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Axial and transverse coupled vibration characteristics of deep-water riser with internal flow

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Abstract

The present paper investigates the axial and transverse coupled vibration law of deep-water top-tensioned riser (TTR) under the combined effects of the internal fluid flow and external wave and current loads. The paper aims to derive nonlinear vibration equations of deep-water riser, which account for the coupling of axial and transverse vibration including vortex-induced vibration, the internal fluid flow and the changes of the riser cross-sectional area caused by internal and external pressure alteration. With all factors above involved, a coupling vibration model is developed for deep-water riser. Based on the numerical model established, the influences of internal flow and the changes of internal flow velocity on the coupled vibration of deep-water riser are analyzed. In addition, parameter excited dynamic response of the riser under complex environment is also studied. The comprehensive analysis demonstrates that the internal flow can greatly change the vibration characteristics of the riser, comparing with a hollow one. The results lend support to the conclusion that the vibration of riser is not sensitive to changes of the internal flow velocity.

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*Keywords:*coupled vibration, internal flow, dynamic response, flow-induced vibration, vibration characteristics

1. Introduction

As the exploration of oil and gas moves into deeper water area where marine structures encounter extreme hydrodynamic loads, flow-induced structure vibration becomes an increasing challenge for engineering design. For instance, marine risers may suffer damage due to excessive stress or significant fatigue because of coupled vibration

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or resonance. Deep-water riser may experience large axial and transverse coupled vibration due to the combined effects of the internal flow and external loads. In case of extreme deep-water-state, the complex nonlinear vibration of riser will significantly influence the vibration of deep-water riser. Therefore, it is essential to explore the complex dynamic responses of riser under combined excitations in order for structure safety.

Some studies have been carried out on pipes vibration. Thurman and Mote [1] derived nonlinear dynamic model by considering that the pipe axis is extensible. The model assumed that movement is against the influence of gravity; flow is steady; moment and the curvature is a linear relationship. Holmes [2] considered the axial force change due to axial deformation, and supposed the material satisfies the Kelvin-Voigt model. Namachchivaya [3] derived first order nonlinear equation of transverse vibrations using the Hamilton principle by considering wall tension, linear moment - curvature relationship, harmonic change of flow velocity. Semler et al. [4] derived a more comprehensive nonlinear dynamic model. The model takes into account the impact of the "stiffening" effect caused by the pipeline initial axial strain and stress on the vibration of the system. In this model, the effects of unsteady fluid flow velocity and gravity are also considered. Lee and Park [5] proposed nonlinear fluid-structure coupling 4-equation model for pipeline conveying fluid based on Newton's method and N-S equations. Zhang and Huang [6] improved 4-equation model by considering the second-order nonlinearity of pipes conveying fluid.

But for risers, the nonlinear coupling vibration is more complex because of vortex induced vibration, internal and external flow, axial and transverse coupled vibration, wave loads. In-depth research in this area needs to be carried out.

The purposes of the present study are to develop a coupling vibration model subject to top tension, platform motion, internal and external loads for deep-water riser, and investigate the influence of some important parameters on risers' vibration under the combined effects of the internal fluid flow and external wave and current loads.

2. Theoretical model

Marinerisers can be stretched along the axial direction under the extreme deep-water-state. Internal and external pressure alteration can cause the changes of the riser cross-sectional area, which will have a great impact on the internal flow velocity.

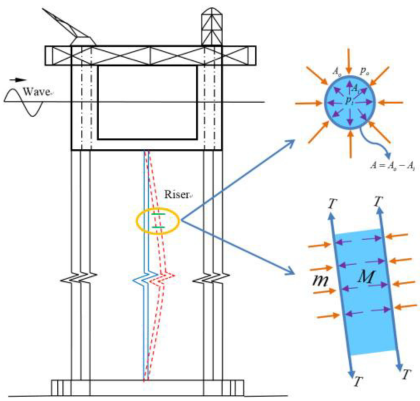

Fig. 1. Theoretical model schematic diagram with all factors

Figure.1 shows all factors which will affect the axial and transverse coupled vibration of deep-water risers. Considering the factors above, the internal flow velocity can be expressed as follows

$$U_2 = U_0\left[1+-\frac{2}{E}(1+\mu)\frac{A_i}{A_0-A_I}(p_i-p_0)-\frac{(2-4\mu)(p_iA_i-p_0A_0)}{EA}+2\mu\varepsilon+2\mu\frac{T}{EA}\right] \tag{1}$$

where U_0 and U_2 are internal flow velocities for static riser and vibrating riser, respectively. p_o and p_i are external and internal pressure, A_o and A_i are riser external and riser internal area. Hence, the riser wall area can be defined $A = A_o - A_i$. And T and ε are top tension and strain for riser differential element. E and μ are Young's modulus and Poisson's ratio of riser material.

