DYNAMIC POSITIONING OF FLOATING PLATFORM COUPLED WITH A DRILLING RISER

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For the drilling of petroleum wells in deep and ultra deep, the use of floating platforms such as semi-submersible platforms and drillships is necessary. The platform is connected to the well by the drilling riser. This riser is a rigid and vertical orientated pipe wherein the drillstring moves through and the drilling mud returns to the platform.

This paper presents a study of the influence of platform displacements on the riser behavior. The dynamics of a semi-submersible platform coupled with a drilling riser in ultra deep water is featured. A nonlinear system equation is used to represent the platform dynamics. In addition, the Dynamic Positioning System (DPS) that is responsible to keep the platform stationary is also included in the numerical model. Furthermore, the mechanical behavior of the drilling riser is modeled using the Finite Element Method (FEM). Environmental loads like current and waves are also included in both dynamical systems: floating platform and drilling riser.

In ultra deep water, a special attention must be paid on the stresses and the bending moments of the riser. These stresses and moments are caused mainly by hydrodynamics forces on the riser and the platform displacements at the top end of riser. One of the hydrodynamics loads is oscillatory and caused by the vortices shedding around the pipe denoted Vibration Induced by Vortices (VIV).

Numerical simulations in time domain have been carried out. Simulation results in time domain of the platform displacements with DPS and riser displacement are shown. Discussions in terms of environmental loads and riser and platform displacements are also included.

Platform Dynamics, Riser Dynamics, Dynamic Positioning System, Offshore Drilling

1. INTRODUCTION

The Exploration & Production (E&P) of offshore petroleum fields has been carried out since the late 1800's. However, in the last thirty years, the E&P has increased strongly especially off the Brazilian Coast, the Gulf of Mexico and the West Africa. The E&P in deep and ultra deep water requires the use of floating platform such as semi-submersible platforms and drillships.

The drilling of offshore petroleum wells is realized in four phases. In the first two phases are drilled without drilling riser and BOP. The platform is connected to the well through the drillstring (Figure 1-a). Before the last two phases can proceed, the BOP and drilling riser must be installed (Figure 1-b). Then the last two phases are drilled (Figure 1-c).

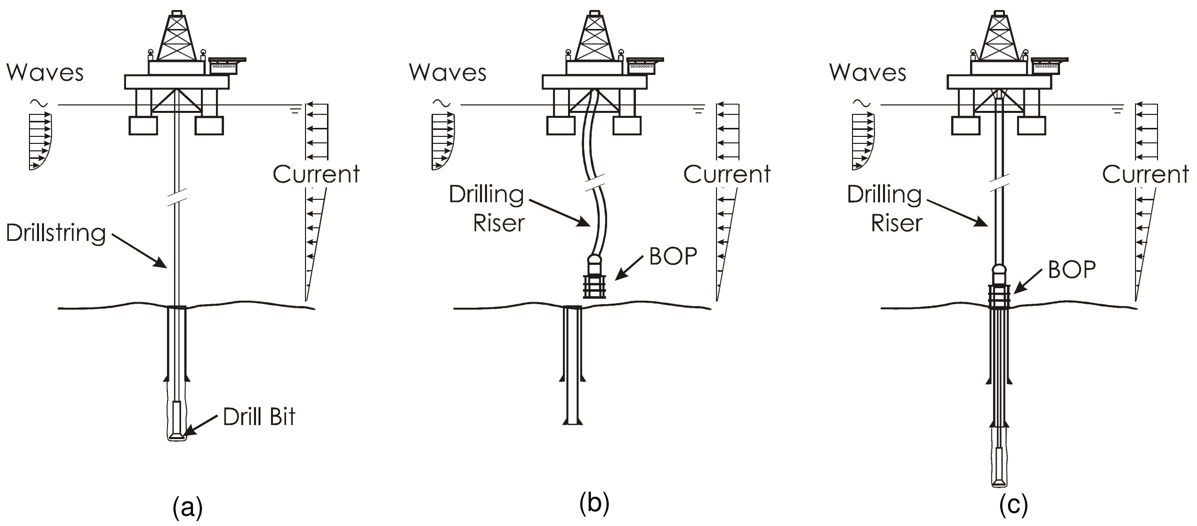


Figure 1. (a) 2nd drilling phase; (b) re-entry operation; (c) 3rd drilling phase.

The floating platform must be kept stationary at the sea surface above the well location in order to accomplish drilling, completion and/or workover operations. In deep and especially in ultra-deep water, a Dynamic Positioning System (DPS) is utilized to keep the platform stationary (Yamamoto *et al.*, 2003). The DPS is a feedback control system that controls the platform position. It receives the platform position data from a sensor system, and then controls the thrusters installed on the bottom of the platform hull (Figure 2), bringing the platform back to the desired location.

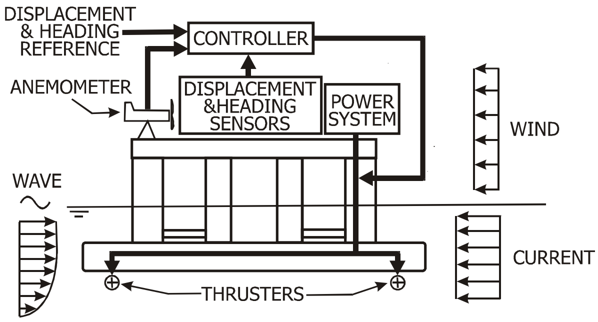


Figure 2. An example of DPS.

