SELF STANDING HYBRID RISER SYSTEM BEHAVIOR IN CURRENT AND WAVES

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Abstract. *Hybrid riser system concepts have being considered as an alternative offshore petroleum production for ultra-deep water depth applications up to 3000 meters. Among those, the Self Standing Hybrid Riser (SSHR) has been shown as an economical and technically feasible solution, particularly when high petroleum production rates are needed. Three main components compose this system: a vertical riser connected to the subsea well, a subsurface buoy close to the sea surface and a flexible riser connecting the buoy to a floating production facility. In the present study, dynamic behavior of a vertical riser suspended by a subsurface buoy, in tower configuration, is described by applying the Finite Element Method. Hydrodynamic loads due to currents and waves are assumed to act in one direction (in-line) and are described by the Morison Equation. Loads acting in the transverse direction due to vortex shedding are represented by a semi-empirical approach. In particular, the influence of buoy oscillations on the riser behavior is observed in the system dynamics. Results in terms of displacements are calculated around the connection between riser and buoy, and as a first attempt of the developed model, comparisons with available experimental results are also been carried.*

Keywords: *Offshore Riser, Sea Current, Vortex Induced Vibration*

1. INTRODUCTION

The hybrid riser system concept is being considered as an attractive option for ultra-deep water offshore petroleum production systems, particularly when high rates of oil and gas production are involved. Despite desirable performance of the overall concept, many problems still remain concerning the design of this type of riser system dealing with oil and gas production or exporting petroleum production.

One of the biggest challenges in the offshore industry is the prediction of the VIV response of deepwater risers and free spanning flowlines. In recent years, lot of works has been published on efforts to improve methods for calculating VIV effects and for free span pipelines (Suzuki and Maeda, 2000; Martins *et al.*, 2003; Morooka *et al.*, 2006). Flow induced vibration was investigated by Blevins (1977), and Bearman and Zdravkovich (1978) which demonstrated hydrodynamics of a rigid cylinder close to a wall. Bruschi *et al.* (1989) performed full scale measurement of free span pipeline response. Two dimensional (2D) solutions of the Navier-Stokes equation were combined with the application of a 3D beam model by Halse and Larsen (1998). Important contributions to the understanding of the VIV effect in free span pipelines have also been published by Huse *et al.* (2002) and Nielsen *et al.* (2002). Interaction between adjacent spans is studied by Koushan and Larsen (2003). In addition, many experiments have been carried out and results of different semi-empirical and CFD models are compared by Chaplin *et al.* (2005). Moreover, the influence of strakes in VIV and the vibrations in catenary and tensioned risers induced by VIV is studied by Vandiver (2006).

Champi *et al.* (2005) carried out analytical investigations for the vertical component of the Self Standing Hybrid Riser (SSHR) system (Figure 1), and observed the dynamics of the structure in terms of maximum and minimum motions for different current velocities and wave periods. Parametric analysis for a SSHR, which has a rigid vertical riser and a subsurface buoy, submitted to different currents, waves and combinations for both were performed by Pereira *et al.* (2006a). The effects of the current velocity, subsurface buoy geometry, wave period, hydrodynamics coefficients (drag, added mass and lift) and the presence of internal fluid on the dynamic behavior of the riser structure were verified. Results were shown in terms of maximum and minimum envelops of displacement. Moreover, it was demonstrated that the buoy exerts a great influence on the SSHR dynamics, thus needing special attention.

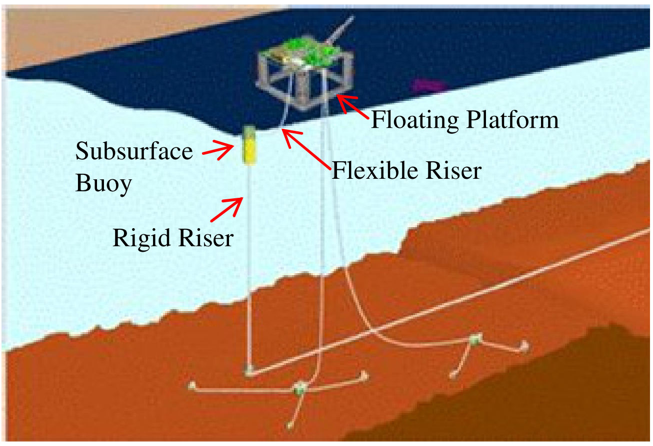

Figure1. Self Standing Hybrid Riser System Schematics.