The axial and bending deformation energy can be defined as

$$V_f = \frac{1}{2} EA \int_0^L \varepsilon^2 dx_0 \tag{2}$$

$$V_p = \frac{1}{2} EI \int_0^L (1+\varepsilon)^2 \kappa^2 dx_0 \tag{3}$$

where I is the polar moment of inertia for riser, and κ is curvature of riser.

The kinetic energy of riser and internal fluid can be expressed as

$$T_p = \frac{1}{2} m \int_0^L \left(\left(\frac{\partial u}{\partial t} \right)^2 + \left(\frac{\partial w}{\partial t} \right)^2 \right) dx_0 \tag{4}$$

$$T_f = \frac{1}{2} M \int_0^L \left[\left(\frac{\partial u}{\partial t} + U_2 + U_2 \frac{1}{1+\varepsilon} \frac{\partial u}{\partial x_0} \right)^2 + \left(\frac{\partial w}{\partial t} + U_2 \frac{1}{1+\varepsilon} \frac{\partial w}{\partial x_0} \right)^2 \right] dx_0 \tag{5}$$

where m and M are mass of riser wall and internal fluid, respectively. u and w are the axial and transverse displacement of riser.

The gravitational potential energy is considered as

$$V_G = \left(-(m+M) g + \rho A_o g \right) \int_0^L x dx_0 \tag{6}$$

where ρ is seawater density and g is the acceleration of gravity.

For a variable mass system, Hamilton Principle can be applied

$$\delta \int_{t_1}^{t_2} \left(T_f + T_p - V_f - V_p - V_g \right) dt = \int_{t_1}^{t_2} \left\{ MU \left[\left(\frac{\partial \mathbf{r}_L}{\partial t} \right) + U \tau_L \right] \cdot \delta \mathbf{r}_L \right\} dt \tag{7}$$

By substituting Eq. (1) ~ Eq. (6) into Eq. (7), we obtain the coupling vibration model equations subject to parametric excitation, vortex-induced and forced vibration.

3. Numerical simulation and discussion

Based on the coupling vibration model established above, the influences of internal flow on the coupled vibration of deep-water riser are analyzed. The work has concentrated on a 1500m water depth case. The parameter of 1500 m riser is shown in Table 1.

Table 1. Parameter of 1500 m riser.

Parameter name	Parameter Unit	Parameter Value
External diameter	D_o (m)	0.25
Internal diameter	D_i (m)	0.22
Water depth	L (m)	1500
Riser material density	ρ_R (kg/m^3)	3.317
Internal fluid density	ρ_L (kg/m^3)	2.012
Tensile and compressive stiffness	EA (N)	2.32556E9
Bending stiffness	EI (Nm^2)	1.6119E7
Top tension	T_0 (N)	1.0E5
Top pressure	P_0 (N)	4.47E5
Drag coefficient	C_D	1.10
Seawater density	ρ_f (kg/m^3)	1025
Ocean current velocity	V_f (m/s)	0.1

3.1. Influences of internal flow on the parametric excitation, vortex-induced and forced coupling vibration

Given that the top tension and platform motion are simple harmonic motion, top tension and riser displacement can be shown as $T = T_0 + \Delta T \sin \omega t$ and $y = y_0 \sin \omega t$, here $\omega = 2\pi / 15$, $\Delta T = 3.0E5$ N, $y_0 = 5.0$ m.