In Yamamoto & Morooka (2007), a BOP position control system was featured. This feedback control system intends to control the BOP position acting on the platform position through the DPS (Figure 5). This paper includes the results of numerical calculations about the re-entry operation to a subsea well in ultra-deep water. During this operation, a piece of safety equipment called a Blow-Out Preventer, or BOP, is lowered down to the sea bottom attached to the drilling riser. The objective of this operation is the approximation, and later the connection of the BOP on to the wellhead (Figure 1-b).

2. EQUATIONS OF MOTION

This section presents mathematical models for the dynamics of both the floating platform and drilling riser.

2.1 Dynamics of a Floating Platform

In this work, the integral-differential equation proposed by Cummins (1962) is used as the mathematical model for the dynamics of each degree of freedom for the floating platform, as shown by Equation 1.

$$(M+m)\cdot\ddot{x}+\int_{-\infty}^{\infty}K(t-\tau)\cdot\dot{x}(\tau)\cdot d\tau+B\cdot|\dot{x}|\cdot\dot{x}+C\cdot x=F_T \tag{1}$$

In the above equation, x is the platform displacement; M represents the platform mass; m is the constant added mass calculated by Equation 2; K is the impulse response function calculated Equation 3; B is the platform viscous damping coefficient; C is the hydrostatic restoration coefficient that is zero for surge, sway, and yaw, and non-zero for heave, roll and pitch; F_T is the resulting force acting on the platform.

$$m=a(\omega)+\frac{1}{\omega}\cdot Im\left[\int_{-\infty}^{\infty}K(t)\cdot e^{i\cdot\omega\cdot t}\cdot dt\right] \tag{2}$$

$$K(t)=\frac{2}{\pi}\cdot Re\left[\int_{-\infty}^{\infty}b(\omega)\cdot e^{i\cdot\omega\cdot t}\right] \tag{3}$$

In the above equations, a is the platform added mass depending on the movement frequency; b is platform damping coefficient depending on the movement frequency; and ω is the frequency. The current loads on the platform are obtained using Equation 3.

$$F_D = 0.5 \cdot \rho \cdot C_D \cdot A \cdot |U_C - \dot{x}| \cdot (U_C - \dot{x}) \tag{4}$$

where, F_D is the drag force on the platform caused by the current; ρ is the fluid density; C_D is the drag coefficient; A is the platform exposed area; U_C is the current velocity; and $\dot{x}$ is the platform velocity.

In the present study, the interaction of wakes and vortices due to the fluid flow around the platform columns and pontoons are neglected. Furthermore, the platform was divided into elementary shapes in order to evaluate the overall platform drag coefficient similar to DnV (1977).

According to Dalzell (1976), wave loads can be modeled as the first two terms of Volterra series, as shown in Equation 5.

$$F_W(t) = \int_{-\infty}^{\infty} h_1(\tau) \cdot \zeta(t-\tau) \cdot d\tau + \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} h_2(\tau_1, \tau_2) \cdot \zeta(t-\tau_1) \cdot \zeta(t-\tau_2) \cdot d\tau_1 \cdot d\tau_2 \tag{5}$$

In the above equation, F_W is the forces due the wave's action; h_1 and h_2 are the impulse response function for the 1st and 2nd orders, respectively, obtained by Equation 6; and ζ is the wave elevation.

$$h_1(t) = \frac{1}{2\pi} \cdot \int_{-\infty}^{\infty} H_1(\omega) \cdot e^{i \cdot \omega t} \cdot d\omega \tag{6.a}$$

$$h_2(t_1, t_2) = \frac{1}{(2\pi)^2} \cdot \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} H_2(\omega_1, \omega_2) \cdot e^{i \cdot (\omega_1 \cdot t_1 - \omega_2 \cdot t_2)} \cdot d\omega_1 \cdot d\omega_2 \tag{6.b}$$

Where H_1 and H_2 are the first and second order transfer functions, respectively, for wave loads in frequency domain.

Thruster forces can be expressed as a first-order system, in Time Domain (Zunderdorp and van der Vlies, 1972), as in the Equation 7.

$$E_C(t) = E(t) + \tau_T \cdot \frac{dE}{dt} \tag{7}$$

Here, a time constant of 5.0s has been adopted. The reduction of thruster force by current influx is not taken into account in the simulations.

2.2 Mechanical Behavior of the Drilling Riser

A drilling riser can be modeled as a slender tensioned beam with transverse loads acting due to the effects of hydrostatic and hydrodynamics pressure (Morooka *et al.*, 2003; Martins *et al.*, 2003).

Figure 3 shows the static equilibrium of an infinitesimal element of the riser. Equation (8) describes the deflection of the element.

