A novel centralizer layout scheme of TTR pipe-in-pipe system applied for vibration mitigation

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Abstract. The top tension riser (TTR) pipe-in-pipe system which includes outer pipes and inner pipes is widely used in offshore oil and gas development for production, water injection, completion, drilling and gas lift. Due to the complex external excitation and the violent collision between the outer pipe and the inner pipe, it is necessary to perform the vibration analysis for the production safety and service life of the entire TTR system. In this paper, a novel independent dual-pipe centralizer layout scheme based on the Absolute Difference Filter Method (ADFM) is generated for vibration mitigation. Another layout scheme based on multi-pipe model is provided for comparison. Result illustrates that the independent dual-pipe scheme is precise and economizes the cost of calculation. Dynamic analysis of a typical TTR pipe-in-pipe system considering the independent dual-pipe layout scheme is implemented via ABAQUS. Dynamic responses are discussed and compared with non-centralizer scheme and equidistant layout scheme. Results demonstrate that independent dual-pipe layout scheme has the best vibration mitigation effect.

1. Introduction
Top tension riser (TTR) is widely used in offshore oil and gas development for production, water injection, completion, drilling and gas lift. As shown in figure 1, a typical TTR pipe-in-pipe system includes outer pipes and inner pipes. The outer pipe provides effective mechanical protection for the entire riser system, while the inner pipe serves as a passage for fluids such as oil and gas. Between the inner and outer pipes is filled with thermal insulation material, which is used for thermal insulation to ensure that the inner pipe oil and gas resources can maintain fluidity. During production, the TTR pipe-in-pipe system is subjected to complex external loads. Due to the difference of the external excitation, the vibration characteristics of the inner and outer pipes are completely different, resulting in violent collision and contact between the inner and outer pipes, which will seriously damage the production safety and service life of the entire TTR system. Thus, for preventing the inner pipe from colliding with the outer pipe, the centralizer is arranged between the inner pipes and the outer pipes, as shown in figure 2. Due to the complex external excitation of the TTR pipe-in-pipe system and the collision between the outer pipe and inner pipe, it is necessary to perform the vibration analysis.
Roger Chang and Jim Yu built multi-pipe model where the gap element (GAP) was applied calculating responses of pipe-in-pipe system with the acceleration of stress increase factor (SIF). Result demonstrated that misplacing centralizers or improper spacing increased the contact load at the stress joint and keel joint [1]. C. H. Luk adopted PIP substructure model using pipe-in-pipe elements analyzing responses of the pipe-in-pipe consisting of buoyancy can and riser [2]. Jason Sun and Paul Jukes utilized Simulator which was an ABAQUS based in-house Finite Element Analysis (FEA) engine calculating the load and stress responses of the PIP at all installation stages [3]. Yongming Cheng et al. presented a theoretical formulation for a PIP riser system coupled with fluids in the annuli and centralizers between pipes and built composite model for modeling a PIP riser system in ABAQUS [4]. Kaiming Bi and Hong Hao proposed using pipe-in-pipe systems considered as a non-conventional structure-TMD system for the subsea pipeline vibration control. Results showed that the proposed pipe-in-pipe system could effectively suppress seismic induced vibrations of subsea pipelines without changing too much of the traditional design [5]. Kevin Chuanjian Man et al. provided a mathematical model for efficient calculation of the elongation of string subjected to gravity, pressure and thermal expansions where inner riser pipe pretension could be determined efficiently considering load conditions during the life time of the riser system [6]. Bin Yue et al. did tension and expansion analysis of pipe-in-pipe risers simulations with two widely used riser analysis finite element software, OrcaFlex and Flexcom [7].

From the above review, most researchers studied the dynamic analysis of the TTR pipe-in-pipe system via multi-pipe model calculated by FEM which has a high cost of computing. However, few attentions had been paid to the centralizer layout scheme which had significantly influence on vibration mitigation. Therefore, a novel centralizer layout scheme based on The Absolute Difference Filter Method (ADFM) is generated. In order to ensure the correctness of this scheme, another layout scheme based on multi-pipe model is provided for comparison. Dynamic analysis of a typical TTR pipe-in-pipe system considering the centralizer layout scheme is implemented via ABAQUS. Stress and displacement responses are discussed and compared with non-centralizer scheme and uniform layout scheme.

