A STUDY ON INLINE AND TRANSVERSE DYNAMIC BEHAVIOR OF A VERTICAL RISER IN TIME DOMAIN

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Nowadays, major petroleum discoveries in Brazil are located in offshore sites and are placed in ultra-deep water depths. In the explotation of this petroleum, a tubular elemen responsible for making the connection between a petroleum well at the sea bottom and a production processing vessel at the sea surface is used. This tubular element is denominated riser. In order to make the explotation economically viable the application of vertical risers with dry completion is done.

In general, a mathematical model of a vertical riser for ultra-deep water applications considers the riser as a long slender tubular body. At the riser top, actions caused by the motion of a floating production platform under the effects of sea waves, currents and winds are considered, and the direct action of the sea current and wave loads are also considered.

The present assignment is based on the Ferrrari and Bearman's (1999) numerical solution approach for hydrodynamic 3-D flow problems around the riser. The fluid-structure interactions and the fundamental numerical model applied for a vertical riser are described, and time domain solutions for inline and transverse riser displacements are presented. Calculations for a typical vertical riser have been carried out and discussions have been proposed for riser displacements in several environmental conditions. In this work, waves are considered unidirectional and co-linear with current and wind directions.

***Keywords**. vertical riser, riser displacements, current loads, sea waves.*

1. Introduction

In the past few years, great effort has been carried out to understand and to predict riser dynamics, particularly for deep-water use, and mathematical methods have been proposed in the literature to estimate hydrodynamic forces in a riser (Chakrabarti and Frampton, 1982; Chakrabarti, 1987). The most recent methods are based on the time dependent Navier-Stokes equations (Meneghini, 2000; Oliveira, 2001), and most of them are limited to two-dimensional flow solutions with relatively low Reynolds numbers. Although the methods in which Reynolds numbers near to the critical flow are considered, the obtained results can not be taken as a practical design tool, yet. In general, riser sectional hydrodynamics are calculated, and three-dimensional hydrodynamic effects along the entire riser length are taken into account throughout the riser structure behavior itself.

In the present assignment, the mathematical modeling adopted considers the vertical riser as a long slender tubular element under the direct action of sea waves and currents (Kubota et al., 2002). The wave action is considered unidirectional, and it is considered that the wave reach the riser structure in a single direction of propagation, i.e., unidirectional and co-linear with the current and wind direction. Floating platform motions at the riser top caused by waves, currents and wind loads (Nishimoto et al., 1989; Leite et al., 1992) are taken into account.

2. Vertical production riser

The vertical production riser is a long tubular element that connects the petroleum well at the sea bottom to a floating process platform at the sea surface. The petroleum, usually a mixture of oil, gas and water, flows throughout the production tubing in the well following to the riser up to the platform. Many times, the riser can also be used to conduct injection fluids (water) into the petroleum reservoir. Figure 1 shows a typical configuration of an offshore floating production system using vertical oil and gas production riser.

The most relevant factors in a vertical riser behavior are the direct actions of current and wave loads and the motion forced by a surface process platform at the riser top, under the effects of waves, winds and currents. Furthermore, the riser mechanical properties, as well as the hydrostatic pressures of both fluids (internal and external) have effects that cannot be neglected. Although the riser is designed to support high stress levels, the combined action of the vortex induced vibration (VIV), caused by currents along the riser, and vessel motions at the riser top need to be carefully considered because their effect contribute for reducing the operational riser life.

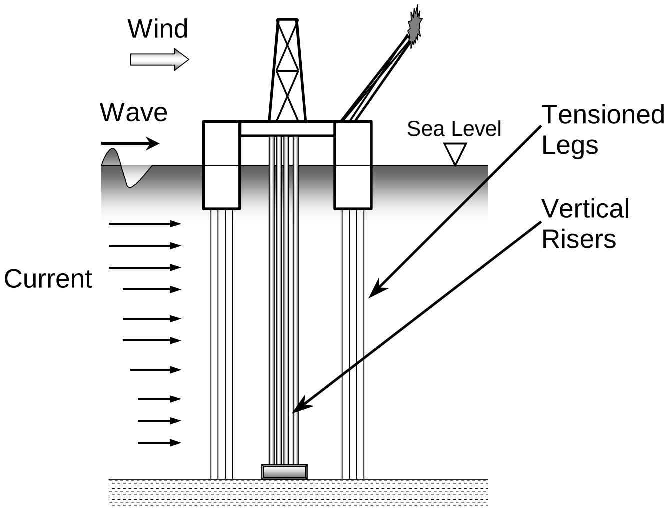

Figure 1. Typical configuration of riser and platform

In such manner, the riser dynamic behavior in deep water depends on several factors related to operational and environmental conditions, such as water depth, diameter, internal pressure, hydrostatic pressure of the internal and external fluids, ocean waves conditions, current profile, maximum offset and motions of the surface platform. All these factors have to be considered for estimating the riser dynamic behavior.