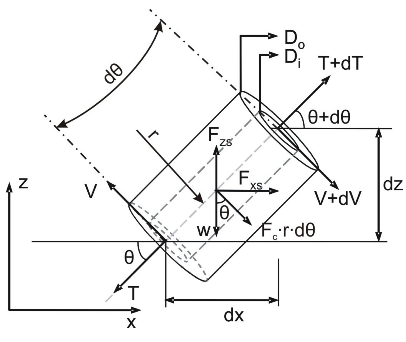


Figure 3. Infinitesimal element of riser.

$$\frac{d^2}{dz^2}\left(EI \cdot \frac{d^2 x_S}{dz^2}\right) - (T + A_0 \cdot P_0 - A_I \cdot P_I) \cdot \frac{d^2 x_S}{dz^2} - [\gamma_S \cdot (A_0 - A_I) - F_{ZS} - A_0 \cdot \gamma_0 + A_I \cdot \gamma_I] \cdot \frac{dx_S}{dz} = F_{XS} \tag{8}$$

where, x_S is the riser displacement; z is the riser height; EI is the bending stiffness; T is the axial tension of the riser; A_0 (A_I) is the external (internal) cross sectional area of the riser pipe; P_0 (P_I) is the external (internal) pressure acting on the riser pipe wall; γ_S is the specific weight of the riser material; γ_0 (γ_I) specific weight of the external (internal) fluid; and F_{ZS} (F_{XS}) is the resulting forces in vertical (horizontal) direction of the riser.

Conventions for the directions of loads and displacements of the riser need to be established. Therefore, the direction parallel to the flow is referred as in-line, and the direction perpendicular to the flow is called the transverse direction.

The solution of Eq. (8) is obtained by using the weak approach to the Galerkin formulation for Finite Elements Method, and this solution is used as a stiffness matrix in the Eq. (9) (Morooka et al. 2003; Martins *et al.*, 2003).

The in-line load is estimated by the modified Morison Equation (Morooka et al. 2003; Martins *et al.*, 2003). The transverse load is mainly due to the shedding of alternating vortices from the flow around a circular cross sectional pipe, which causes a sinusoidal load on the pipe (Sarpkaya and Isaacson, 1981). This transverse load phenomenon results in displacements in elastic pipes, and it is usually named Vortex Induced Vibration (VIV). Special care must be paid to that sinusoidal vibration in the transverse direction of a pipe, because it can reduce the service life of risers due to fatigue (Morooka et al., 2005). In this paper, the transverse load is described in terms of the semi-empirical approach proposed by Ferrari & Bearman (1999).

Furthermore, the structure of the riser is divided into finite elements, with their masses concentrated at the nodes. The dynamic behavior of the riser can be obtained for the in-line and transverse directions by Equation 9 which reproduces three-dimensional dynamics.

$$\mathbf{M} \cdot \ddot{\mathbf{x}}_S + \mathbf{B} \cdot \dot{\mathbf{x}}_S + \mathbf{K} \cdot \mathbf{x}_S = \mathbf{F}_S \qquad (9)$$

Further details regarding the riser dynamics can be found in Morooka *et al.* (2003) and Martins *et al.* (2003).

The connection of the upper end of the riser and the floating platform is taken to be through the center of gravity of the platform, and the riser reaction on the platform is assumed to be equal to the riser's shear force at its upper end. This shear force is added to term F_T of Equation 1 (Morooka & Yamamoto, 2006).

2.3 Dynamic Positioning Control System

The Dynamic Positioning System (DPS) is applied for the 3 degrees of freedom (surge, sway, and yaw) where the hydrostatic restoration forces are null in order to vanish the drift in those directions. The DPS is a feedback control for the platform displacement in the horizontal plan, as shown in

Figure **4**.

Furthermore, the additional feedback loop, proposed by Yamamoto, Morooka & Ueno (2007), to control the BOP positioning has been applied in this work (Figure 5).

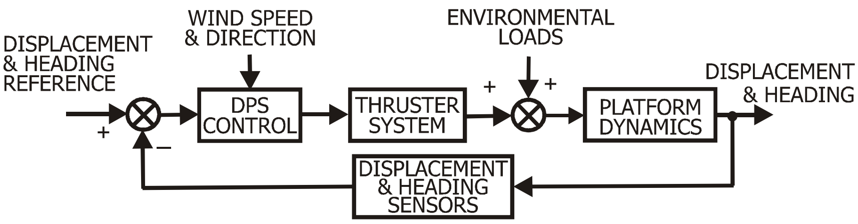


Figure 4. Block diagram of a Dynamic Positioning System.

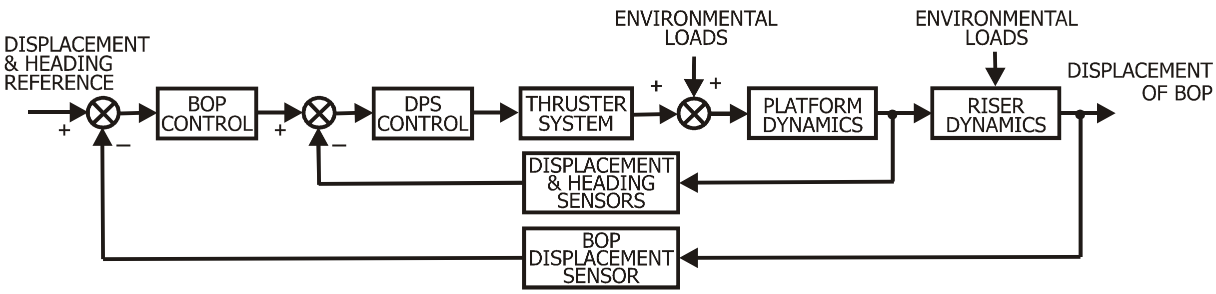


Figure 5. Block diagram of the feedback control system for the BOP position.

