Semi-Active Magneto-Rheological Damper to Reduce the Dynamic Response of Top-Tension Risers

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ABSTRACT

The exploration and extraction of offshore hydrocarbon is currently facing stricter requirements in environmental conditions, structural integrity, and dynamic performance. If the structural responses can be monitored and controlled, then smart-platform technology can greatly widen the applicability of current technology toward deeper waters and more severe environmental conditions. This paper is focusing on the robust dynamic simulations and analysis of a top-tension drilling riser in a generic tension leg platform (TLP), incorporated with a fuzzy-logic-controlled magneto-rheological (MR) damper-tensioner system. The innovation is inspired from the successful engineering applications of MR dampers in land-based buildings as isolators against large-amplitude earthquake vibrations. The specific characteristic of MR dampers in alternating the damping forces has great potential to interactively change the structural behaviors corresponding to various external loadings. The main objectives of this paper are (i) to model a MR damper-tensioner that is tailored for use in the drilling riser on the TLP, (ii) to implement the MR damper-tensioner and its control scheme in the TLP global simulation program, (iii) to numerically study the proposed coupled tendon-riser-hull system under an extreme condition to verify its feasibility. This research is expected to provide a reliable and cost-effective solution for greatly expanding the capability of future smart offshore-platform technology.

KEY WORDS: MR (magneto-rheological) damper; riser stroke; tension; fuzzy-logic control; hull-tendon-riser coupled dynamic analysis.

INTRODUCTION

At present, an increasing number of floating offshore production platforms are planned, designed, and built in deep waters due to the booming development of new deepwater offshore oil fields. Those platforms are subjected to ever increasing wind and wave forces and it is necessary to minimize the dynamic responses of these structures (Colwell and Basu, 2009). If there is a reliable and cost-effective way to monitor the real-time condition and control the vibration of platform and its operating modules, such as the drilling riser, the risk of system failures can be reduced. The active or semi-active vibration reduction of offshore structures is still a challenging research area and its application has been limited to DP (dynamic positioning), ART (anti-rolling tank), and OWT (offshore wind turbine) areas.

The wave-induced dynamic force is one of the most important excitations to be dealt with in the design of offshore structures (Patil and Jangid, 2005). For a reliable design of an offshore structure, it is important to reduce the wave-induced dynamic responses. Studies have indicated that the dynamic interaction between the TLP hull and its tendons/riser system plays a significant role in the functionality and safety of the system (Kanda et al. 1998; Kim et al., 2001). As water depth gets deeper and deeper, the TLP’s heave-pitch natural frequencies get closer to high-wave-energy range and the corresponding dynamic effect can be significant (Kim, 2003). For a safer and more reliable design of a TLP in such large depths, the mitigation and control of TLP heave-pitch responses need to be seriously considered. In case of semi-submersibles with top tension riser (TTR) and dry tree, an on-deck blowout preventer (BOP), for ultra deepwater development, minimizing the riser stroke at its top joint is also a very critical issue.

This research is focusing on the robust dynamic simulation and control of a drilling riser incorporating a conceptual MR damper-tensioner (working cooperatively with its hydro-pneumatic tensioner counterpart) under extreme conditions. The innovation in this paper is inspired from the successful engineering applications of MR dampers for land-based buildings as isolators against large-amplitude earthquake vibrations. The MR dampers can function in alternating tension and compression regimes and can exert large range of damping forces to interactively change the structural behaviors correspond to various external loadings (Friedman et al., 2010; Wang and Liao, 2011).

The main objectives of this paper are (i) to model a MR damper-tensioner that is tailored for use with the drilling riser on the TLP, (ii) to implement the MR damper-tensioner and its control scheme in the TLP global simulation program, (iii) to numerically study the proposed coupled tendon-riser-hull system under extreme conditions to verify its feasibility. The difficulty in modeling the MR damper-tensioner mostly comes from the nonlinearity of the damping force. The upstroke and down-stroke limitation of a conventional pneumatic tensioner mostly comes from the nonlinearity of the damping force. The upstroke and down-stroke limitation of a conventional pneumatic tensioner also requires nonlinear modeling (Yang and Kim, 2010). In the conventional coupled analysis method, the riser tensioner is modeled by using a linear spring and then the tensioner nonlinearity is subsequently modeled in the separate finite element (FE) analysis for only the riser by applying the calculated responses at its top. This kind of approach cannot be used when MR-damper control is involved. To illustrate the benefits of the MR damper-tensioner concept, the results
with the controlled MR damper-tensioner on a drilling riser of a TLP are compared with those without it to demonstrate its applicability in a realistic problem.

NUMERICAL MODEL

A generic TLP model with eight tendons, seven production top tension risers (TTRs), and one MR damper-tensioner controlled drilling riser is selected for the analysis. The principal dimensions of the TLP platform are tabulated in Table 1. The TLP consists of four circular columns of 16.46 m (54 ft) outer diameter which are connected at the keel by rectangular pontoons of 8.23 m (27 ft) width and 7.31 m (24 ft) height. The center to center distance is 60.96 m (200 ft). It has 13.7×4.6 m² (45×15 ft²) rectangular center wells that connected to the risers on production deck. The detailed specification of this generic TLP model can be retrieved from the works of Kim et al. (2001) and Yang (2009).