Pereira *et al.* (2006b) observed the subsurface buoy oscillations influence on riser behavior and numerical and experimental results were compared, regarding the tower configuration of a SSHR. Loads due to waves and current in the in-line direction and due to vortex shedding in the transverse direction were considered. In order to solve the system's dynamics in the numerical solution, the subsurface buoy is modeled as a beam element. It was observed optimum buoy geometry for a specific environmental loading to minimize the vortex shedding effect in the transverse direction should exist. In addition, the numerical solution was in good agreement with the experimental results for both in-line and transverse directions.

In the present work, the dynamic behavior of the SSHR in the tower configuration for ultra-deep water depth is described with respect to the in-line and transverse directions of the system. Comparisons have been carried out between numerical solutions and experimental results available in terms of maximum displacement amplitudes. Numerical solutions are performed in time domain and discussions are mainly focused on riser vortex induced vibration (VIV). Experiments concluded at the Deep-Sea Basin of National Maritime Research Institute (NMRI), described by Tamura (2005) and Pereira *et al.* (2005) have been used in the comparative analysis.

2. METHODOLOGY

In the present work it is considered that the rigid vertical riser is a slender tubular element with axial and flexural stiffness (Ferrari Jr. *et al.*, 1999; Martins *et al.*, 2003). The subsurface buoy is modeled as a riser element, although buoy main dimensions and its geometry had been considered to calculate hydrodynamic effects. The behavior of the Euler-Bernoulli beam riser element in the in-line and transverse directions are described by Equation (1) and Equation (2), respectively (Chakrabarti and Frampton, 1982). To reach these equations, it is assumed for the riser: small deflections, unstretched and normal to neutral plane.

$$\frac{d^2}{dz^2}\left(EI\frac{d^2x}{dz^2}\right)-(T+p_0A_0-p_iA_i)\frac{d^2x}{dz^2}-(\gamma_sA_s-f_z+\gamma_iA_i-\gamma_0A_0)\frac{dx}{dz}+m\ddot{x}=f_x \tag{1}$$

$$\frac{d^2}{dz^2}\left(EI\frac{d^2y}{dz^2}\right)-(T+p_0A_0-p_iA_i)\frac{d^2y}{dz^2}-(\gamma_sA_s-f_z+\gamma_iA_i-\gamma_0A_0)\frac{dy}{dz}+m\ddot{y}=f_y \tag{2}$$

where, x and y are the in-line and transverse displacement of the riser, respectively, $\ddot{x}$ and $\ddot{y}$ are the accelerations, z is the vertical coordinate of the riser, EI represents the bending stiffness of the riser, T represents the axial tension, p_i is the internal hydrostatic pressure, p_0 is the external hydrostatic pressure around the riser, A_i is the internal area, A_0 is the cross-sectional area of riser, A_s is the cross-sectional area of rigid riser wall, γ_i is the specific weight of the fluid in the riser, γ_0 is the specific weight of sea water, γ_s is the specific weight of riser wall, m is the mass of the segment including added mass per unit length, f_x, f_y and f_z are the forces per unit length in the in-line, transverse and vertical directions, respectively.

