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Movement optimization of freely-hanging deepwater risers in reentry

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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

Due to the complexity of riser dynamic behavior in various sea conditions, the reentry of the deepwater drilling riser to the seabed wellhead is difficult to perform. To facilitate reentry operation, Ant Colony Optimization (ACO) algorithm is adopted to optimize the movement of the riser upper end. Under optimized movement, the distance between the riser lower end and the seabed wellhead is shortened, and the oscillation of the riser lower end is damped quickly. To test the efficiency of reentry motion optimization, the water-tank experiments are carried out. The experimental results show the good efficiency of the movement optimization. For a 1500 m riser in deepwater drilling, the numerical simulations of ordinary and optimized reentry motions are shown also.

1. Introduction

In the installation, the riser needs to be moved from the initial position to the above of the seabed wellhead, and then put it into the wellhead. This is the operation of riser reentry (Suzuki et al., 1994; Ioki et al., 2006). In the reentry of a deepwater riser, its lower end is completely free without connection with the seabed wellhead. Under the motion of its surface supporting structures such as floating platforms, drilling ships, etc., the riser lower end will oscillate in the ocean, which causes the difficulty of riser reentry for the uncertain position of the lower end. As Fig. 1 shows, after the movement of the upper end, the position of the riser lower end is uncertain for the oscillation.

To position the lower end of the freely-hanging deepwater riser, research has been carried out in the past decades. Suzuki et al. (1993, 1994) presented an active motion control scheme for deepwater reentry operating systems. The displacement of the floating body and the deformation of the model riser were measured by ultrasonic sensor, and optimal forces were generated by thrusters installed on the floating body and the model riser. The coupled governing equations of motion of the riser and vessel were derived from Hamilton's principle, and the performance of the control scheme was verified by a basin test with 1/2000 scale mode. Ohtsubo et al. (2005) applied the Linear Parameter Varying (LPV) method for the reentry of flexible marine risers, and experiments performed in a towing tank validated the effectiveness of the LPV control methods for reentry operations. Ioki et al. (2006) applied the LPV control method to the oscillation control research of freely-hanging risers. A gain scheduling controller for a model riser was designed to move the model riser to a target position as fast as possible so as not to excite unstable oscillation. The control parameters were set experimentally. Xu et al. (2007) applied PID control with the adjustable settings for the reentry study of freely-hanging drilling risers. By means of underwater image processing technology, the riser lower end could be moved and then positioned to the target location. Kajiwara and Noridomi (2009) had carried out research on an automatic control system for riser dynamic reentry in steady current. The linear quadratic control methodology had been applied to the reentry controller, and its efficiency has been validated by tank experiments.

The past researches about riser reentry were mainly focused on the position control of riser lower end and the reduction of riser oscillation. However, a usually neglected fact is that the different movements of the riser upper end may result in the different oscillations after the movements, although the riser could be moved from the original position to the target one. Thus there is a problem to be solved: what is the optimal movement of riser upper end by which the riser is moved from the original position to the target position with the least oscillation in a given time interval? Obviously, the movement optimization is conducive to improve efficiency of riser reentry.

In our research, this paper tries to optimize the movement of riser upper end via the Ant Colony Optimization (ACO) algorithm, by which the riser is moved to the target position with the reduced oscillation. The paper is organized as follows: Section 2 introduces the physical model of a freely-hanging marine riser and numerical calculation method of riser dynamics. Section 3 gives details of the ACO algorithm. In Section 4, the effectiveness of the proposed

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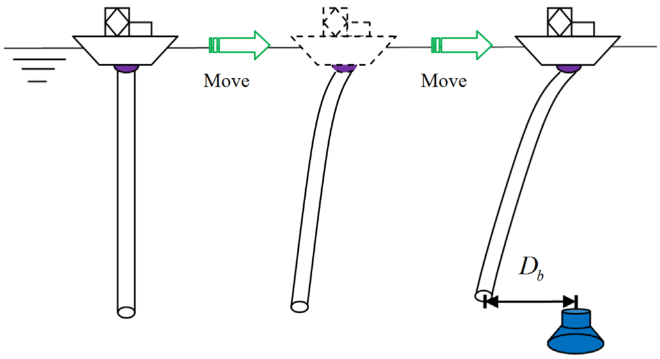

Fig. 1. Reentry process of a freely-hanging riser. D_b is the lateral distance between the riser lower end and the seabed wellhead, uncertain for the oscillation after movement.

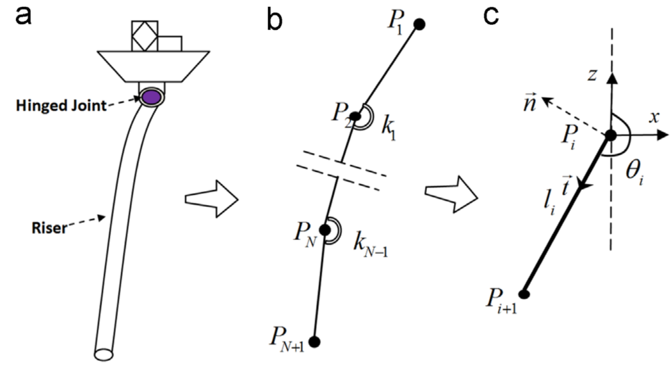

Fig. 2. Physical model of a freely-hanging marine riser: (a) a riser in reentry, (b) its dynamic model, and (c) magnified P_i node.

optimization method is validated. Section 5 presents the simulation results of movement optimization of a 1500 m riser by the proposed optimization method.

