	773,40	776,03
	HIB3DGRAF	772,63	772,70	771,89	772,26	771,85	771,36	770,54
	relactive error (%)	0,11	0,13	0,08	0,02	0,10	0,26	0,71
	absolute error (KN)	0,86	0,98	0,63	0,14	0,81	2,04	5,49
Tether (KN)	PROSIM	1614,70	1615,50	1620,76	1620,80	1631,60	1642,20	1683,70
	HIB3DGRAF	1617,67	1618,08	1617,20	1625,17	1637,96	1651,80	1702,81
	relactive error (%)	0,18	0,16	0,22	0,27	0,39	0,58	1,14
	absolute error (KN)	2,97	2,58	3,56	4,37	6,36	9,60	19,11
x (m) (surge)	PROSIM	280,55	280,52	279,80	280,64	280,77	280,80	280,46
	HIB3DGRAF	279,78	279,78	280,59	279,78	279,42	279,06	277,98
	relactive error (%)	0,27	0,26	0,28	0,31	0,48	0,62	0,88
	absolute error (KN)	0,77	0,74	0,79	0,86	1,35	1,74	2,48
y (m) (sway)	PROSIM	0,00	10,79	25,16	36,38	59,61	76,62	122,70
	HIB3DGRAF	0,00	10,06	23,79	38,82	63,97	82,66	129,22
	relactive error (%)	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	absolute error (KN)	0,00	0,73	1,37	2,44	4,36	6,04	6,52
z (m) (heave)	PROSIM	-103,54	-103,60	-103,81	-104,26	-105,49	-106,80	-111,77
	HIB3DGRAF	-103,47	-103,35	-103,84	-104,29	-105,67	-107,14	-112,46
	relactive error (%)	-0,07	-0,24	-0,03	-0,03	-0,17	-0,32	-0,62
	absolute error (KN)	0,07	0,25	0,03	0,03	0,18	0,34	0,69

As observed, the found numeric differences treated under form of numeric error, can be considered acceptable, being relevant just for currents with larger speeds than 1,5 m/s in the surface. The Figure 6 shows a three-dimensional configuration of the structural behavior based on the action of the current applied.

Figure 6 – 3D View (V=0,5m/s - North).



7 CONCLUSIONS

The new trends on petroleum exploitation for deep and ultra-deep waters, points to production systems based on floats and sub-surface buoys. At this new scenario, the hybrid riser system, suggests a technical and economical viable solution.

Starting up from this premise, it was herein presented, an analytical/numerical procedure to verify the static equilibrium of the forces that acts on the hybrid risers system. It was presented a formulation based on the tether inextensible principle that constitutes the HIB3DGRAF tool, for 3-dimensional structural analysis of hybrid risers systems based on sub-surface buoy concept, under marine current profiles. This computational tool makes possible the visualization of the 3-dimensional behavior of this kind of structural analysis seen in Figures 5 and 6. The comparison results with FEM structural analysis tool, has shown the efficiency of the formulation herein presented.

It can be concluded that the strategy considered here is intended to be an approach that will speed up the preliminary tasks involved in the design of hybrid risers systems based on the sub-surface buoy concept, which may eliminate the transient effects during a nonlinear dynamic finite element structural analysis and to facilitate de accuracy of the design of the marine structures destined oil and gas in deep and high deep water production.

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