Waves and current loads cause forces that act in the in-line and transverse directions. The in-line force per unit length is calculated by the semi-empirical Morison's Equation, as described in Eq. (3). The transverse force per unit length is represented by Eq. (4) and it is composed by a force due to vortex shedding and the fluid reaction (Ferrari & Bearman, 1999; Martins *et al.*, 2003).

$$f_x = A_I \dot{u} + C_D A_D |V_r| (u + U_c - \dot{x}) + C_A A_I (\dot{u} - \ddot{x}) \quad (3)$$

$$f_y = f_{VIV} - C_D A_D |V_r| \dot{y} - C_A A_I \ddot{y} \quad (4)$$

where, C_A, and C_D are added mass and drag coefficients, respectively, u and $\dot{u}$ are the wave velocity and acceleration calculated by the Linear Airy Wave Theory, U_c is the current velocity, $\dot{x}$ and $\dot{y}$ are the structure velocity in the in-line and transverse directions, respectively, V_r is the relative velocity given by $|V_r| = \sqrt{(U_c + u - \dot{x})^2 + \dot{y}^2}$ which represents the coupling between the in-line and transverse motions through the fluid, $A_I = \frac{\pi D^2 \rho_0}{4}$ and $A_D = \frac{1}{2}\rho_0 D$, ρ_0 is the density of sea water and D is the external diameter of the riser.

When there is flow around the riser transverse cross-section, difference of pressure occurs and causes vortex induced vibration. This difference of pressure also causes separation of the flow on the riser's external surface resulting in vortex shedding. The VIV force per unit length that acts on the structure is given by Eq. (5), which was proposed by Bearman *et al.* (1984).

$$f_{VIV} = \frac{1}{2}\rho_0 D\left[(u - \dot{x}) + U_c\right]^2 C_L \cos(2\pi f_s t + \varphi) \quad (5)$$

where, C_L is the lift coefficient, f_s is the mean frequency of the vortex shedding given by $f_s = \frac{|\overline{U}| St}{D}$, St is the Strouhal number which is considered constant and equal to 0.2 in this work, $\overline{U}$ is the mean oscillatory flow velocity given by $\overline{U} = \frac{1}{t}\int_0^t U dt$, U is the instantaneous oscillatory flow velocity and φ is the phase difference between the transverse riser response and hydrodynamic force in the transverse direction.

The system's dynamic behavior in the in-line and transverse directions is represented in matrix form by the Equations (6) and Eq. (7), respectively.

$$[M]\{\ddot{x}\} + [B]\{\dot{x}\} + [K]\{x\} = \{F_x\} \quad (6)$$

$$[M]\{\ddot{y}\} + [B]\{\dot{y}\} + [K]\{y\} = \{F_y\} \quad (7)$$

where, $[M]$ is the structure mass matrix (riser, fluid inside the pipe and added mass), $[B]$ is damping matrix (given by the Rayleigh's Method), $[K]$ is the global stiffness matrix, $\{F_x\}$ and $\{F_y\}$ are the excitation force in the in-line and transverse directions, respectively. A quasi 3D approach is used to solve the dynamic behavior of the system.

3. RESULTS AND DISCUSSIONS

The main dimensions of the studied system are shown in Table 1. Dimensions in model scale (1:100) applied in the experiments (Tamura *et al.*, 2005; Pereira *et al.*, 2005) are reproduced in the Table 1, as reference for the analysis. Parameters in the numerical calculations are shown in prototype scale. Results are presented in terms of maximum motion amplitude for the in-line and transverse directions in model scale and the static offset are not represented. Figure 2 shows a scheme of the studied configuration in the experiment which is a riser tower configuration submitted to a constant current profile in water depth range from 0.5 to 2.0 m. The vortex shedding on the riser and buoy are also taken into account.

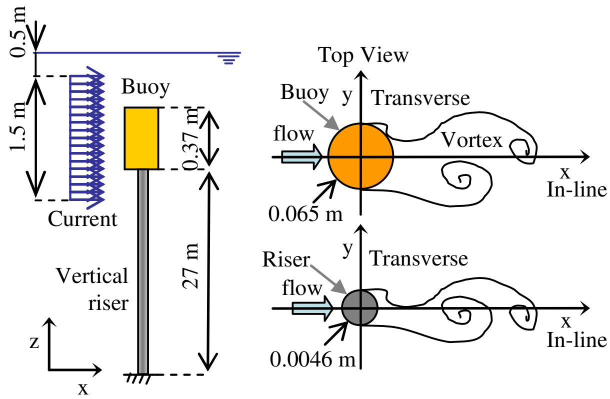

Figure 2. Experimental System Schematics.

