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Natural frequency analysis of a marine riser considering multiphase internal flow behavior

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ABSTRACT

Marine risers are subjected to several types of excitation loads, such as motions induced by the floating production system, external hydrodynamics forces due to currents and waves and internal forces due to the internal fluid flow regularly composed by water, oil and gas. When internal flow conditions as pressure, temperature and flow rate fluctuations appear in a riser, they can induce vibration motion to the system.

This paper shows a numerical algorithm to evaluate the vibrations of vertical rigid production risers under internal multiphase flow behavior. The numerical algorithm developed computes the natural frequencies of vertical risers model coupled with a hydrodynamic numerical model. The internal flow was composed of water, oil and gas and was treated as a pseudo-single phase (mixture). The numerical algorithm was developed using difference finite method. The results were compared with information available in the literature.

1. Introduction

The oil and gas industry has extracted hydrocarbon resources from a great number of petroleum reserves located in the ocean. In case of oil fields discovered mainly in deep ocean waters, the use of marine risers is vital for oil and gas production. The risers are structures that connect the production system at the seabed with the platform on the sea surface. Such risers can be subjected to several types of internal and external excitation loads. The external loads such as motions induced by the floating platform and hydrodynamics forces caused by currents and waves have been the object by innumerable scientific studies. However, the internal forces related to the oscillation caused by the hydrodynamic behavior of flux inside the riser have not being deeply investigated although it has been observed that the dynamics of the internal flow from the well to the production platform generally occurs in multiphase flow. This shows the need to perform numerical models in order to evaluate the dynamic behavior of marine riser under different flow conditions.

In the literature, there are numerous papers related to slender riser analysis as reported by Ertas and Kozik (1987, Jain (1994) and Patel and Seyed (1995) trying to include different phenomenology principally presented as consequence of external forces (platform movements, current velocities) and internal forces (internal fluids). Because of complexity some simplifications have been done where some terms of the motion equation have been neglected. A realistic result can be obtained by combining the actions that can influence the structural effects in the riser. However numerical models that take into account all types of external and internal forces effects has not been elucidated (Meng and Chen, 2012).

The influence of internal flow has been ignored in several research works. However, some works have been developed to have a better understanding of the dynamic behavior of the riser; in this sense, various aspects of marine risers conveying fluids have been attracted by some researches, Griffith (1984) detected the mechanism whereby the internal flow produces vibration on slender marine risers. When two phase internal flow is presented, especially as slug flow, mass fluctuations occur as a consequence of the intermittence condition. This force can cause vibrations on the riser when the fluctuations are close to the natural frequencies of the system. Irani et al. (1987) indicated that the internal flow diminishes the stiffness of marine risers and it provides a negative damping mechanism. Moe and Chucheepsakul (1988) investigated the effects of single internal fluid flow through a vertical riser neglecting a bending rigidity. The authors also showed that the natural frequencies were reduced slightly at a low internal fluid rate but contrary, it is reduced significantly at a very high flow rate. The authors concluded that instabilities on the riser can occur due to the internal flow, mainly when it is presented a specific flow

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pattern (Slug flow). Patel and Seyed (1989) studied the internal slug fluid induced vibration on flexible risers, concluding that the effect of the slug was significant from moderate to large water depths or in the larger pressure area, and the slug fluid caused additional source of cycling fatigue loading. Wu and Lou (1991) determined the effects of the internal flow and bending stiffness of the pipe on the dynamic behavior of the riser, and found that the stiffness has more importance to the dynamic response of risers at high internal flow velocities. Seyed and Patel (1992) presented a detail treatment on the equations governing internal fluid and pressure effects on the risers and showed an overlap in the action mode of the pressure and internal fluid forces. Lee et al. (1995) showed that the vibration and stability analysis on the riser with internal flow, in an oscillatory regime, that the natural frequencies decrease when the flow velocity is increased. Chucheepsakul et al. (1999), (2001) studied the influence of fluid transported by the riser under static and dynamic behaviors. The results showed that the natural frequencies of the riser decrease while both the internal flow velocity and the static displacement increased; the transported fluids revealed to be more significance on the high extensible risers than for the low extensible ones. Monprapussorn et al. (2007) determined that impulsive acceleration of internal flow could seriously relocate the vibrational equilibrium positions of the riser pipe. The fluctuation of the pulsatile flow relatively introduced the expansion of amplitudes and the reduction of frequencies of riser's vibrations. Kaewunruen et al. (2008) found the fundamental natural frequencies for various internal flows by neglecting flexural stiffness of riser. It was also found that the velocity of the internal fluid increases as the fundamental natural frequencies decreases.