In this work, the Linear Quadratic Regulator (LQR) is used as a control law for both the DPS and BOP position control system. The LQR is an algorithm that determines the gain vector for optimal control using State Space Model which minimizes the quadratic cost function J (Equation 10) through the Riccati's Equation. For more details, see Stengel (1994).

$$J = \int_0^\infty \left[\mathbf{x}^\mathrm{T} \cdot \mathbf{Q} \cdot \mathbf{x} + \mathbf{u}^\mathrm{T} \cdot \mathbf{R} \cdot \mathbf{u}\right] \cdot dt \qquad (10)$$

where, J is the quadratic cost function; **x** is the state vector; and **u** is the control vector.

4. RESULTS

The standard semi-submersible platform of the International Towing Tank Conference (ITTC) was used for the numerical simulations (Figure 6). This semi-submersible platform has two pontoons, each one with a length of 115 m, width of 15 m and height of 8 m. The platform has a total of eight vertical columns, with diameters of 10 m for the four external corner columns, and 8 m for the four central columns.

The riser properties and its main dimensions used in the simulations are shown in the Table 1. The BOP in the simulations weighs 300 ton with its mass assumed to be concentrated at the lower most element of the riser. Simulations have been carried out in time domain, and the results for the coupled floating platform and riser dynamics by applying the proposed system were obtained.

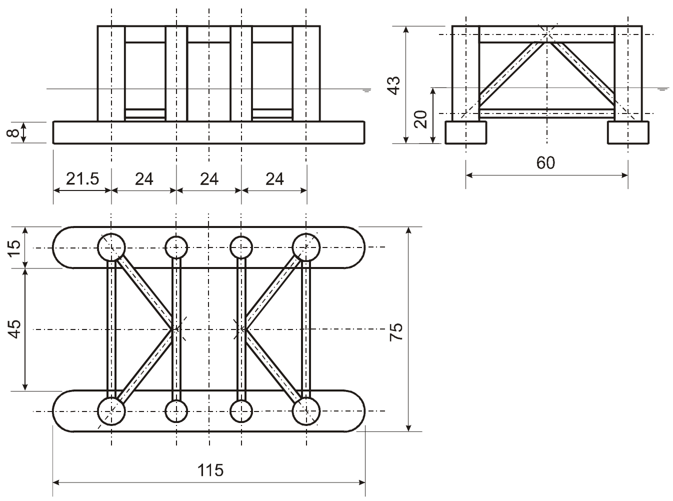


Figure 6. The ITTC standard semi-submersible platform.

Table 1. Riser properties

External Diameter	0.533 m
Internal Diameter	0.486 m
Young's Modulus	210 MPa
Material Density	7860 kg/m^3
Drilling Mud Density	1198.2 kg/m^3 (10 ppg)

Furthermore, an additional external feedback loop was used to control the BOP position (Figure 5). An integral term has been also added to the external feedback loop, in order to reduce observed stationary error, which is particularly evident in the presence of high current velocities.

The first results (Figure 7) show the platform and BOP displacement with a riser with a length of 3000 m of length and it will be the reference case for the next results with environmental loads. In this case, no environmental loads are taken in account. There is an input signal (reference), in the sway direction, with a step shape of 40 m which the BOP should follow. The platform moves to the reference towing the BOP. Before it reaches the reference, the platform decelerates and the BOP reaches the desired location. Figure 8 shows the effects of the VIV on the BOP displacement in the direction perpendicular to the platform surge. The VIV effect on the platform displacement in the surge direction can be neglected.

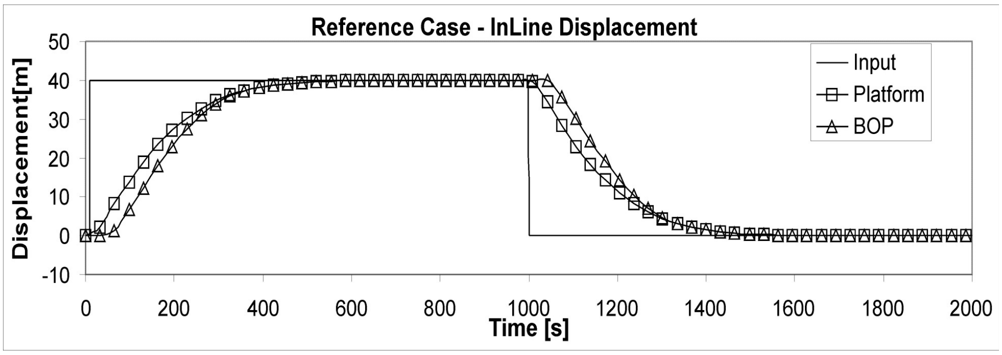


Figure 7. Platform and BOP displacements without environmental loads.