2. Analysis methodology

2.1. Independent dual-pipe model

Because the TTR pipe-in-pipe system vibration involves complex gap collisions of the inner and outer pipes, a centralizer is provided in the pipe-in-pipe system for reducing vibration. In order to control the production cost, centralizers are provided only in particularly severely impacted regions. However, the key issue is how to find these regions. Therefore, this paper proposes an independent dual-pipe centralizer layout scheme which consider the inner pipe and outer pipe as separate systems and study their vibration responses under external excitation. By extracting the lateral displacements in the study
time-course, data processing is performed to obtain collision-intensive regions. The data processing method will be described in detail in Section 2.4.

2.1.1. Outer pipe mechanical model. As shown in figure 3, the outer pipe is subjected to the combined action of wave loading, top axial tension and top platform displacement excitation. The static part of top tension can be expressed as [8]

\[ T_S = f W \]  

where, \( W \) is the submerged weight of riser per unit length in seawater; \( f \) is the pretension factor, and \( f = 1.3 \sim 1.6 \).

The time-varying part of top tension can be expressed as [9]

\[ T_t(t) = S_T \sin(\omega_T t) \]  

where, \( S_T = A \frac{L_W}{a_c} \), \( A \) is amplitude of platform heave motion, \( a_c \) usually equals to 10 in engineering; \( \omega_T \) is frequency of platform heave motion.

So, the total time-varying top tension can be written as a function of time \( t \)

\[ T(t) = T_S + T_t(t) \]  

As shown in figure 1, the governing equation based on the Euler-Bernoulli theory can be expressed as

\[ EI_o \frac{\partial^4 y}{\partial z^4} - T(t) \frac{\partial^2 y}{\partial z^2} + m_{ro} \frac{\partial^2 y}{\partial t^2} = F(z, t) \]  

where \( EI_o \) is the bending stiffness; \( m_{ro} \) is the mass of unit length of the outer pipe, \( F(z, t) \) the hydrodynamic force per unit length on the outer pipe and can be calculated by Morison Equation

\[ F(z, t) = \frac{1}{2} C_D \rho_w D \left( u_y - \dot{y} \right) \left| u_y - \dot{y} \right| + C_m \rho_w \frac{\pi D^2}{4} \frac{\partial u_y}{\partial t} - C_m \rho_w \frac{\pi D^2}{4} \ddot{y} \]  

where, \( \rho_w \) is the seawater density; \( D \) is the external diameter of the riser; \( u_y \) is the instantaneous seawater particle velocity along the y-axis; \( \dot{u}_y \) is the instantaneous seawater particle acceleration along the y-axis; \( C_D \) is the drag coefficient; \( C_m \) is the added mass coefficient and \( C_m = C_M - 1 \).

The bottom boundary conditions can be expressed as

\[ \begin{cases} y(z, t) |_{z=0} = 0 \\ \frac{\partial^2 y(z, t)}{\partial z^2} |_{z=0} = 0 \end{cases} \]  

The top boundary conditions can be expressed as

\[ \begin{cases} y(z, t) |_{z=L} = S(t) \\ \frac{\partial^2 y(z, t)}{\partial z^2} |_{z=L} = 0 \end{cases} \]  

where \( S(t) \) represents the vessel horizontal motion. In this paper, \( S(t) \) can be expressed as

\[ S(t) = a_v \sin \left( \frac{2\pi t}{T_v} \right) \]  

where \( a_v \) represents the amplitude of vessel surge, \( T_v \) represents the period of vessel surge.

\[ \text{Figure 3. Mechanical Model of Outer Pipe.} \quad \text{Figure 4. Mechanical Model of Inner Pipe.} \]
2.1.2 Inner Pipe Mechanical Model. As shown in figure 4, the inner pipe is acted upon by both the top axial tension and the top platform displacement excitation. The governing equation can be expressed as

$$E_l I \frac{\partial^4 y(x,t)}{\partial x^4} + m_{rl} \frac{\partial^2 y(x,t)}{\partial t^2} = 0$$

where $E_l$ is the bending stiffness; $m_{rl}$ is the mass of unit length of the inner pipe.

The bottom boundary conditions are the same as the outer pipe.

2.2. Multi-pipe model

The multi-pipe model has been applied by many researchers and is considered as the most accurate model for the pipe-in-pipe riser system. The key point is to use ABAQUS's ITT element for inner and outer pipe collision contact simulation, which is characterized by allowing contact clearance and relative slip between inner and outer pipes. In the modeling, the contact element is established on the inner pipe, and the slip line of the contact element is established at the corresponding position on the outer pipe.

The multi-pipe model considering centralizers is built for simulating actual engineering case, which most previous scholars ignored. The centralizers are set by means of Tie linker between the outer and inner pipes in ABAQUS.