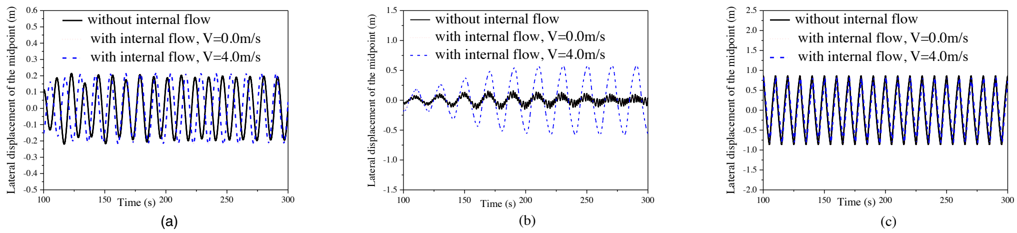

Fig. 2. Harmonic vibration time course curve (a) Vortex-induced vibration; (b) Parametric excitation vibration; (c) Forced vibration;

Fig. 2 shows four different vibration time course curves considering without internal flow and with different internal flow velocity (0 m/s and 4m/s). It is obviously that the internal flow can greatly change the vibration characteristics of the riser, comparing with a hollow one, especially for self-excited vibration. The results lend support to the self-excited vibration and forced vibration of riser are not sensitive to changes of the internal flow velocity, but parametric excitation vibration is significantly affected.

If the top tension and platform motion are random variation motion, which can be assumed follow P-M spectrum. Top tension and platform motion can be shown as $T = T_0 + \Delta T \times A\sum_0^{\infty} a_n \cos(\omega_n t + \varphi_n)$ and $y = B\sum_0^{\infty} a_n \cos(\omega_n t + \varphi_n)$.

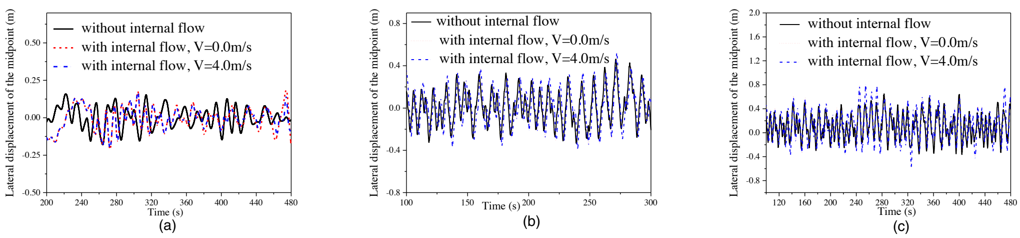

Fig. 3. Random vibration time course curve (a) Parametric excitation vibration (b) Forced vibration; (c)Parametric excitation, vortex-induced and forced coupling vibration;

Fig. 3 showsthree different vibration time course curves considering without internal flow and with different internal flow velocity (0 m/s and 4 m/s).The resultsdemonstrate that the internal flow can greatly change the vibration characteristics of the riser, especially for self-excited vibration.

3.2. Influences of top tension amplitude variationon the parametric excitation of riser with internal flow

In this section, simple harmonic motion and random variation motion are analyzed. By changing the value of ΔT (1.0×10^5, 3.0×10^5, 5.0×10^5), the influences of top tension amplitude variation on the parametric excitation of riser with internal flow are studied.

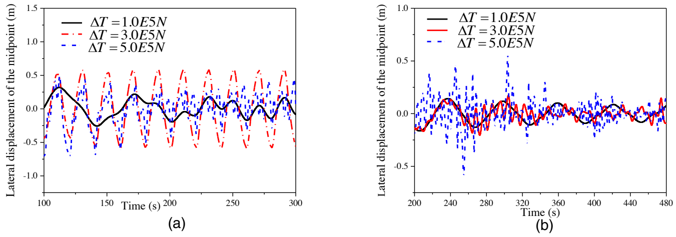

Fig. 4. Parameter Vibration under different top tension amplitudes (a) Harmonic vibration (b) Random vibration

Fig. 4 shows parameter vibration under different top tension amplitudes(1.0×10^5, 3.0×10^5, 5.0×10^5). When top tension amplitudes increases, the vibration of riser becomes more cluttered and fierce.

4. Conclusion

In the present study, a coupling vibration model is developed for deep-water riser by considering the coupling of axial and transverse vibration including VIV, the internal fluid flow and the changes of the riser cross-sectional area caused by internal and external pressure alteration. Based on the numerical model established, the following conclusions can be drawn:

(1) The internal flow can greatly change the vibration characteristics of the riser, comparing with a hollow one, especially for vortex-induced vibration.

(2) Vortex-induced vibration and forced vibration of riser are not sensitive to changes of the internal flow velocity, but parametric excitation vibration is significantly affected.

(3) The vibration of riser becomes more cluttered and fierce as top tension amplitude increases.

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