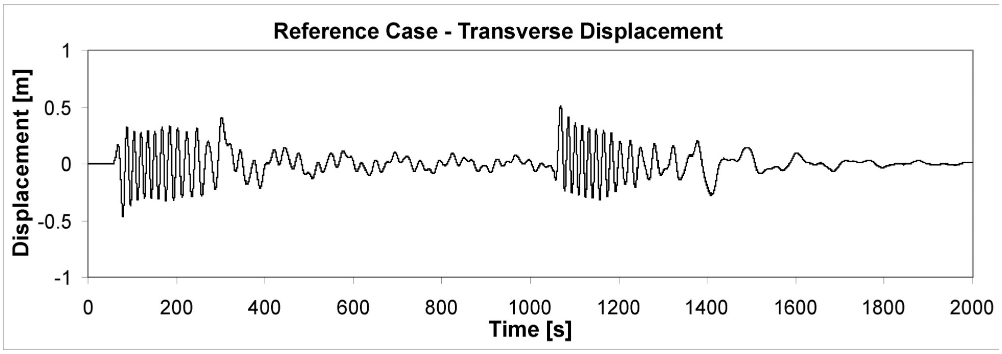
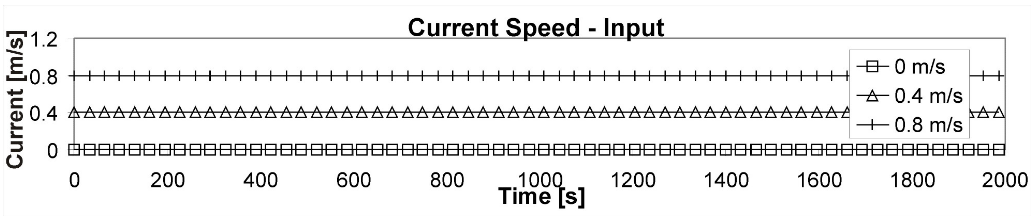
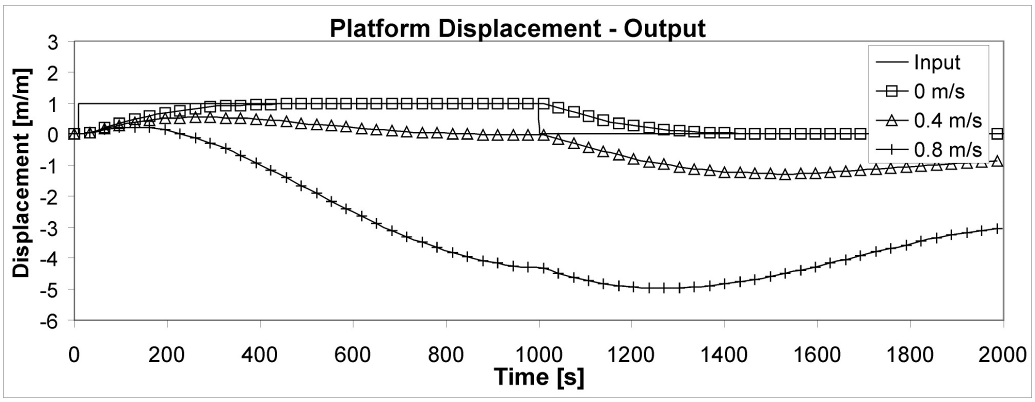


Figure 8. BOP displacement due to VIV in the surge direction.

Figure shows the effect of constant current from the sea bottom up to the sea surface acting on the platform and entire riser. The graph features the dimensionless BOP displacements for three different current speed including the 0 m/s which is the comparison reference.

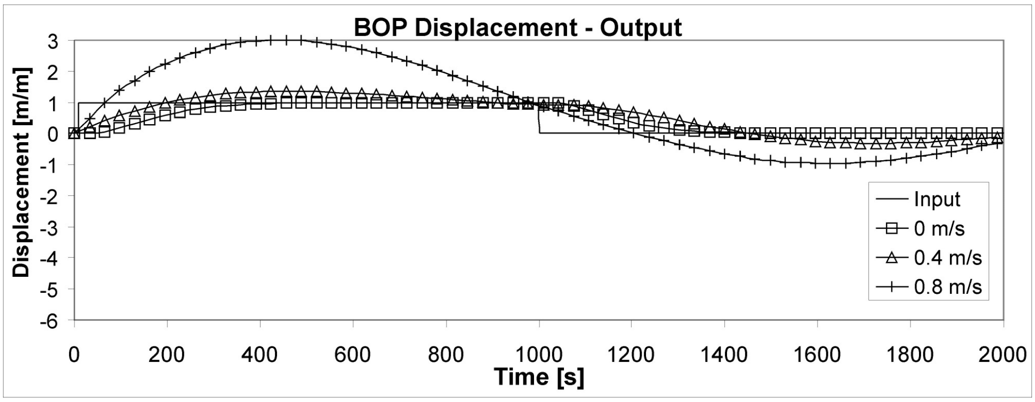


(a)



(b)

Figure 9. Current input (a) and dimensionless platform displacement (b) for different current conditions.



(c)

Figure 9. Current input (a); dimensionless platform displacement (b) and BOP displacements (c) for different current conditions.

In order to quantify the performance of the BOP position control system, the quadratic error index is used (Equation 11).

$$I = \int_{t_0}^{t_f} \left[r(t) - x(t) \right]^2 \cdot dt \qquad (11)$$

The index is the time integral of the square of the difference between the input signal *r* and the BOP position *x*. Figure 10 shows the index for different current velocity, normalized with the current of 0 m/s. The current has a significantly effect on the performance because probably the current bends the riser which changes the riser's shape and dynamical system.

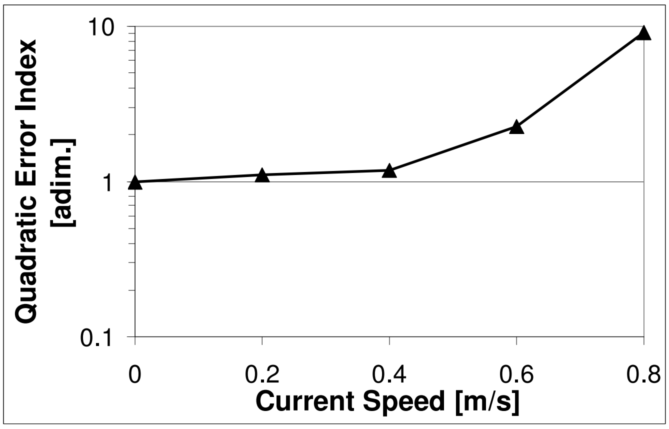


Figure 10. Quadratic Error Index for different currents.