2.1. Riser mechanics

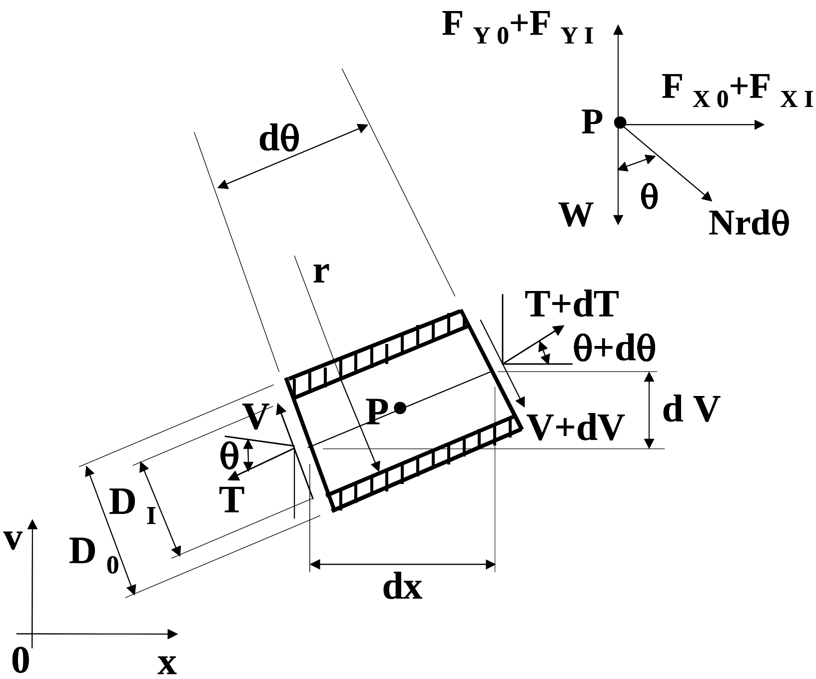

Figure 2. Scheme of equilibrium for a riser element

If the equilibrium of the elementary riser segment are considered, the equation of riser behavior (Chakrabarti et al., 1982) can be derived, as shown in Fig. (2). The equivalent load resulted from the riser weight, internal and external pressures of fluids, is considered to act in the center of the riser element. Considering linear and angular displacements in the horizontal and vertical directions, the equilibrium of forces and moment in the riser element can be obtained as follows:

Vertical equilibrium:

$$-2V\,\mathrm{sen}\frac{d\theta}{2}\cos\theta - dV\,\mathrm{sen}\,\theta\cos\frac{d\theta}{2} - 2T\,\mathrm{sen}\,\theta\,\mathrm{sen}\frac{d\theta}{2} + dT\cos\theta\cos\frac{d\theta}{2} + F_{ZS} - F_W = 0 \quad (1)$$

Horizontal equilibrium:

$$-2V\,\mathrm{sen}\frac{d\theta}{2}\mathrm{sen}\,\theta + dV\cos\theta\cos\frac{d\theta}{2} + 2T\cos\theta\,\mathrm{sen}\frac{d\theta}{2} + dT\,\mathrm{sen}\,\theta\cos\frac{d\theta}{2} + F_{XS} - m\ddot{x}\,ds = 0 \quad (2)$$

Momentum equilibrium:

$$\frac{dM}{ds} + V = 0 \quad (3)$$

where, m is the mass per unit of length; F_{ZS} is the vertical force; F_W is the weight of riser; F_{XS} is the horizontal force; M is the bending moment; V is the shear force and θ is the deflection angle.

Applying the small riser deflections assumptions in the equations (1) to (3), finally following equation is obtained for the riser displacements:

$$\frac{d^2}{d^2z}\left(EI\frac{d^2x}{dz^2}\right) - (T + A_0\overline{P}_0 - A_I\overline{P}_I)\frac{d^2x}{dz^2} - \left[(\gamma_S(A_0 - A_I) - f_{ZS} - A_0\gamma_0 + A_I\gamma_I)\right]\frac{d^2x}{dz^2} + m\ddot{x} = f_{XS} \quad (4)$$

where, x, $\dot{x}$, $\ddot{x}$ are: riser displacement, velocity and acceleration in inline direction, respectively; EI represents the bending stiffness; T the axial tension in the riser wall; P_0 and P_i the external and internal pressures; γ_0, γ_i and γ_S are the specific weight of the external and internal fluids, and the riser material, respectively. Further, A_0 is the cross sectional area of the riser including thickness and A_i is the cross sectional area of the riser without the thickness.

The second term of Eq. (4) corresponds to the effective tension in the riser and it is related to the actual tension T as follows:

$$T_E(z) = (T(z) + A_0(z)\overline{P}_0(z) + A_I(z)\overline{P}_I(z)) \quad (5)$$

The effective tension ($T_E(z)$) in each riser segment is obtained from riser static calculations and it is assumed constant for riser dynamic calculations. Equation (5) represents the mathematical relationship between the actual riser wall tension (T(z)) and the loading caused by the internal and external pressure fields perpendicularly to the riser wall.

