Hang-off Analysis on Deepwater DST String Evacuation in Typhoon Condition

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Abstract. A Drill-stem tested (DST) string system requires relatively longer time for full retrieval, and evacuation during typhoon is an important event in deepwater testing. The hang-off DST string system has a high risk as it experiences strong load due to ocean currents and multi-DOF motion of the floating platform. In this paper, a multi-tube model of DST string system that considers multi-point constraints is presented. Hang-off dynamic analysis, platform heading analysis, and evacuation window analysis are conducted. The results show the stress of the DST string system increase dramatically at top. The translational response of the floating platform has a great influence on the safety of the DST string system. The evacuation window is large in the downstream direction and is infeasible in the upstream direction. The operational performance of the DST string system during hang-off evacuation can be improved when driven in a smaller angle with current and orient the platform heading to reduce heave motion.

1. Introduction

Deepwater testing is of great significance for timely discovery and accurate evaluation of subsea oil and gas reservoirs, and it has become a research hotspot in the offshore petroleum industry [1]. In recent years, remarkable progress in deepwater testing has been made in China. The first deepwater testing of a proprietary well at the LS17-2 location was completed by HYSY981 in August 2014. The first ultra-deepwater gas field in China was discovered in December 2015. Offshore methane hydrate was successfully produced from the Shenhu Sea area in May 2017.

Drill-stem tested (DST) can save time and reduce the appraisal cost of offshore wells. However, there are a number of challenges to the use of DST string with mobile platforms [2]. For example, the release and retrieval process of a DST string system is complex. The DST string system requires relatively longer time for full retrieval. Once harsh weather exceeds allowable operation conditions, the DST string and outer riser should be disconnected with down-hole strings from a blowout preventer (BOP), and transferred to the hang-off mode [3]. There were as many as 50 recorded release events in 446 deepwater tests conducted in Brazil. If the development of a typhoon is too rapid and there is no time to retrieve a DST string system, the platform must be evacuated with a hang-off DST string system that will be significantly influenced by harsh weather and multi-DOF motion of the platform. The interaction between a DST string and the outer riser makes evacuation during a typhoon more dangerous. Hence, conducting dynamic analysis and contingency plans is essential for ensuring the safety and reliability of a hang-off DST string system in the typhoon condition.

At present, some scholars and field engineers have conducted research on the dynamic characteristics of deepwater drilling risers in hard and soft hang-off modes [4-8]. However, there are few reports on the dynamic characteristics and the typhoon-avoidance strategy of a DST string system. The
bottom of the deepwater DST string system hangs free during evacuation. The nonlinear interactions between a DST string and the riser are more significant due to the strong drag load from the ocean current. Convergence in computational model of the coupled system is difficult. In view of the industrial and evacuation requirements, this study focuses on hang-off analysis on deepwater DST string system evacuation in the typhoon condition. A multi-tube model of deepwater DST string system with multi-point constraints is presented. Thereafter, hang-off dynamic analysis, platform heading analysis, and evacuation window analysis are conducted based on the analysis model. Finally, measures for improving the operational safety of a DST string system in evacuation are proposed.

2. Analysis model

2.1. Physical model
Deepwater testing is usually conducted from a mobile platform. The deepwater DST string system, which includes an inner DST string and an outer riser, is connected platform at sea level to a conductor through a submarine wellhead. The outer risers provide protection for the DST string and form a circular channel for the testing fluid, while the inner DST string is the channel that transports oil and gas from the reservoir. The DST string system is a crucial equipment and is vulnerable in deepwater testing. During deepwater testing, a problem that cannot be ignored regards what actions should be taken during a storm. When the environmental conditions exceed the operation limits, the DST string and riser must be disconnected from the down-hole strings and removed individually. The basic procedure can be described as closing the well, disconnecting the DST string, and disconnecting the riser[9]. Typhoons sometimes develop rapidly and spread along complex paths, and the contractor may miss the best opportunity to retrieve strings. Then, the deepwater DST string system should be shut-down using a BOP shear ram in emergency, and transferred to the hang-off mode in order to protect the integrity of the wellhead and other facilities.

Figure 1. Deepwater DST string system during evacuation.