The FE model of the MR damper-tensioner coupling the drilling riser and the hull motion is implemented in CHARM3D, a fully-coupled time-domain dynamic-analysis program for floating bodies, mooring lines/tendons, and risers (Ran and Kim, 1997; Ran et al., 1999; Yang and Kim, 2010). The frequency-dependent hydrodynamic coefficients and the first-order wave excitation forces and moments are calculated by the near-field method by using WAMIT, a diffraction/radiation panel program. The corresponding forces are converted to the time-domain using a two-term Volterra series expansion in CHARM3D. The frequency-dependent radiation damping was included in the form of a convolution integral in the time domain simulation. Viscous forces are included through the drag force term in Morison’s equation (Yang and Kim, 2010).

Table 1: Principal dimensions of the generic TLP model

<table>
<thead>
<tr>
<th>Water Depth</th>
<th>914.36 m (3000 ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of column</td>
<td>4</td>
</tr>
<tr>
<td>Column cross section diameter</td>
<td>16.46 m (54 ft)</td>
</tr>
<tr>
<td>Column center to center distance</td>
<td>60.96 m (200 ft)</td>
</tr>
<tr>
<td>Column freeboard</td>
<td>20.42 m (67 ft)</td>
</tr>
<tr>
<td>Pontoon breadth</td>
<td>8.23 m (27 ft)</td>
</tr>
<tr>
<td>Pontoon height</td>
<td>7.31 m (24 ft)</td>
</tr>
<tr>
<td>Height of deck bottom from MWL</td>
<td>22.86 m (75 ft)</td>
</tr>
<tr>
<td>Deck height</td>
<td>12.19 m (40 ft)</td>
</tr>
<tr>
<td>Draft</td>
<td>24.38 m (80 ft)</td>
</tr>
<tr>
<td>Total weight</td>
<td>24157 MT (236980 kN)</td>
</tr>
<tr>
<td>Tendon pretension at the top</td>
<td>7031 MT (68974 kN)</td>
</tr>
<tr>
<td>Riser pretension at the top</td>
<td>1588 MT (15578 kN)</td>
</tr>
<tr>
<td>Displacement</td>
<td>32775 MT (321522 kN)</td>
</tr>
</tbody>
</table>

*MWL = Mean water level

Tendons and risers are modeled using an FE representation of an elastic rod (Garrett, 1982; 2005; Yang and Kim, 2010). The definition sketch and the free body diagram are shown in Figure 1. The tendons and risers mostly have circular cross sections thus there is no distributed torsional motion from the hydrodynamic forces. In addition, the torsion in the line is usually small enough to be neglected (Ran, 2000). The rod is assumed as inextensible where the arclength s is the same in both the deformed and the undeformed states (Garrett, 1982). Under these assumptions, the equations of motion for the elastic rod can be represented as follows:

\[ -\{EI\dddot{r}\} + \{\lambda r\}' + q = \rho \ddot{r} \]  

where \( EI \) is the bending stiffness, \( r(s,t) \) is the centerline of the rod, \( \lambda \) is the Lagrange multiplier, \( q \) is the applied load (weight and drag, for instance), \( \rho \) is the mass of the rod per unit length. If the rod is considered stretchable and the stretch is linear and small, the above inextensibility condition can be approximated by:

\[ \frac{1}{2} (r' \cdot r' - 1) = \frac{T - T_0}{AE} \]  

where \( T \) is the tension, \( T_0 \) is the un-stretched tension, and \( AE \) is the axial stiffness. The cubic shape functions are used for the line elements to calculate the displacement and tangential vectors. On the other hand, the tensions in the line elements are determined by using the quadratic shape functions. The direct wave and current loads \( q \) are described using a Morison formulation (Rodenbusch et al., 1986):

\[ q = C_d V_n |V_n| + C_m a_n - C_a r'_n \]  

where \( C_d \) is the drag coefficient, \( C_m \) is the inertia coefficient, \( C_a \) is the added mass coefficient, \( V_n \) is the normal component of relative velocity, \( a_n \) is the normal component of water particle acceleration, \( r'_n \) is the normal component of rod acceleration, and \( n \) is the simulation step.

\[ M\ddot{y} = F + H \]  

\[ M\ddot{z} = F + H \]  

\[ \dot{y} = \dot{z} \]

where \( M \) is the inertia matrix, \( y \) is the vector of unknowns in FE equations, \( F \) is the internal loads and external loads for which derivative are available, and \( H \) is the hydrodynamic load. For numerical integration, the first order equations are written in discrete form (Garrett, 2005):

\[ M \left( \frac{z_{n+1} - z_n}{h} \right) = \frac{1}{2} (2F_n - K(y_{n+1} - y_n)) + \frac{1}{2} (3H_n - H_{n-1}) \left( \frac{y_{n+1} - y_n}{h} \right) \]

\[ = \frac{1}{2} (z_n + z_{n+1}) \]  

where \( K \) is the stiffness of rod. The hydrodynamic loads, including radiation terms, are integrated using the explicit Adams-Bashforth method.