2.2. Riser hydrodynamics

Morison's equation is adopted to describe the current and wave hydrodynamic forces acting on the vertical riser. The riser is considered a cylindrical slender element. The hydrodynamic force caused by waves acting on the riser is composed by two terms, inertial and drag ones.

The inertial force is proportional to the water particle acceleration that passes perpendicularly through the riser surface. The drag force is proportional to the water particle velocity and it can be calculated if the drag coefficient (C_D) is known. In the steady state flow pattern, the drag coefficient is dependent of the Reynolds number. Besides, the increase of the roughness contributes to the increase of C_D.

When both terms — inertial and drag — are taken into account to describe the force per length unity (f) in a riser element (Ferrari, 1999), it yields the following equation:

$$f = C_M A_I \frac{\partial u}{\partial t} + C_D A_D |u|\,u \quad (6)$$

where, C_M is the inertial coefficient, u is the water particle velocity from the Stokes fifth order waves , $A_I = \frac{\pi D_I^2 \rho_0}{4}$, $A_D = \frac{1}{2}\rho_0 D_0$,where D_0 and D_I are the external and internal riser diameters, respectively.

Equation (6) can be integrated at the entire extension of the riser, resulting the total force acting on it.

Inline hydrodynamics. The Morison's equation for the current and wave hydrodynamic forces (Eq. (6)), acting perpendicularly on the vertical riser, is considered for inline hydrodynamic forces estimation. Analyzing the inline hydrodynamics, the external force acting on the riser can be written as:

$$F_x = C_M . A_I . \frac{\partial u}{\partial t} + C_D A_D \, | V_R \, | (u - \dot{x}) - C_A . A_I \, \ddot{x} \tag{7}$$

where, F_x is the inline force, C_A is the added mass coefficient and U_c is the external fluid flow velocity.

The term V_R is the relative velocity, which can be can be written as:

$$V_R = \sqrt{(u + U_C - \dot{x})^2 + (\dot{y})^2} \tag{8}$$

The $(u + U_C - \dot{x})$ term is the inline velocity and $(\dot{y})^2$ term by the transverse velocity.

The accuracy of the results obtained from the above equation is directly dependent on the correct choice of the hydrodynamic coefficients (C_D, C_M, C_A), which can normally be determined from experiments (Sarpkaya and Isaacson, 1981). In general, hydrodynamic forces are functions of the Reynolds number (Re), the riser surface roughness and the Keulegan-Carpenter number (KC).

From dimensional analysis of the riser problem of the force per length unit of the riser caused by waves and currents acting on the riser in function of different parameters on a non-dimensional form can be obtained. This equation is expressed as follows:

$$\frac{f}{\rho u_0^2 D} = \psi\left(\frac{t}{T}, \frac{k}{D}, \frac{u_0 T}{D}, \frac{u_0 D}{\nu}, \frac{u_0}{v_0}, \frac{D}{L}, \frac{U_c}{u_0}\right) \tag{9}$$

where, D is the riser diameter, T is the incident wave period, L is the wave length, k is the roughness, u_0 is the maximum water particle horizontal velocity, v_0 is the maximum water particle vertical velocity, ρ is the water density, ν is the cinematic viscosity, t / T is the dimensionless time parameter, k /D is the roughness parameter, u_0/v_0 is the water particle velocity parameter, U_C/u_0 is the relative current number and D/L is the diffraction parameter.

Therefore, KC (u_0T/D) and Re (u_0D/ν) are related to the importance of the viscous drag force, whereas the diffraction parameter (D/L) determines the importance of the wave diffraction effect. It can be noted that KC is a relatively high number, whereas the diffraction parameter is low Even so, it can be concluded that the bigger the diffraction effects are, the smaller the drag effects will be. Otherwise, if the drag component were big, the diffraction component could be neglected. In particular case of a riser, the drag component is the predominant term in the hydrodynamic force.

Transverse hydrodynamics. Analogous to inline hydrodynamic, transverse hydrodynamic problem solution is here, also based on the Morison's formulation.