The deepwater DST string system in typhoon-avoidance evacuation is shown in figure 1. The deepwater DST string system bears a wide range of loads, including wave, current, weight of the strings, buoyancy, and interaction between the outer riser and inner string. The outer barrel and inner barrel of the telescopic joint are locked together to avoid exceeding the maximum stroke length for
evacuation in the typhoon condition, thus the multi-DOF motion of the floater will pass to the top of the DST string and riser. The dynamic axial response of the hang-off strings will be aggravated due to the weight and axial stiffness of the string. During evacuation, the hang-off strings will suffer strong lateral drag effect at greater depths below water. In addition, the interaction between a DST string and riser makes the forces acting on the deepwater DST system very complex. The motion of the DST string system is nonlinear because the bottom of the string is free, thus the time domain method is required to analyse the dynamics of the deepwater DST string system.

2.2. Mechanical Model
The DST string and riser has a large aspect ratio, thus the DST string and riser can be modelled as flexible beams. Considering the DST string and riser are composed of linear elastic homogeneous pipe elements with small deformation, the mechanical model of DST string and riser can be presented as:

\[ m \dddot{y} + \dddot{u} - \frac{E I}{T} \dddot{y} = F(z,t) \]  
\[ m \dddot{u} = \frac{E I \dddot{u}}{z} \]  

where \( m \) is the mass per unit length, \( y \) is the horizontal displacement, \( t \) is time, \( z \) is the vertical height, \( E \) is the elastic modulus, \( I \) is the moment of inertia, \( T \) is the effective tension, \( F \) is the transverse load per unit length including environmental loads and the interaction between the DST string and the riser, and \( u \) is the vertical displacement.

Horizontal motion of the DST string system with platform navigation will create an additional drag load on the string system during an evacuation. The resultant force from the current and additional drag depend on the speed and direction of navigation. Based on Morrison Equation, the model for calculating the load on DST string system from platform navigation and current can be expressed as:

\[ F_{NC} = \frac{1}{2} \rho C_d d l (v(t) \cos \theta + u(t) \cos \theta)^2 + (u(t) \sin \theta)^2 \]  

where \( F_{NC} \) is the force due to motion of the platform and current, \( \rho \) is the sea water density, \( C_d \) is the drag coefficient, \( d \) is the hydrodynamic diameter of the outer riser, \( l \) is the force bearing length, \( v \) is the current flow velocity, \( u \) is the navigation speed of the platform, and \( \theta \) is the angle between the navigation speed and current flow.

Waves are the primary load that drives the dynamic response of a DST string system. Waves affect a deepwater DST system in two ways. First, they produce hydrodynamic loads on the outer riser directly. Second, they cause the platform to move in three dimensions and form a dynamic boundary at the top of the DST string system. Random wave theory and the Response Amplitude Operator (RAO) are used to imitate the motion of the platform. The dynamic boundary of a deepwater DST string system can be denoted by:

\[ U_i(t) = \sum_{n=1}^{N} R_i(\omega_n) D_n \cos(k_n x - \omega_n t + \varphi_n + \alpha_n) \]  

where \( U_i (i=1 \text{ to } 6) \) is the motion response of the platform for each degree of freedom, \( R \) is the response amplitude operator (RAO), \( D_n \) is the amplitude of the nth wave component, \( \omega_n \) is the phase difference between wave motion and wave frequency motion, and \( k_n, \omega_n \) and \( \varphi_n \) are the wave number, frequency, and phase angle of the \( n \)th wave component, respectively.

There is an interaction between the riser and the DST string during evacuation. The displacement of a DST string is influenced by the constraints on the riser. The multi-point constraint approach is used in the mechanical analysis model. Specifically speaking, the freedom of the point in the riser is defined as a standard value. Then, establish the linear correlation between the freedom of point in the...
DST string and standard value. Based on the Abaqus Theory Manual, the linear constraint equations of DST string system can be expressed as:

\[ U^T_i = \sum C_i U^R_i + C_0^T : U^R_i = \sum C_i U^R_i + C_0^R \]  

(5)

where \( U^T \) is the slaver degrees of freedom (the DOF of point in DST string), \( U^R \) is the master degrees of freedom (the DOF of point in riser), \( C_i \) is the weight coefficient, \( C_0 \) is the increment of intercept, \( Y \) and \( Z \) are the identifiers for horizontal direction and vertical direction, respectively.