Figure 11 shows the dimensionless BOP displacements under the effects of a regular wave of the 4 m height at different wave periods for the same riser length of the previous case.

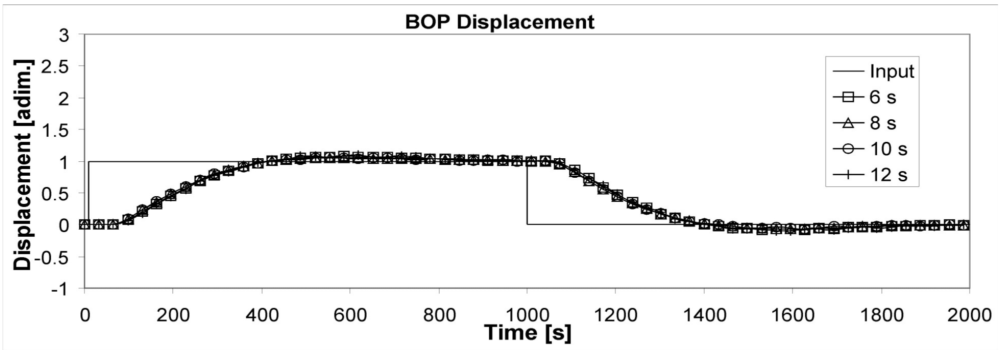


Figure 11. BOP displacements for different wave's frequencies.

The Quadratic Error Index (Equation 11) is used to verify the influence of a regular wave on the BOP position control system. The index was evaluated for two different wave heights and for the periods between 5 s and 30 s (Figure 12). Figure 13 shows the wave elevation, platform and BOP displacements for the 4 wave periods of the Figure 11. The influence of the waves on the BOP position control system is smaller than the current because the forces of the waves are stronger at the sea surface.

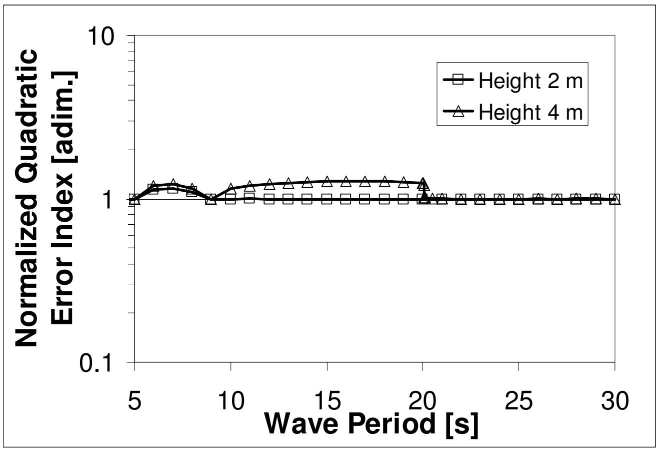
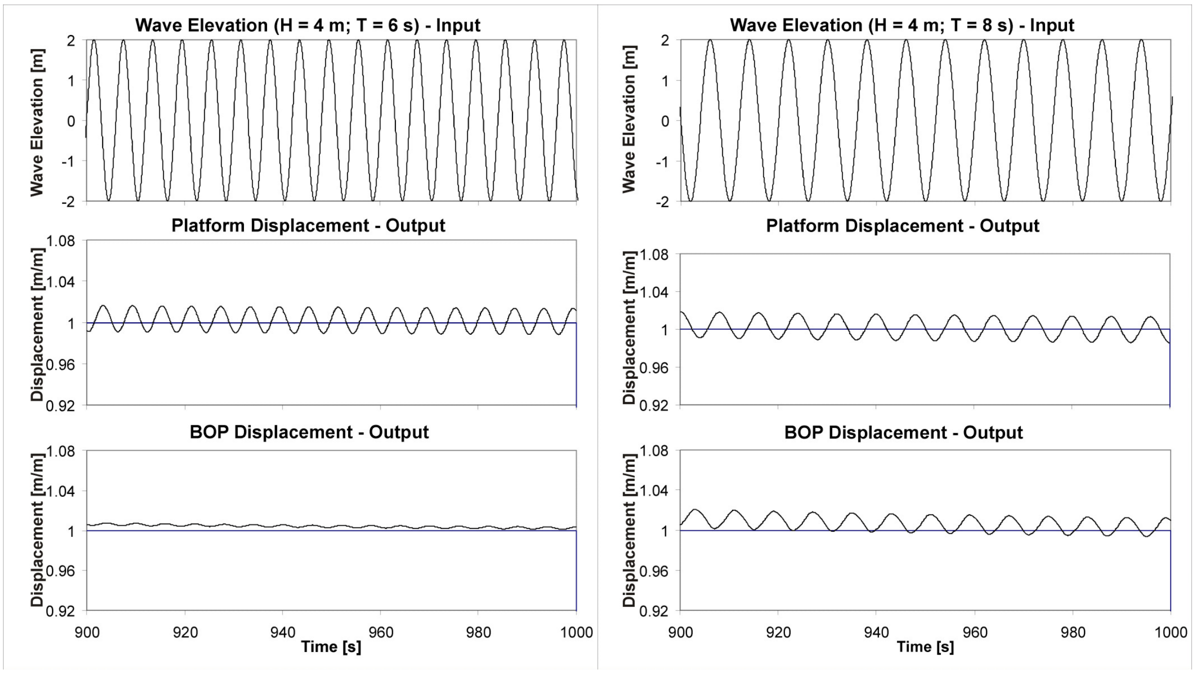
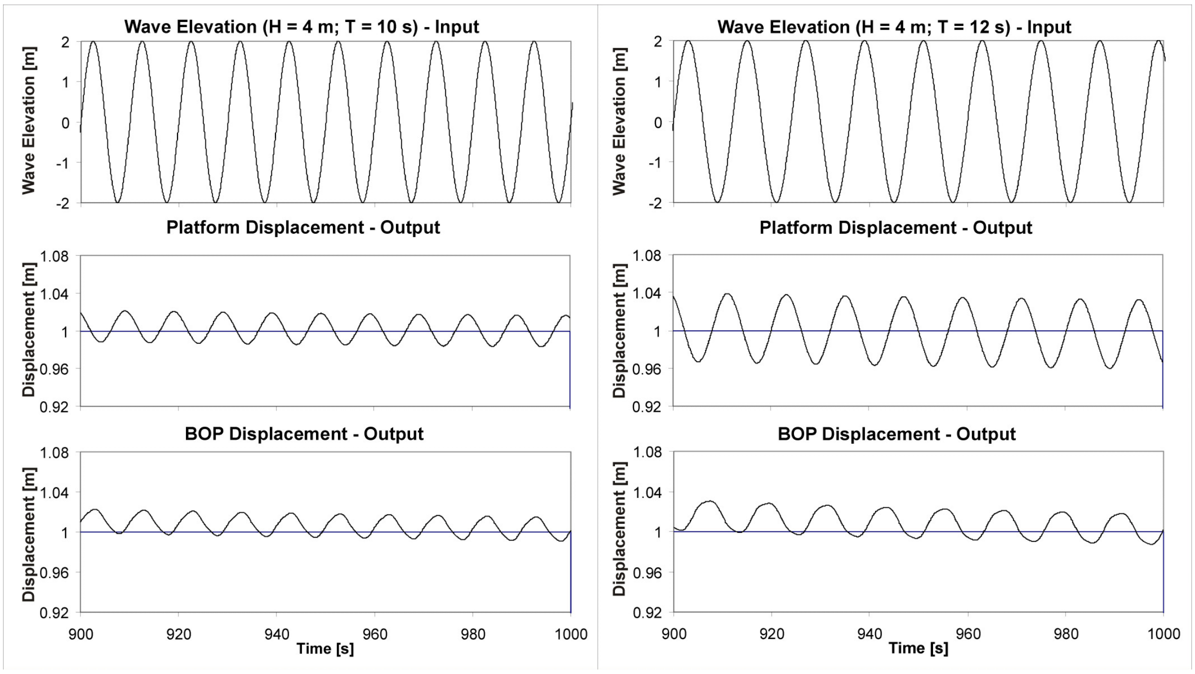