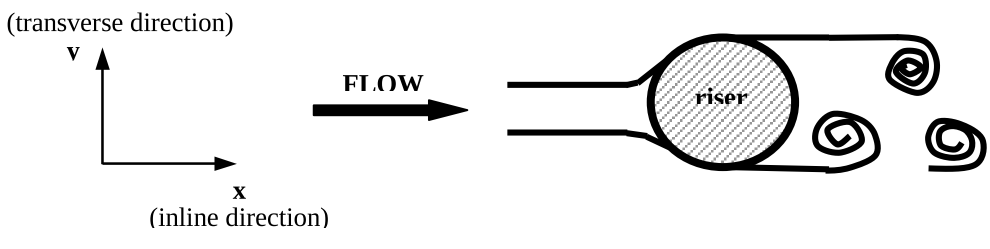

Figure 3. Scheme of a cross section of the riser and vortex formation

As the flow separation happens in the flow around a riser cylinder, an alternate vortex appears on each transverse side of the riser cross section, as illustrated in Fig. (3). This alternate vortex generation (Sapkaya and Isaacson, 1981) provokes pressure differences on each side of the riser and asymmetric dynamic forces occur, inducing the vibration of the riser. This phenomenon is known as vortex induced vibration (VIV) and it usually increases the stress levels in the riser structure and contributes for reducing its operational life (Kubota et al., 2002).

In the present calculations, the following equation (Ferrari, 1999) is used to estimate the force caused by the VIV:

$$F_{VIV} = \frac{1}{2}\rho((u - \dot{x}) + U_C)^2 D \bar{C}_t \cos(2\pi \bar{f}_S \, t' + \varphi) \tag{10}$$

where, $\bar{f}_S = \dfrac{|\bar{U}|St}{D}$ and $\bar{U} = \dfrac{\int_0^t U dt}{t}$, $\bar{C}_t$ is the mean amplitude of the transverse force, $\bar{f}_S$ is the mean frequency of the vortex shedding, φ is the phase difference between the transverse riser response and force, St is the Strouhal number, $\bar{U}$ is the mean oscillatory flow velocity, U is the instantaneous oscillatory flow velocity and F_{VIV} is the force caused by the VIV.

The mean frequency of the vortex shedding ($\bar{f}_S$) can be understood as the memory effect of the flow whereas cumulative relative mean velocity is considered in the calculation.

Considering the Morison's equation (Eq. (6)) for the transverse direction of the riser and Eq. (10), the following equation can be obtained:

$$F_y = F_{VIV} - C_D A_D |V_r| \dot{y} - C_A A_I . \ddot{y} \tag{11}$$

where, F_y is the transverse force caused by the waves and y, $\dot{y}$, $\ddot{y}$ are the riser displacements, velocity and acceleration in the transverse direction, respectively.

2.3 Riser top oscillation

Riser top oscillation with action of the current. Three non-dimensional parameters characterize a cylinder under the effect of a current: Reynolds number (Re), reduced velocity ($V_r = \dfrac{UT_0}{D}$) and amplitude parameters. The reduced velocity is given in terms of the current velocity (U). Thus, for riser inline oscillations under the action of a uniform current flow field, the modified Morison equation yields:

$$f = -C_A A_I \ddot{x} + C_D A_D \left| U - \dot{x} \right| \left(U - \dot{x} \right) \tag{12}$$

Riser top oscillation with action of the waves. Riser inline reaction force oscillating under incident waves is given by:

$$f = C_M A_I (\dot{u} - \ddot{x}) + C_A A_I \ddot{x} + C_D A_D \left| u - \dot{x} \right| \left(u - \dot{x} \right) \tag{13}$$

Riser top oscillation with the combined action of current and waves. The Morison's equation applied for a free structure, oscillating under waves and current fields, can be obtained from Eq. (14) and Eq. (18). And it can be written as:

$$f = C_M A_I \dot{u} - C_A A_I \ddot{x} + C_D A_D \left| u \pm U - \dot{x} \right| \left(u \pm U - \dot{x} \right) \tag{14}$$

2.4 Solution

In the present assignment, the solution is obtained in time domain. The direct numerical integration of the Eq. (5), including all existing non-linearities, is calculated. Basically, the analysis in time domain consists of the solution of static equilibrium equations of the riser including parcels of damping and applied loads in each point of its structure. The Newmark-β Method is applied on the numerical solution, with β =1/4.

The general equation of the riser dynamic behavior with top forced oscillation, in matrix representation, can be represented by:

$$[M]\ddot{x} + [B]\dot{x} + [K]x = F \tag{15}$$

where, [M] is the structural mass matrix, [B] is the structural damping matrix, [K] is the global stiffness matrix (elastic and geometric) and F is the external oscillation imposed on the system.

Finally, if Eq. (14) and Eq. (15) are added, the equation for the riser displacements under action of wave and current with the riser top oscillation will be obtained. It is expressed as follows:

$$\left([M] + C_A A_I L\right)\ddot{x} + [B]\dot{x} + [K]x = \left(C_M A_I \dot{u} + C_D A_D \left| u \pm U - \dot{x} \right| \left(u \pm U - \dot{x} \right) \right) L \tag{16}$$

3. Results

In previous assignment, extensive comparative validation efforts were carried out to study the riser dynamic among simulations, experimental results and data available from the literature (Kubota et al., 2002). In the present work, time domain simulations have been achieved for riser dynamics, and calculations have been performed for wave load added to riser top oscillations. Results in the form of time series were obtained for three different locations along the riser (90m, 60m and 30m from the sea bottom). In these calculations, the horizontal floating platform top motion of 2 meters amplitude and the wave height of 4 meters were taken into account. The incident wave periods of 6 and 8 seconds, were also considered in the simulations. In the figures of time series, data for the initial 30 seconds of simulations were eliminated in order to avoid initial transients of the riser dynamic simulation. Then, 60 seconds of simulation of the riser, is presented showing the riser steady state oscillation. Both ends of the riser are adopted as pin connected.