2.3. Simulation Model

Currently, an equivalent composite model is often used to analyse double-layer strings in offshore. The equivalent bending and tension are shared based on the stiffness or bearing area. This model can be used to analyse motion of string, but is unlikely to be accurate for evaluating strength and fatigue damage \[10\]. Based on the multi-point constraint approach, a finite element model of deepwater DST string system is built up by ABAQUS and Python for hang-off analysis during evacuation in this paper. A Partially enlarged view of the DST string system is shown in figure 2. The blue region in figure 2 is the riser element, while the red region is the DST string element. The inner DST string and outer riser are simulated using PIPE31 element. The multi-point constraint approach is used in the simulation, as shown in figure 3. The blue and red lines indicate the riser and DST elements, and the blue and red points are the nodes in corresponding elements, respectively. The nodal displacement of a DST element should be in line with the displacement of the adjacent two nodes in the riser. The multipoint constraint approach defines coupling between master and slaver points. Some parameters, such as the weight coefficient and intercept increment, can be calculated automatically in iterative process. The proposed simulation model provides high computational efficiency and high prediction accuracy.

![Figure 2. Partially enlarged view.](image)

![Figure 3. Multi-point constraint approach.](image)

The top of the DST string and riser have six degrees of freedom in the simulation model. The ends of the DST string and riser are defined as free in order to simulate hang-off mode after an emergency disconnect. One real current and one virtual current are used in the simulation model. The real current refers to the current in the ocean, while the virtual current is a constant value that depends on the evacuation speed and direction of the platform.

3. Results and discussions

A specific deepwater well at a depth of 1500 m in the South China Sea was studied as an example. The outer diameter, thickness, and length of the riser joint is 21 in, 0.875 in and 75 ft, respectively. The outer diameter of the buoyancy block is 54 in. The dry weight of the riser joint is 14728 kg, while the buoyancy force provided by buoyancy block ranged from 10936 to 12812 kg. The outer and inner diameters of the DST string are 4.5 and 3.37 in respectively, and the linear density is 24 lb/ft. The yield strength of the riser and DST string are 550 and 650 MPa. The rotational stiffness of the lower flex joint is 127.4 kN·m/rad. The weight of the lower marine riser package (LMRP) is 129 t. Two centralizers at 750 m and 1450 m height above Mud Line (ML) in inner DST string are considering in
multi-tube model. The environmental conditions in the operation region under typhoon sea states are presented in Table 1. The drag coefficient in Morrison Equation is set 1.2.

Table 1. Environmental condition under typhoon.

|            | 1-year typhoon sea states | 10-year typhoon sea states | 100-year typhoon sea states |
|------------|---------------------------|-----------------------------|-----------------------------|
| Wave       | Wave height (m)           | 3.9                         | 8.6                         | 13.8                        |
|            | Period (s)                | 6.8                         | 12.4                        | 15.4                        |
| Current    | Surface velocity (m/s)    | 1.07                        | 1.55                        | 2.02                        |
|            | Seabed velocity (m/s)     | 0.31                        | 0.36                        | 0.40                        |

3.1. Hang-off Dynamic Analysis

Taking the evacuation speed as 0.3 m/s in the downstream direction and the root-mean-square (RMS) of node lateral deflection (relative to the top of the DST system) in time domain as the steady-state value, the RMS deflection curve and maximum von Mises stress on the DST string system are shown in figure 4 and figure 5, respectively.

As shown in figure 4, the RMS deflection curves of the DST string system are parabolic during the three typhoon conditions when the evacuation speed is 0.3 m/s in the downstream direction. Although the downstream navigation of the platform inhibits the deformation of the DST string system, the lateral deflection of the system is still large in such a harsh environment. Taking the top of the DST string as a reference point, the lateral deflection increases from up to down in the analysis result. Under the influence of current profile in the typhoon condition, the change rate of lateral deflection is larger in the upper portion of the string and the change rate is reduced with the deepening of water depth. The maximum lateral deflections at the bottom of the system are 12.1 m, 26.7 m and 42.2 m under the three different typhoon conditions. A larger current produces larger lateral deflection. Therefore, marine environment is vital for the structural safety of the hang-off DST string system.

Figure 5 shows that the strength of the hang-off DST string system accords with the American Petroleum Institute recommended practice [11] under the 1-year typhoon sea states. However, it is extremely dangerous under the 100-year typhoon sea states. The motion of the platform could directly impact the top of the string, and stress easily concentrates at the top of the hang-off string system. Thus, the top of the DST string system is dangerous and the strength should be considered seriously. For the difference in mass between the inner and outer strings, the von Mises stress on the riser is larger than that on the DST string. The von Mises stress tends to decrease with the water depth as a whole due to vibration attenuation. Besides, the von Mises stress of the DST string exhibits a sudden decline at points where the cross-sectional areas change, such as at the centralizers (at 750 m and 1450 m height above mud line).
3.2. Platform Heading Analysis

The coordinate system is defined as follows: $Z$ is the deck height direction; $X$ is the direction along the bow and stern; $Y$ is the direction along the port and starboard. The six degrees of freedom are heave, sway, surge, pitch, roll, and yaw. The RAO is closely related to the wave period. According to the environmental parameters shown in Table 1, RAO under typhoon conditions are analysed as shown in figure 6.

