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Coupled motion analysis of a tension leg platform with a tender semi-submersible system

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A R T I C L E I N F O

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A B S T R A C T

In this study, an experimental and numerical analysis have been carried out to investigate the coupled behavior of a Tension Leg Platform (TLP) combined with tender semi-submersible platform with focus on the multi-modal behaviors. Free decay tests were conducted for the TLP and semi-submersible, which showed that the TLP and semi-submersible system had complex coupled behaviors with multiple natural mode frequency components. To investigate this behavior rigorously, an eigenvalue analysis was applied. The natural modes and periods of the multi-body system were identified from the eigenvalue analysis. A selected set of model experiments was compared with corresponding numerical simulations which showed a good agreement.

1. Introduction

The economic profit against the capital expenditure(CAPEX) and operating expenditure(OPEX) is one of the most important considerations when developing an offshore oil or gas field. In case that high CAPEX is anticipated, more economical alternatives should be derived to increase the profit of the project. The concept of using a tender vessel is one of promising alternatives, but additional engineering works should be considered to investigate operability and the safety of the production platform and tender vessel system.

The Odin field(1985) is the first example of the production platform with the tender vessel system, in which a tender vessel was attached to a fixed jacket platform (Smith and Dixon, 1987). Since then, many tender support vessels were usually used with the fixed platforms (Christiansen et al., 1994; Mathiesen, 1989). Recently, the tension leg platform (TLP) is regarded as a competitive one to accept tender vessel concept compared with other floating platforms. Since the TLP is more sensitive to the additional topside weight and undergoes smaller motions in waves, it is relatively straightforward to analyze the relative motion of two floating systems (Botker et al., 2001; Korloo et al., 2004; Xia and Taghipour, 2012). Moreover, as they are moored with vertical tendons, interference between the mooring lines can be avoided.

TLP and tender semi-submersible platform system consists with two floating bodies, mooring and hawser system where TLP is taking charge of production through the dry tree while the tender semi-submersible supports accommodation and supplies. This system reduces the payload and functional requirements on the production platform and makes the dry tree completion system more competitive. Moreover, the residence and helideck on the topside could be moved to the tender vessel to diminish the potential risk by separating such structures from the potentially explosive modules. But the utilization of the tender vessel needs more detailed engineering as two floating bodies are connected with hawser lines. It gives a complex behavior on the system due to the coupling effect. Since two bodies are located with close proximity, there is a possibility of collision between two bodies which can damage the hawser lines and the mooring lines due to the relative motions of bodies. Therefore, the verification on the coupled system for various environmental condition should be considered to ensure the safety of the tender vessel system (Xia and Taghipour, 2012).

Many pioneering works on the TLP have been conducted with focus on the higher order phenomena which called as springing and ringing. Chen et al. (1991) analyzed the springing loads on the TLP numerically. To understand the ringing phenomena of the TLP, the third order forces are also needed. Originally Malenica and Molin (1995) suggested the third order wave forces acting on the vertical cylinders, and Teng and Kato (2002) suggested the third order force formulation on the axisymmetric body. Hong and Hong (1996) showed that Morison's drag force model provides the third order components, which is

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effective to simulate the higher order drag forces on the TLP. Cho et al. (2014) revisited the third-order effect by applying Morison drag force and model tests. But there have not been many of studies on the TLP with tender supported vessel. Most of researches on the tender supported vessel have been restricted on the risk assessment or hydrodynamic interaction (Muhammad et al. (1996), Udoh et al. (2014)). Korloo et al. (2004) showed a comprehensive analysis on the TLP with tender semi-submersible for West-Seno field. Xia and Taghipour (2012) conducted a feasibility study on the TLP with tender assisted drilling project, and primally introduced the eigenvalue analysis for mooring designs, but their analysis was restricted to the longitudinal motions of two bodies only. Because of the lack of the model experiments and analysis on the TLP with semi-submersible, the coupling effects of the TLP with tender semi-submersible system is left behind unknown.

In this study, the coupling effects of TLP and tender semi-submersible system were investigated by conducting both numerical analysis and model tests. From a set of free decay tests for the TLP and tender semi-submersible system, the complex coupled motion behavior was observed. From the eigenvalue analysis, those complex behavior was identified as a multi-modal characteristics. To interpret this behavior, the eigenvalue analysis for the coupled horizontal motions had been performed. The eigenvalue analysis provided the natural periods and modes of the TLP with tender semi-submersible system. The natural frequencies measured in the model tests showed good agreements with the results of the eigenvalue analysis. Finally, the fully coupled frequency and time domain analyses had been conducted in wave conditions, which showed fairly good agreements between results of the model experiments and numerical simulations.