2. Physical model and numerical calculation

For a freely-hanging riser, the motion of it lower end is influenced by the movement of its upper end. To get the riser response to the movement of the upper end, a suitable physical model and a corresponding dynamics calculation method are necessary. In the current methods of dynamics calculation about marine risers or pipelines, the axial discrete models are widely adopted. The most common calculation method is the Finite Element Method (FEM), which was previously used by O'Brien and McNamara (1989), Park and Jung (2002), Park et al. (2003), Santillan and Virgin (2011), O'Grady and Harte (2013), Gong et al. (2014), and Connaire et al. (2015). Furthermore, Xu and Wang (2012) and Xu et al. (2013) proposed an efficient numerical calculation method based on a flexible-segment model, in which the equations of moment equilibrium were listed as governing equations. Wang et al. (2012) had also made the numerical simulations of the dynamic behavior of slender marine structures in reentry using a particular Finite Difference Approximation (FDA) method – the Keller Box method. The numerical simulations had been proved accurate compared with the experimental results of Hong (2004). To make full use of the past research platform, the Keller Box method is adopted in the present study to make the numerical calculation of riser motion in reentry.

2.1. Riser physical model

The initial state of the freely-hanging riser is assumed vertical in calm water, with the upper end hinged to the surface vessel or platform. The riser upper end is moved from the initial position to the target position according to the distance between the riser lower end and the seabed wellhead. In the movement, the riser is assumed slightly deflected from the vertical status in the motion. The physical model is shown in Fig. 2. The marine riser is divided into N straight rigid segments with $N+1$ nodes. Two adjacent segments are assumed to be connected by a node joint where a rotational linear spring is used. If there is a bottom weight at the lower end, the bottom weight can be viewed as a lumped mass.

In the movement from the initial position to the target position, only the inline motion is taken into account, and the transverse motion related with Vortex Induced Vibration (VIV) of riser is neglected here. The riser is assumed to be moved in a two-dimensional plane perpendicular to the water surface. The governing equations of riser motion are provided by Triantafyllou (1994), and then simplified by Chatjigeorgiou (2004, 2008), expressed in tangential and normal directions:

$$m\left(\frac{\partial u}{\partial t}-v\frac{\partial \theta}{\partial t}\right)=\frac{\partial T}{\partial l}+EI\frac{\partial^2\theta}{\partial l^2}\frac{\partial \theta}{\partial l}-Q\frac{\partial \theta}{\partial l}-W\cos\theta-F_t \tag{1.1}$$

$$mu\frac{\partial \theta}{\partial t}+(m+m_a)\frac{\partial v}{\partial t}=-EI\frac{\partial^3\theta}{\partial l^3}+\frac{\partial Q}{\partial l}+T\frac{\partial \theta}{\partial l}+W\sin\theta-F_n \tag{1.2}$$

$$\frac{1}{EA}\frac{\partial T}{\partial t}=\frac{\partial u}{\partial l}-\frac{\partial \theta}{\partial l}v \tag{1.3}$$

$$\frac{\partial \theta}{\partial t}=\frac{\partial v}{\partial l}+\frac{\partial \theta}{\partial l}u \tag{1.4}$$

where l is the Lagragian coordinate; t is the time; m is the mass per unit length; m_a is the added mass in transverse direction, and $m_a=(C_m-1)\rho_w A$, where C_m is the inertial coefficient, ρ_w is the water density; E is the Young modulus; A is cross-sectional area; I is the moment of inertia; u and v are the tangential and normal velocities respectively; T is the tension along the riser structure, Q is the shear force of the cross section at each node; $W$is the weight in water per unit length; θ is the angle of each node between the tangential direction and the vertical line; F_t and F_n are the external hydrodynamic forces in the tangential and normal directions in Morrison semi-empirical equations. u, v, T, and θ are variables to be solved, marked by a matrix $\mathbf{Y}=[u,v,T,\theta]^T$.

2.2. Numerical calculation

In the dynamics calculation, the Keller Box method (Ablow and Schechter, 1983) is applied to get the numerical solution. The approximations of $\mathbf{Y}$ partial derivatives with the Lagragian coordinate l and the iteration time t are written in the following forms:

$$\frac{\partial \mathbf{Y}}{\partial t}=\frac{\mathbf{Y}_j^{i+1}-\mathbf{Y}_j^i}{\Delta t} \tag{2}$$

$$\frac{\partial \mathbf{Y}}{\partial l}=\frac{\mathbf{Y}_{j+1}^{i}-\mathbf{Y}_j^i}{\Delta l} \tag{3}$$

And the individual matrix $\mathbf{Y}$ can be approximated:

$$\mathbf{Y}=\frac{\mathbf{Y}_{j+1}^{i+1}+\mathbf{Y}_{j+1}^{i}+\mathbf{Y}_{j}^{i+1}+\mathbf{Y}_j^i}{4} \tag{4}$$

where the superscript means the time step in the iteration, while the subscript is the node number.

In the movement of the riser upper end, the flexible riser is assumed slightly deflected from the vertical in the calm water. In the numerical calculation, $\mathbf{Y}^i$ in the current time step is given, $\mathbf{Y}^{i+1}$ in the next time step needs to be obtained. In order to get $\mathbf{Y}^{i+1}$, the