Figure 12. Quadratic Error Index for different wave's frequencies.



(a) (b)



(c) (d)

Figure 13. Wave elevation, platform and BOP displacement for regular waves: H=4 m T=6 s (a); H=4 m T=8 s (b); H=4 m T=10 s (c); and H=4 m T=12 s (d).

5. CONCLUSION

In this paper, a feedback control system for the BOP position was presented. This control system could be assembled in a dynamic positioned drilling platform with minor changes in the DPS algorithm and adding a BOP position sensor.

The effects of constant current and regular waves on the BOP position control system were studied using numerical simulation. In order to quantify those effects, the Quadratic Error Index (Equation 11) was used. The constant current from the sea bottom up to the sea surface has a great effect on the BOP position control system (Figure 10) probably because the current acts on whole riser system (the block on the right in Figure 5). The regular waves have a reduced effect on the control system (Figure 12) because the wave effect is only near the sea surface acting mainly on the floating platform. The VIV effect on the platform displacement can be neglected and the high frequency vibration due to VIV also did not cause any instability on the control system for the calculations that were carried out.

The feedback control system for the BOP position has a good robustness converging to the input signal with different environmental loads. The regular waves had a reduced effect and the control system converged for the input signal with an acceptable performance. For the high velocity current, the control system did not have instability in the calculations carried out; but the current highly decreases the performance of the control system.

Despite the performance and robustness evaluated by numerical simulations, more investigations should be carried out, including full scale experiments, in order to verify, for example, the effect of delayed data about BOP position and to compare the numerical results with experimental results. The full scale experiment is feasible because an existing dynamic positioning drilling platform can be used with minor changes.

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REFERENCES

CUMMINS, W. E. The impulse-response function and ship motions. **Schiffstechnik**, Vol. 47, no. 9, p. 101-109, junho 1962.

DALZELL, J.F. Application of the Functional Polynomial Model to the Ship Added Resistance Problem. In: Symposium on Naval Hydrodynamics, 11th, 1992. London: University College, 1976.

DNV–DET NORSKE VERITAS. **Rules for the Design Construction and Inspection of Offshore Structures**. 1977, APPENDIX A B.