The aforementioned studies were limited to the marine risers with specific considerations about effect of internal flows, especially when multiphase flow is conveying trough them. It can be also seen that multiphase flow permits to add complexity to the system when heat, mass transfer and non-Newtonian behavior are considered. Therefore add complexity to the implicit phenomenology presented in the risers requires different considerations, simplifications and parameter that in many cases are not fully understood. In the present study, a hydrodynamic model of internal flow was modeled with the aim to obtain the main flow conditions like velocity, pressure and temperature profiles along to the riser for the different flow conditions that can appear in the oil field operations. The hydrodynamic numerical model considers the steady state behavior of fluid inside the riser. This mathematical model was coupled to the structural model in order to obtain the natural frequencies of the riser. Since the external and the internal flows have a remarkable influence on the slender structure behavior, both parameters should be considered in the analysis. The work presented in this paper, was especially based on the influence of the internal fluid flow.

2. Multiphase flow modeling

It has been observed that the flow production from the subsea well production to the floating production system generally occurs in a multiphase flow conditions. Therefore, in this work a multiphase flow composed by water, oil and gas is treated as internal mixed flow. Two and three phase flows, can be approached using homogeneous, drift-flux and two-fluid models. In the homogeneous model, it was assumed that the phase conservation equations (mass, momentum and energy) can be summarized in mixed conservation equation system. The drift-flux model is essentially a separated-flow model, in which the attention is focused on the relative motion rather than on the motion of the individual phases. The two-fluid model takes into account the fact that the phases can have different physical properties and velocities.

The separated mass, momentum, and energy equations are written for each phase. Therefore, in this work for internal multiphase flow modeling, though a vertical slender structure, a one dimensional time-dependent homogeneous mathematical model is used, in order to make the model able to predict pressure, temperature and the velocity profiles of the internal multiphase flow. The homogeneous model was obtained from the following considerations: the water, heavy oil and gas were treated as a pseudo-single incompressible phase with mixture properties. The friction shear stresses of water, gas and oil-wall, were ignored in the model, and then it was considered the friction shear stress of mixture-wall. The mass transfer effects or chemical reactions have been neglected as well as the heat transfer between the flow and the pipe wall. The mathematical internal fluid motion model consisted in simultaneously solving the mass, momentum and energy conservation equations (Ishii, 1975); the equation system is given by:

(i) Mass

$$\frac{\partial p}{\partial t}+\rho c^2\frac{\partial U}{\partial z}+U\frac{\partial p}{\partial z}=0 \tag{1}$$

(ii) Momentum

$$\frac{\partial U}{\partial t}+U\frac{\partial U}{\partial z}+\frac{1}{\rho}\frac{\partial p}{\partial z}=-g\ \sin\ \theta-\frac{\tau_w S_w}{\rho A} \tag{2}$$

(iii) Energy

$$\frac{\partial T}{\partial t}+U\frac{\partial T}{\partial z}-\frac{1}{\rho C_p}\frac{\partial p}{\partial t}-\frac{\beta}{C_p}\left(\frac{\partial p}{\partial t}+U\frac{\partial p}{\partial z}\right)+\frac{U}{C_p}\left(\frac{\partial U}{\partial t}+U\frac{\partial U}{\partial z}\right) =-\frac{Ug\ \sin\ \theta}{C_p} \tag{3}$$

In Eqs. (1)–(3), T is the operating temperature, c is the mixture sound velocity, C_p is the mixture heat capacity, A is the pipe cross-sectional area, p is the average pressure, g is the acceleration due to gravity, θ is the inclination angle of the pipe, τ_w is the wall friction shear stress and S_w is the pipe perimeter. Because the hydrocarbon fluid is composed by water, heavy oil and gas, it can be treated as a pseudo-single phase (mixture), then, U and ρ are the mixture velocity and mixture density, respectively. β is the parameter that contains liquids and gas Joule Thomson coefficient. β, $U$and ρ are expressed as:

$$\beta=\frac{\varepsilon_g\rho_g\eta_g Cp_g+\varepsilon_o\rho_o\eta_o Cp_o+\varepsilon_w\rho_w\eta_w Cp_w}{\rho} \tag{4}$$

$$\rho=\rho_o\varepsilon_o+\rho_g\varepsilon_g+\rho_w\varepsilon_w \tag{5}$$

$$U=\frac{\rho_g\varepsilon_g U_g+\rho_o\varepsilon_o U_o+\rho_w\varepsilon_w U_w}{\rho}=\frac{\rho_g U_{sg}}{\rho}+\frac{\rho_o U_{so}}{\rho}+\frac{\rho_w U_{sw}}{\rho} \tag{6}$$

where η is the Joule–Thomson coefficient, ε is the volumetric fraction and U_s is the superficial velocity. The subscripts w, o, and g represent water, oil and gas phases, respectively. All the thermophysical and transport properties used in Eqs. (1)–(6) must be known.

In order to take into account the shear stress, in literature there exist correlations for gas–liquid mixtures, however there are not correlations for gas–liquid–liquid mixtures. Therefore, in this work various correlations, found in literature, were used. For example if one supposes that water is the only fluid that touches the pipe