Table1. Main parameters of the system.

Parameters	**Experimental**	**Prototype**
Water Depth [m]	28	2800
Density of Water [kg/m^3]	1000	1025
$C_D - C_A - C_L$	1.0 – 1.0 – 1.0	1.0 – 1.0 – 1.0
Subsurface Buoy		
Length [m]	0.37	37
External Diameter [m]	0.064	6.4
Density [kg/m^3]	248.24	248.24
Rigid Vertical Riser		
Length [m]	27	2700
External Diameter [m]	0.0046	0.46
Internal Diameter [m]	----	----
Density [kg/m^3]	1740	1740
Young's Modulus [kPa]	8.23 x 10^5	8.23 x 10^7

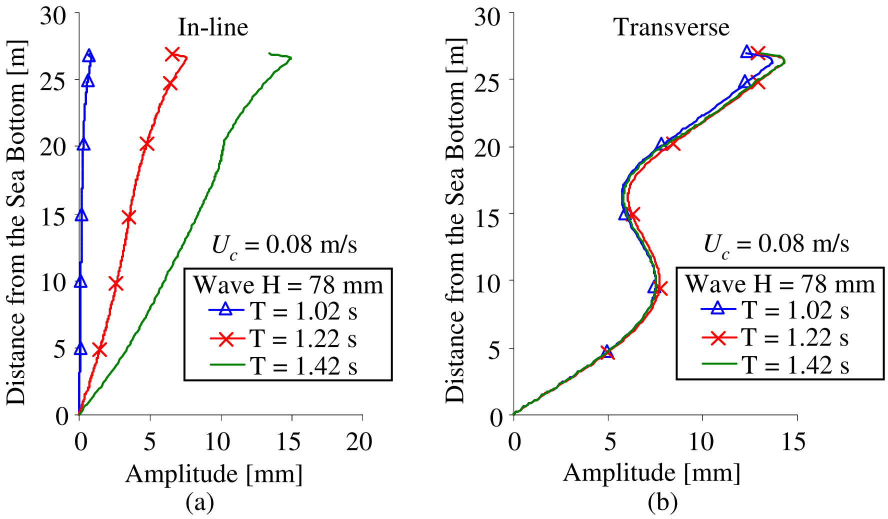

Figure 3. Maximum motion amplitude due to a constant profile current acting on 0.5-2 m water depth range and a regular wave with different periods. (a) In-line direction. (b) Transverse direction.

As mentioned before, the response of the structure in the tower configuration submitted to only current with different velocities has been studied (Champi *et al.*, 2005). In the transverse direction it was observed that the motion amplitude decreases when the current velocity increases. In addition, for cases where only loads due to waves with different periods act on the structure, the motion amplitude in both directions increases when the period wave increases.

Figure 3 represents results from the numerical simulation for a riser in the tower configuration submitted to a current velocity of 0.08 m/s and regular wave with 78 mm amplitude and three different wave periods. Figure 3 (a) is the in-line response and Figure 3 (b) corresponds the transverse response. The vertical axis is the distance from the sea bottom, while the horizontal axis represents the maximum motion amplitude. It is possible to observe that the motion amplitude increases when the wave period increases.