In Table 1 the riser main dimensions applied in the calculations are shown.

Table 1: Riser main dimensions (real scale)

Riser Dimensions	
Material	Steel
Outer Diameter (m)	0,25
Inner Diameter (m)	0,21106
Modulus of Elasticity (N/m^2)	$2{,}1 \times 10^{11}$
Density of Material (kg/m^3)	7860
Water Depth (m)	100
Riser Length (m)	120
Top Tension (kN)	196
Mass / Length (kg/m)	197,01

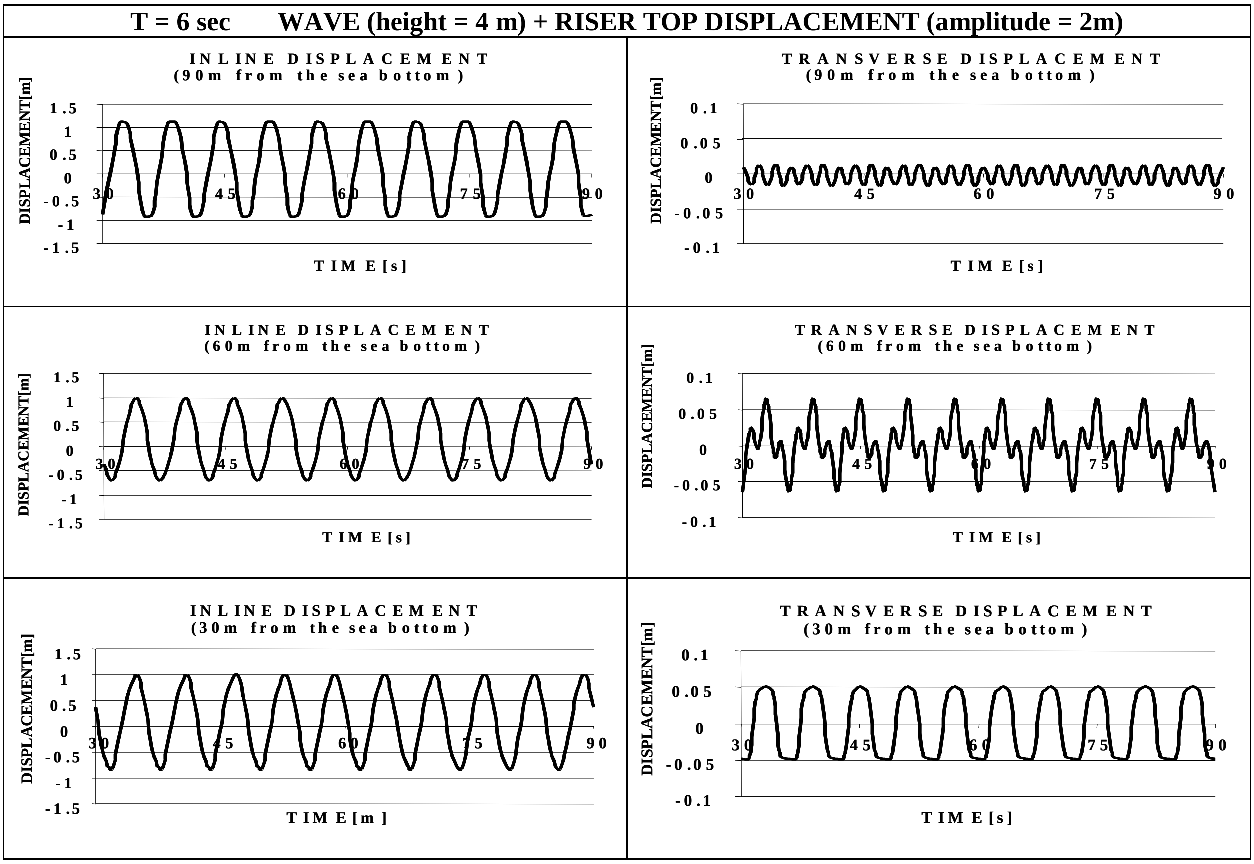

Figure 4. Riser inline and transverse displacements from simulations for three different locations along the riser for combined top displacement and wave excitations with 6 seconds wave period.