2. Numerical analysis

2.1. Eigenvalue analysis

To investigate the characteristics of the TLP with tender semi-submersible, an eigenvalue analysis was performed with focus on coupled horizontal mode motions, e.g. the surge, sway and yaw of the TLP and tender semi-submersible. The horizontal motion vector for the TLP with tender semi-submersible system is given by Eq. (1). First three components are the horizontal motion components of the TLP, and the last three components are those of the semi-submersible.

$$[\mathbf{x}] = [\,\xi_T \quad \eta_T \quad \psi_T \quad \xi_S \quad \eta_S \quad \psi_S\,] \tag{1}$$

where $[\mathbf{x}]$, ξ, η and ψ represent the horizontal motion vector and the surge, sway and yaw motion, respectively, and the subscript T and S denote the TLP and semi-submersible, respectively. The mass-spring system equation of the TLP with tender semi-submersible in frequency domain can be given by Eq. (2).

$$\left\{-\omega^2([\mathbf{M}] + \boldsymbol{a}(\omega)) + [\mathbf{K}]\right\}[\mathbf{x}] = 0 \tag{2}$$

where ω, $[\mathbf{M}]$, $[\boldsymbol{a}(\omega)]$ and $[\mathbf{K}]$ are circular frequency, the genuine mass matrix, added mass matrix and horizontal motion stiffness matrix which includes the components of the tendons, mooring lines and hawsers. The genuine mass terms are given in Eq. (3), of which the details are derived in Appendix A.

$$\mathscr{D}[\mathbf{M}] = \left[M_T \quad M_T \quad M_T r^2_{66,T} \quad M_S \quad M_S \quad M_S r^2_{66,S}\right] \tag{3}$$

where $\mathscr{D}$, M_T, M_S, $r^2_{66,T}$ and $r^2_{66,S}$ are diagonal terms of the matrix, genuine mass of TLP and semi-submersible, yaw radius of gyration of the TLP and semi-submersible, respectively. These genuine mass terms do not change but the added mass matrix of the two floating systems involves coupling terms and is a function of wave frequency. Because the horizontal motions of system have low frequency behaviors, the added mass matrix can be approximated as the values at the zero frequency.

$$[\boldsymbol{a}(\omega)] \approx [\boldsymbol{a}(\omega \sim 0)] \tag{4}$$

The horizontal motion stiffness matrix is composed of three parts; from the tendons, mooring lines and hawsers.

$$[\mathbf{K}] = [\mathbf{K}]^{\mathrm{T}} + [\mathbf{K}]^{\mathrm{M}} + [\mathbf{K}]^{\mathrm{H}} \tag{5}$$

where $[\mathbf{K}]^{\mathrm{T}}$, $[\mathbf{K}]^{\mathrm{M}}$ and $[\mathbf{K}]^{\mathrm{H}}$ are the stiffness matrices of the tendon, mooring lines and the hawsers, and those are given by Eqs. (6)–(8). Derivations on the stiffness of the hawser and mooring lines are included in Appendices A and B. In this study, the linearized stiffness matrix is utilized and the coupled terms between two floating bodies are considered in hawser stiffness matrix.

$$k^T_{ij} = \begin{cases} \displaystyle\sum_{i=1}^{N^T} \frac{T_{0,i}}{l_{line,i}} & i = j = 1, 2 \\ \displaystyle\sum_{i=1}^{N^T} \frac{T_{0,i}}{l_{line,i}}\left(l^2_{x,i} + l^2_{y,i}\right) & i = j = 3 \\ 0 & else \end{cases} \tag{6}$$

$$[\mathbf{K}]^{\mathrm{M}} = \begin{bmatrix} [\mathbf{K}]^{\mathrm{M}}_T & [0]_{3\times3} \\ [0]_{3\times3} & [\mathbf{K}]^{\mathrm{M}}_S \end{bmatrix} \tag{7}$$

where

$$[\mathbf{K}]^{\mathrm{M}}_{T,S} = \begin{bmatrix} \displaystyle\sum_{i=1}^{N^{\mathrm{M}}_{T,S}} k^{\mathrm{M}}_{x,i} & 0 & \displaystyle\sum_{i=1}^{N^{\mathrm{M}}_{T,S}} -T_{0,i} sin\beta_i \frac{l_{moor,i}}{l_{line,i}} - k^{\mathrm{M}}_i l_{moor,i} \sin(\gamma_i - \beta_i) cos\beta_i \\ & \displaystyle\sum_{i=1}^{N^{\mathrm{M}}_{T,S}} k^{\mathrm{M}}_{y,i} & \displaystyle\sum_{i=1}^{N^{\mathrm{M}}_{T,S}} T_{0,i} cos\beta_i \frac{l_{moor,i}}{l_{line,i}} - k^{\mathrm{M}}_i l_{moor,i} \sin(\gamma_i - \beta_i) sin\beta_i \\ Sym. & & \displaystyle\sum_{i=1}^{N^{\mathrm{M}}_{T,S}} T_{0,i} l_{anchor,i} \cos(\alpha_i - \beta_i) \frac{l_{moor,i}}{l_{line,i}} + k^{\mathrm{M}}_i l_{moor,i} l_{anchor,i} \sin(\gamma_i - \beta_i) \sin(\alpha_i - \beta_i) \end{bmatrix}$$