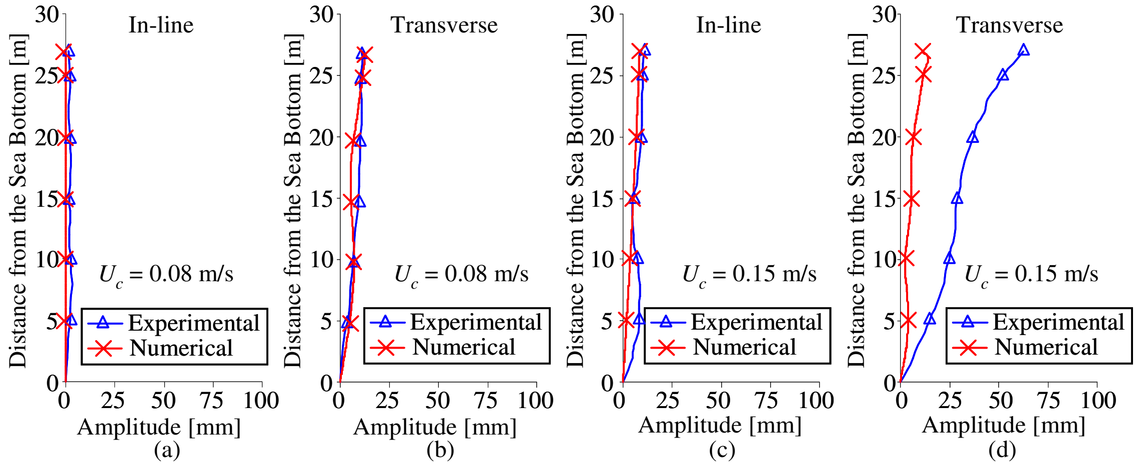

Figure 4. Comparisons between numerical and experimental maximum motion amplitude due to a constant profile current acting on 0.5-2 m water depth range.

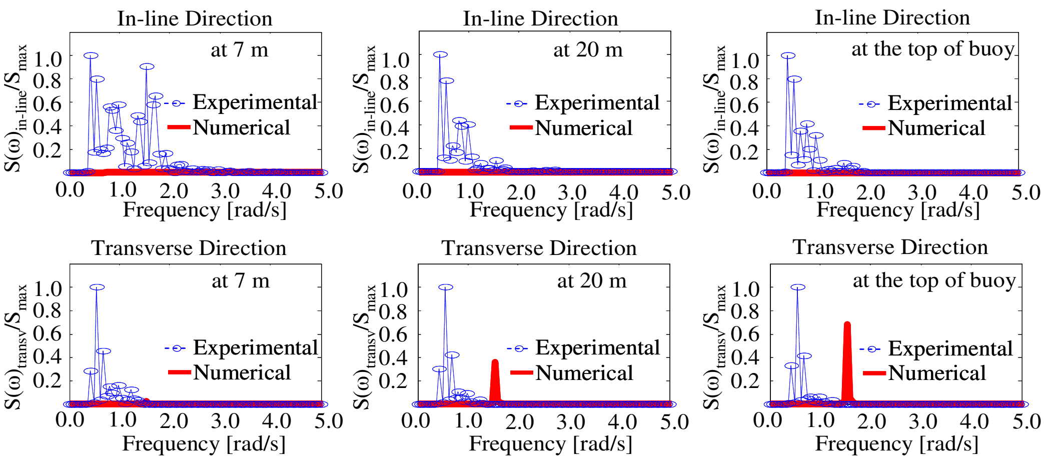

Figure 5. Non dimensional energy spectra for the in-line and transverse directions. Constant current velocity profile of 0.08 m/s between 0.5 and 2 m of water depth.