In figure 6, the angle refers to the direction of incident wave angle, which is the angular difference between the direction of wave motion and the positive $X$-axis (the direction of bow). The RAO radar charts are symmetric in the whole. The motion RAO radar charts along the $X$ and $Y$ directions have important relevance. The platform will surge severely but will not sway when waves propagate along the $X$-axis, and vice versa when waves propagate along the $Y$-axis. Pitch motion and roll motion exhibit the same characteristics. The wave periods are 6.8, 12.4, and 15.4 s in 1-year, 10-year, 100-year typhoon sea states. The translational RAO of the platform is gradually increased as the wave period increases in the case study. Namely, the motion of floating platform will be reinforced with the worsening of typhoon environment.
Translational motion (heave, sway and surge) RAO is measured in m/m, while rotational motion (pitch, roll, and yaw) RAO is measured in °/m. Figure 6 shows the rotational motion is much smaller than translational motion. Therefore, the translational response of the floating platform has a greater influence on the safety of the deepwater DST string system in typhoon-avoidance evacuation. The heave motion of the platform primarily affects the axial dynamic tension in the DST string system, while surge and sway primarily affect the bending moment. Therefore, the platform heading should be set along the wave propagation direction whose RAO due to heave motion is minimized in typhoon-avoidance evacuation process.

3.3. Evacuation Window Analysis

When a typhoon comes, floating platforms need to drive away from the center of typhoon. The evacuation direction and speed of the platform are influenced by the hang-off DST string system. Operability windows play an important role in guiding the operation of a deepwater DST string system. According to field experience and operating procedures, several risk factors needed to be considered when determining the safe evacuation window. First, the bottom of the DST string system cannot crash into the seabed. Second, the DST string and riser must not compress dynamically. Third, the von Mises stress in the DST string and riser must meet the requirement. Fourth, the hang-off DST string system cannot crash into the moon pool. Finally, the angle of the low flex joint cannot exceed its mechanical limits. Safe evacuation speeds of platform in different evacuation directions can be determined through a series of calculations using the proposed analytical model. The safe evacuation windows in different typhoon conditions are shown in figure 7.

![Figure 7. Safe evacuation window.](image)

The angle in figure 7 is the platform evacuation angle, which is the angular difference between the platform evacuation direction and the direction of the current. The green areas show safe evacuation directions and speeds. Fig. 7 shows that the safe evacuation window of DST string system is symmetrical along the marine current direction. The platform evacuation speed range narrows as the platform evacuation angle increases. The evacuation window is large in the downstream direction and is infeasible in the upstream direction. The maximum allowable downstream evacuation speeds ranges from 0.10 to 1.22 m/s, 0.35 to 1.29 m/s, and 0.91 to 1.37 m/s in the different typhoon sea states, respectively. When the evacuation speed is offset by the current, the maximum allowable evacuation speed increases slightly as the typhoon environment worsens, while the allowed speed range is noticeably decreased. The navigation route and speed can be selected by the contractor based on a safe evacuation window in the typhoon condition.

4. Conclusions

A multi-tube model of a deepwater DST string system using multi-point constraints is presented to describe evacuation during typhoon. The hang-off dynamic analysis results show that the deflection curve of the DST string system is parabolic with maximum lateral deflection at the bottom of the string. Marine waves and motion of the platform increase the von Mises stress at the top of the string. Overall, stress tends to decrease along the string from the top to the bottom.
Based on the proposed dynamic analysis model, the safe evacuation window of hang-off DST string system is determined from the views of platform heading, evacuation direction and speed. The results show that the translational response of floating platform has a great influence on the safety of the DST string system. The safe evacuation window of DST string system is symmetric along the marine current direction. The evacuation window is large in the downstream direction and is infeasible in the upstream direction.

Several measures are proposed to improve the operational safety of the DST string in evacuation. These measures include orienting the platform heading with respect to the wave propagation direction such that heave motion RAO is minimized, driving in a smaller direction with current and using a suitable evacuation speed by safe evacuation window.

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