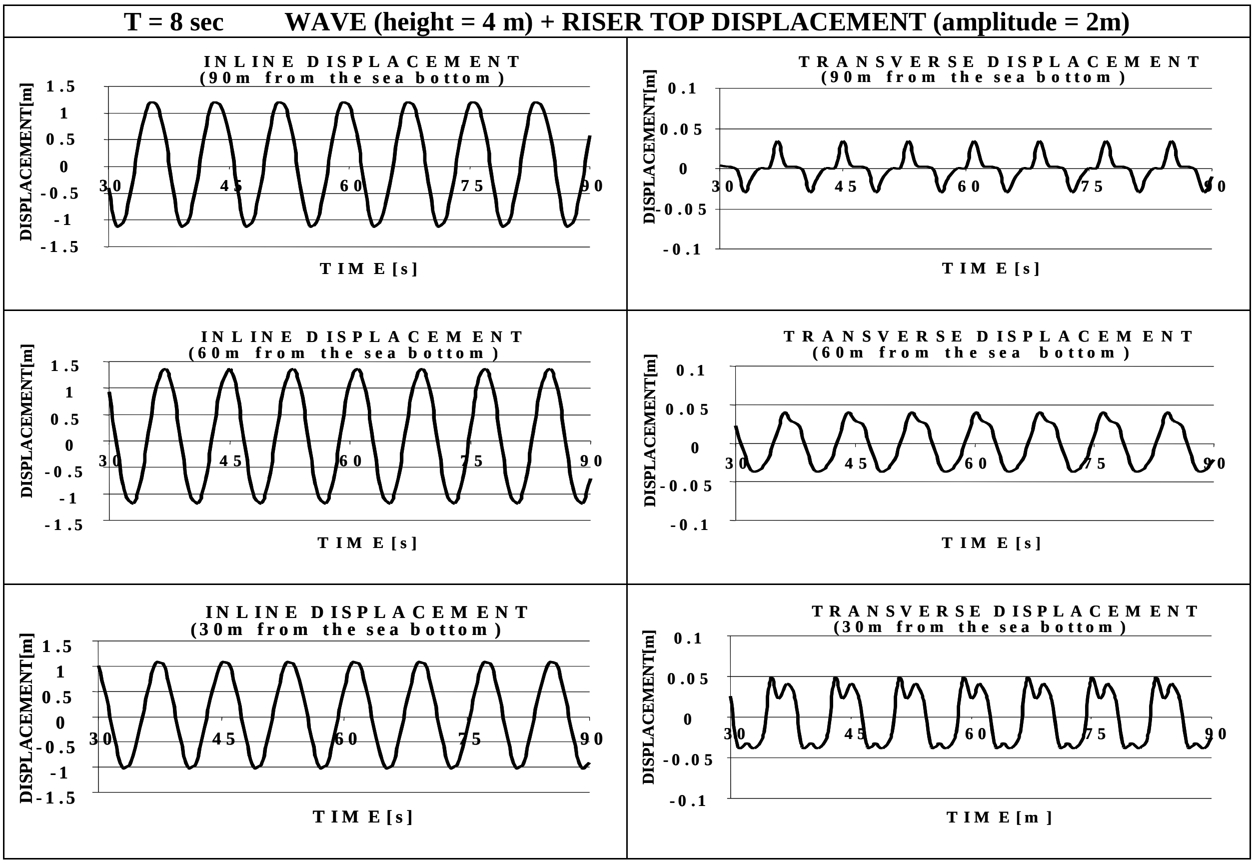

Figure 5. Riser inline and transverse displacements from simulations for three different locations along the riser for combined top displacement and wave excitations with 8 seconds wave period.