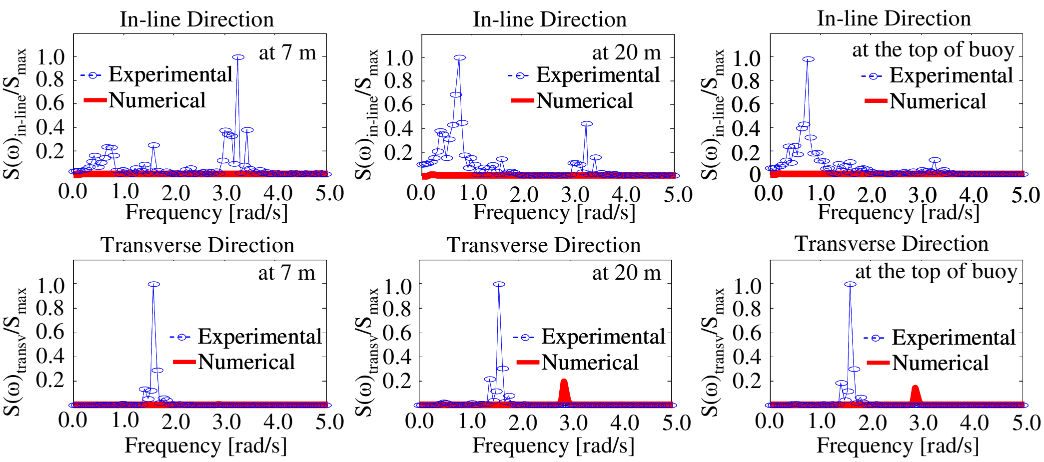

Figure 6. Non dimensional energy spectra for the in-line and transverse directions. Constant current velocity profile of 0.15 m/s between 0.5 and 2 m of water depth.

Figure 4 describes the comparison between the numerical solution and the experimental results for the same riser in tower configuration submitted only to two different constant profiles current velocities: 0.08 m/s and 0.15 m/s. The line with cross mark shows the numerical results and the line with triangle mark is the experimental results. Figures 4 (a) and (b) correspond to the maximum in-line and transverse motion amplitude for a current velocity of 0.08 m/s, while the Figures 4 (c) and (d) for a current velocity of 0.15 m/s. It can be observed an agreement with the experimental results. As expected, the motion amplitude in the in-line direction is smaller than that in the transverse. The in-line vibration is a consequence of the relative velocity (*Vr*) in this direction, which is very small once the system is submitted only to current (static load). The amplitude of the relative velocity oscillation is bigger when waves are considered.

Figures 5 and 6 represent energy spectra for motion amplitude at three points on the structure of a riser tower system submitted to a 0.08 m/s and 0.15 m/s current velocity, respectively. The points considered are located 7 m and 20 m from the sea bottom and at the top of the buoy, and was calculated for the in-line and transverse direction. The energy spectra for motion amplitude were divided by the maximum experimental result (S_{max}) in each case, which means that the maximum value obtained is a unit. Frequency, shown in rad/s, is on the horizontal axis. The solid line represents a response from the numerical analysis and the dashed line with circles represents the experimental results. The in-line hydrodynamic force considers the drag and the inertia effects. From comparisons, it is observed that there is a discrepancy between the numerical simulations and the experimental results in both Figures. It could happen due to difficulties for modeling hydrodynamic forces involved, and perhaps, it could be improved considering coupling effects between transverse and in-line riser cylinder motions with the current and waves, in the numerical simulations. Further, the peak frequency of the numerical simulations result set in comparison the calculated shedding frequency, as it was expected. In the numerical simulation, the Strouhal number is calculated for a static rigid cylinder while in the experiments the riser cylinder is in motion. It is important predict precisely these frequencies once the period of motion is very important in lifetime service calculations.

4. CONCLUSIONS

Numerical simulation results for a self standing hybrid riser system have been compared with experiment for amplitudes of riser and subsurface buoy displacements and motions, and good agreement between results have been observed. From comparisons, maximum motion amplitudes increase when wave period increases, in waves and currents.

Flow-induced oscillation in the in-line direction for the riser dynamics in current is very important and more investigation is still demanded.

From the results, riser motion peak frequency in the transverse direction from the numerical simulation is close to the experiment and corresponds to the shedding frequency. However, improved understanding of a riser moving against the fluid is still needed in order to describe precisely the vortex shedding effects (VIV). This riser behavior is very important for lifetime service predictions.

Finally, results obtained from the present study correspond to an important step in the development of a numerical simulation model for the dynamic behavior of a SSHR. Furthermore, consideration of jumper and irregular wave effects are also aim for future works.

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