FERRARI Jr., J.A.; BEARMAN, P.W. Hydrodynamics Loading and Response of Offshore Risers. In: International Conference on Offshore Mechanics and Arctic Engineering (OMAE), 18th, 1999, Newfoundland, Canada. **Proceedings of OMAE 1999.**

MARTINS, F.P.; KUBOTA, H.Y.; MOROOKA, C.K.; FERRARI Jr., J.A.; RIBEIRO, E.J.B. Estudo do Comportamento Dinâmico "In-Line" e Transversal de "Riser" Rígido de Produção. In: Congresso Brasileiro de P&D em Petróleo & Gás, 2º, 2003, Rio de Janeiro. **Anais do 2º Congresso Brasileiro de P&D em Petróleo & Gás.** Article number 2065.

MOROOKA, C.K.; KUBOTA, H. Y.; NISHIMOTO, K.; FERRARI JR., J. A.; RIBEIRO, E. J. B. Dynamic Behavior of a Vertical Production Riser by a Quase 3D Calculations. In: International Conference on Offshore Mechanics and Arctic Engineering (OMAE 2003), 22nd, 2003. Cancun, Mexico. **Proceedings of OMAE 2003.**

MOROOKA, C.K.; COELHO, F.M.; RIBEIRO, E.J.B.; FERRARI Jr., J.A.; FRANCISS, R. Dynamic Behavior of a Vertical Riser and Service Life Reduction. In: International Conference on Offshore Mechanics and Arctic Engineering (OMAE 2005), 24th, 2005, Halkidiki (Greece). **Proceedings of OMAE 2005.**

MOROOKA, C.K; YAMAMOTO, M. Dynamic Positioned Semi-Submersible Platform Motion with Riser in Ultra-Deep Water. In: International Conference on Stability of Ships and Ocean Vehicles (STAB 2006), 9th, 2006, Rio de Janeiro. **Proceedings of STAB 06.** M.A.S. Neves, ed., Rio de Janeiro, Vol. 2, pp. 857-865.

SARPKAYA, T.; ISAACSON, M. **Mechanics of Wave Forces on Offshore Structures.** New York: Van Nostrand & Reinhold Inc., 1981.

STENGEL, R. F. **Optimal Control and Estimation.** 2.ed. Mineola: Dover Publications. 1994. 637p. Title of the 1st edition: Stochastic Optimal Control, 1986.

YAMAMOTO, M.; MOROOKA, C.K.; GUILHERME, I.R. Posicionamento Dinâmico de Plataformas Petrolíferas Flutuantes com o Uso de Lógica Nebulosa. In: Congresso Brasileiro de P&D em Petróleo & Gás, 2º, 2003, Rio de Janeiro. **Anais do 2º Congresso Brasileiro de P&D em Petróleo & Gás.** Article number 2063.

YAMAMOTO, M.; MOROOKA, C.K.; UENO, S. Dynamic Behavior of a Semi-Submersible Platform Coupled With Drilling Riser During Re-Entry Operation in Ultra-Deep Water. In: International Conference on Offshore Mechanics and Arctic Engineering (OMAE 2007), 26th, 2007, San Diego. **Proceedings of OMAE 2007.**

ZUNDERDORP, H.J.; VAN DER VLIES, J.A. How to Optimize a Dynamic-Stationing System. In: SPE-European Spring Meeting, 1972, Amsterdam. Richardson: Society of Petroleum Engineers-SPE, 1972, SPE-3757.

DINÂMICA DE UMA PLATAFORMA FLUTUANTE ACOPLADA COM RISER DE PERFURAÇÃO

Para a perfuração de poços de petróleo em águas profundas e ultra-profundas, é necessário o uso de plataformas flutuantes como, por exemplo, plataformas semi-submersíveis e navios-sondas. A plataforma é conectada ao poço através de um *riser* de perfuração. Este *riser* é um tubo rígido orientado na direção vertical, por onde a coluna de perfuração desce até o poço e a lama de perfuração retorna a plataforma

Este trabalho pretende apresentar um estudo a respeito da influência do movimento da plataforma sobre o comportamento dinâmico do *riser* de perfuração. A dinâmica da plataforma semi-submersível acoplado com o *riser* de perfuração em águas ultra-profundas será apresentado. Um sistema de equações não-lineares será utilizado para representar a dinâmica da plataforma flutuante. Além disso, o Sistema de Posicionamento Dinâmico (DPS), que é responsável em manter a plataforma estacionária sobre a sua locação, também será incluído no modelo numérico. O comportamento dinâmico do *riser* de perfuração é modelado usando o Método de Elementos Finitos. Esforços ambientais como, por exemplo, corrente marinha e ondas também estão incluídos nos dois sistemas dinâmicos: plataforma flutuante e *riser* de perfuração.

Em águas ultra-profundas, é necessário ter uma atenção especial sobre as tensões e momentos fletores sobre o *riser.* Estes momentos e tensões são causados principalmente por forças hidrodinâmicas sobre o *riser* e pelo movimento da plataforma na extremidade superior do *riser.* Uma das forças hidrodinâmicas é oscilatória e gerada pelo descolamento de vórtices em torno do tubo (Vibração Induzida por Vórtices – VIV).

Foram realizadas simulações numéricas no domínio do tempo. Os resultados, no domínio do tempo, do deslocamento da plataforma com DPS e deflexão do riser são apresentados. Discussões a respeito da profundidade, deflexão do *riser* e deslocamento da plataforma também são apresentadas.

Dinâmica de Plataforma, Dinâmica de Riser, Sistema de Posicionamento Dinâmico, Perfuração Marítima