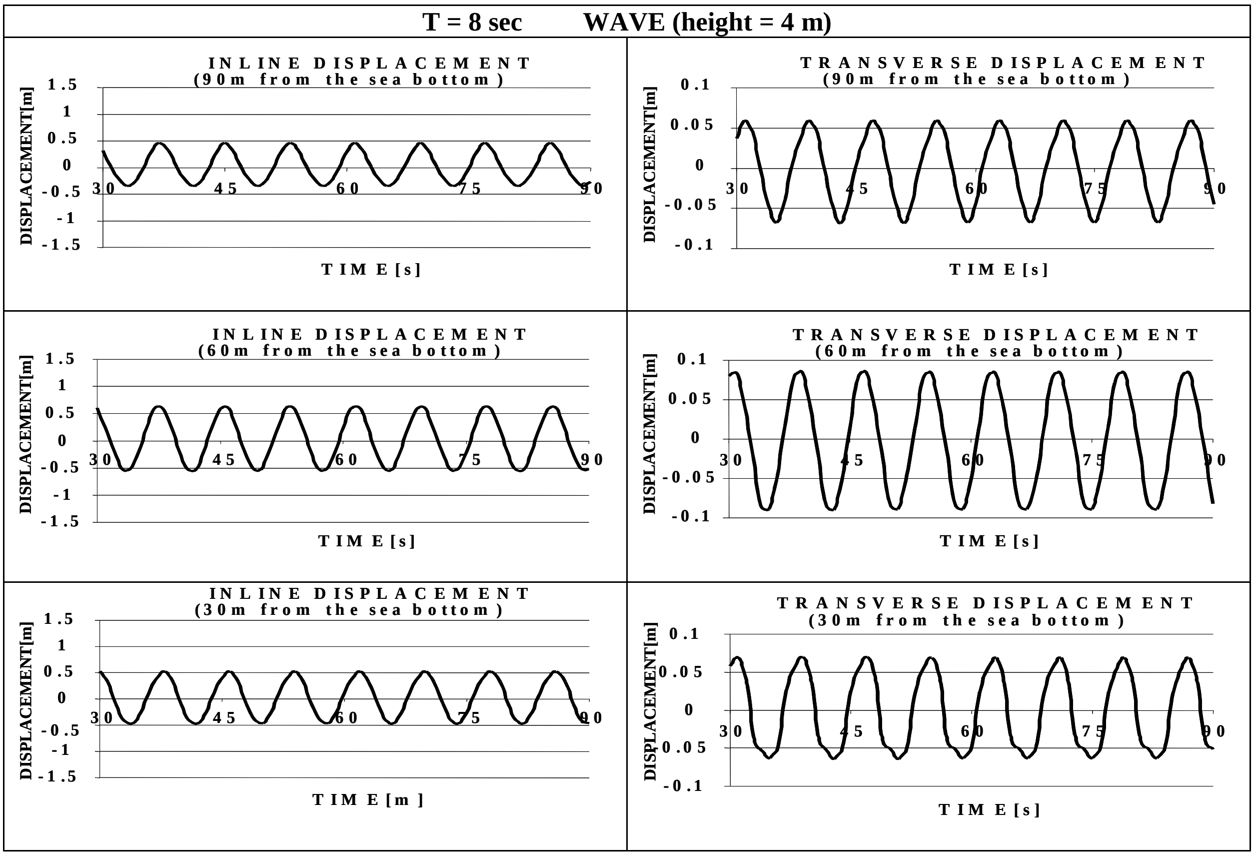

Figure 6. Riser inline and transverse displacements from simulations for three different locations along the riser for wave excitation with 8 seconds wave period.

Figure 4 shows simulated time series of riser inline and transverse displacements for an incident wave with 6 seconds wave period. The wave height of 2 meters and the horizontal riser top oscillation 2 meters is considered. Riser displacements for 90, 60 and 30 meters from the sea bottom along the riser are shown.

In an analogous way, Fig. (5) pointed out the riser displacements for the same wave and the riser top oscillation conditions, however, the incident wave period in this case is 8 seconds.

Figure 6 reproduces the calculation conditions of Fig. (5), without the presence of the riser top oscillations. Finally, Fig. (7) shows the riser planar displacements for each indicated location around the riser length, for each condition previously presented.

In general, when a riser top oscillation is present, larger inline displacements can be noted along the riser if compared to the condition without the riser top motion. Besides, larger displacements are usually observed, inline and transverse directions, around the middle length of the riser.

In the inline direction, riser displacements following a wave oscillation period can be noted. Nevertheless, in the transverse direction, the riser displacements oscillating under the effects of the vortex shedding frequency can be observed from the results.

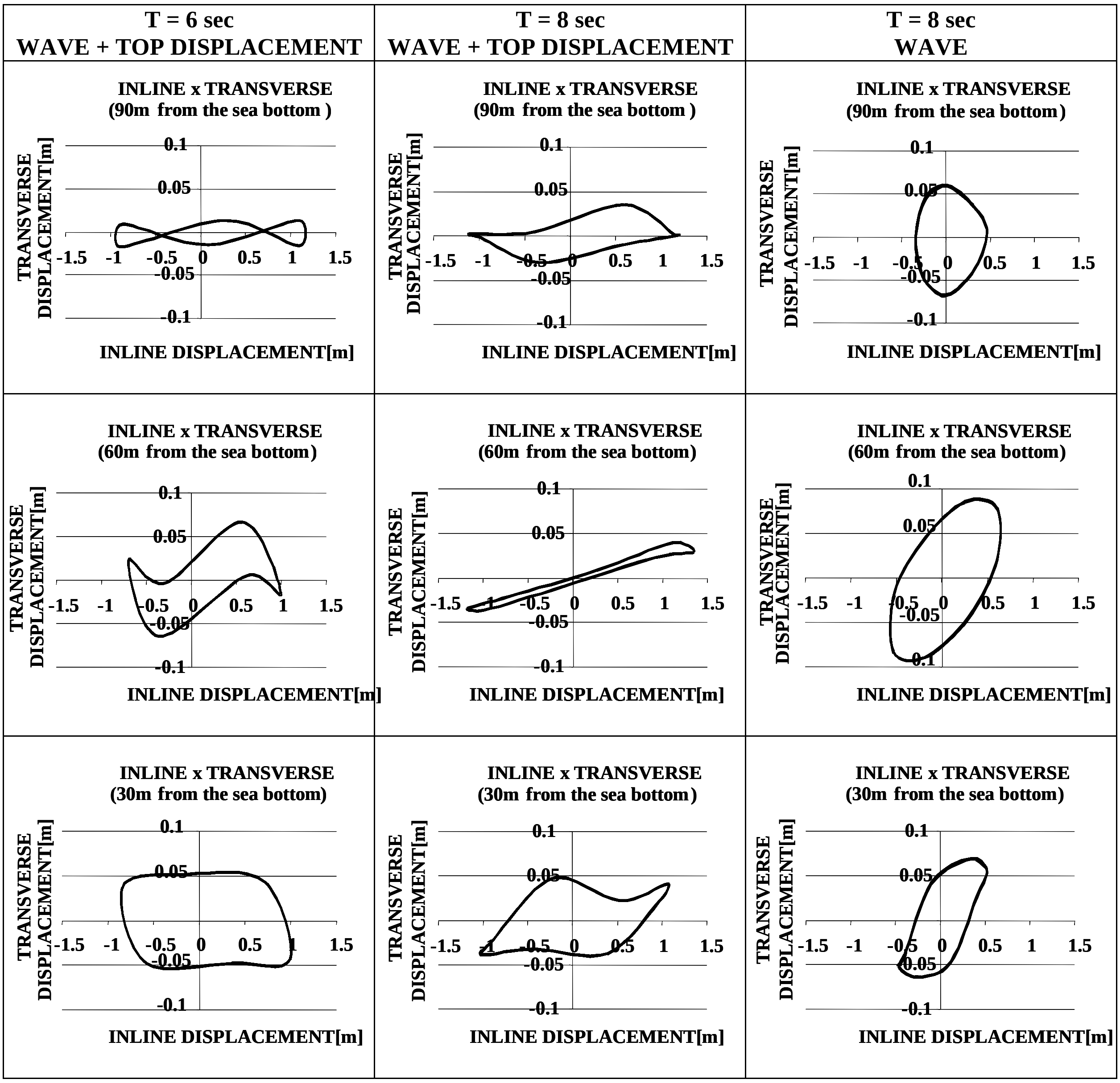

Figure 7. Riser planar displacements from simulations for the three different locations along the riser.

4. Conclusions

The observations of the results from the present research follow a previous one with good agreement. Generally, the riser displacements at the inline direction are greater than in the transverse direction. From the results, riser displacements are not deeply affected by changing incident wave period. In addition to that, it can be noted that the riser top oscillation has a great impact on the riser displacements. In general, such effect is more relevant than the effect of the direct wave action on the riser behavior.

5. Acknowledgements

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6. Nomenclature

M = bending moment
V = shear force
θ = deflection angle
D_0 = external diameter of the riser
D_I = internal diameter of the riser
EI = bending stiffness
T = axial tension in the riser wall
F_{ZS} = vertical component of force
F_W = weigh riser component
F_{XS} = horizontal component of force
F_y = transverse force caused by waves
F_{VIV} = vibration induced by vortex forces
T_{TOP} = top tension
P_0 = external pressure
P_i = internal pressure
A_0 = cross sectional area (including thickness)
A_i = cross sectional area (excluding thickness)
γ_0 = specific weight of external fluid
γ_i = specific weight of internal fluid
γ_S = specific weight of riser material
x = inline displacement
$\dot{x}$ = riser velocity in inline direction
$\ddot{x}$ = riser acceleration in inline direction
y = transverse displacement
$\dot{y}$ = riser velocity in transverse direction
$\ddot{y}$ = riser acceleration in transverse direction.
C_M = inertial coefficient
C_D = drag coefficient
C_A = additional mass coefficient
V_R = relative velocity
t = time
T = wave period
D = riser diameter
L = wave length
k = characteristic dimension of roughness
V_r = reduced velocity
v_0 = maximum vertical velocity of water particle
ρ = water density
ν = cinematic viscosity
U_c = flow velocity
$\bar{C}_t$ = mean amplitude of transverse force
$\bar{f}_S$ = mean frequency of vortex shedding

$\bar{U}$ = mean velocity of oscillatory flow
φ = phase difference between transverse riser response and force
u = water particle velocity
u_0 = horizontal water particle velocity
T = oscillation period of water particle (structure)
t / T = dimensionless time
k /D = roughness parameter
u_0/v_0 = water particle velocity parameter
D/L = diffraction parameter
U_C/u_0 = relative current number
KC = Keulegan-Carpenter number
Re = Reynolds number
St = Strouhal number
[M] = structural mass matrix
[B] = structural damping matrix
[K] = global stiffness matrix (elastic and geometric)
F = external oscillation imposed to the system

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