2.3. Solution technology

The finite element software ABAQUS is adopted for simulation. The ABAQUS/AQUA module is invoked to apply a wave load to the riser system, which is simulated by the Stokes fifth-order wave theory. In the analysis of deep water pipe-in-pipe system, the beam element is usually taken advantage in order to improve the efficiency of calculation. The ITT element model is an accurate model for the pipe-in-pipe structural analysis, which is capable of simulating both the lateral and axial relative motion of inner and outer pipes. Using ITT21 element to simulate the interaction between inner and outer pipes. The entire dynamic analysis is solved by the ABAQUS Implicit Dynamic Solver.

2.4. Data process

2.4.1. Data Process for Independent Dual-pipe Model. The Absolute Difference Filter Method (ADFM) is applied and the specific process is displayed as following.

1) Outer pipe lateral displacement matrix $[u_o]_{N \times T_N}$ and inner pipe lateral displacement matrix $[u_i]_{N \times T_N}$ are given, where $N$ represents element node number and $T_N$ represents time point number.

2) Absolute difference matrix is obtained $[dx]_{N \times T_N} = [u_o]_{N \times T_N} - [u_i]_{N \times T_N}$

3) Data filtering can be expressed as $dx_{ij} = 0$ if $dx_{ij} < 80\% \cdot \max([dx]_i)$, where $[dx]_i$ represents the i th row of $[dx]_{N \times T_N}$

4) The effective displacement vector is expressed as $\{dx_e\} = \sum_{j=1}^{T_N} \{dx\}_j$, where $\{dx\}_j$ represents the k th column of $[dx]_{N \times T_N}$

5) Get peak values from $\{dx_e\}$, which are represented for the collision-intensive regions.

2.4.2. Data Process for Multi-Pipe Model. The multi-pipe model applied for data processing of centralizer layout scheme and the specific process are displayed as following.

1) Modeling the multi-pipe system in ABAQUS, then set the environment and loads parameters, get the solutions of each pipe’s lateral displacement.

2) Calculate the relative displacement of outer and inner pipes at the same position.

3) Find out the contact positions by comparing relative displacement to the annular clearance.
3. Result and discussion
Numerical studies are carried out to analyze the response characteristics of a TTR pipe-in-pipe system subjected to combining axial excitation and time-varying displacement boundary. The basic data of the riser is given in table 1. The effective wave period is 12.3s. Effective wave height is 6.5m. Drag coefficient $C_D$ is 1.5. Add mass coefficient $C_M$ is 0.6. The water depth is 500 m.

| Table 1. Geometric and Material Properties of Outer Pipe and Inner Pipe. |
|-----------------|-----------------|-----------------|
| Introduction    | Inner pipe      | Outer pipe      |
| Outer diameter, $D_o$ | 0.2984 m         | 0.5334 m         |
| Inner diameter, $D_i$  | 0.2348 m         | 0.4698 m         |
| Density of pipe, $\rho_r$ | 7800 kg/m$^3$    | 7800 kg/m$^3$    |
| Elastic modulus, $E$  | $2.1 \times 10^{11}$ Pa | $2.1 \times 10^{11}$ Pa |
| Poison ratio, $\mu$   | 0.3              | 0.3              |
| Top tension factor, $f$ | 1.6              | 1.6              |
| Platform surge amplitude, $a_v$ | 2 m              |                  |
| Platform surge period, $T_v$  | 25 s             |                  |
| Platform heave amplitude, $A$  | 1.5 m            |                  |
| Platform heave period, $T_H$ | 25s              |                  |
| Centralizer diameter, $D_c$ | 0.2984 m         |                  |

3.1. Independent dual-pipe centralizer layout scheme validation
For comparison, another equidistant model where centralizers are evenly arranged on the inner pipe. The independent dual-pipe model, multi-pipe model and equidistant model are calculated with solution technology demonstrated in Section 2. 3. Data process is implemented with the method proposed in Section 2. 4.

Figure 5. Accumulated Relative Displacement of Pipes from Different Models.

Figure 6. Collision Frequency of Pipes.

As shown in figure 5, the peak values of accumulated relative displacement are concentrated in the region of 75m–300m both in independent dual-pipe model and multi-pipe model whose distribution fits closely. The collision frequency of independent dual-pipe model and multi-pipe model is displayed in figure 6. It can be seen that high collision frequency happens in the region of 75m–300m both in independent dual-pipe model and multi-pipe model and the distribution of the high collision frequencies of the two models has a good fit. For collision mitigation, the centralizer should be set in the regions of high frequency collision. The centralizer layout schemes of all the three models are shown in figure 7. From the view of the collision frequency, the uniform distribution scheme also sets
centralizers in regions of low collision frequency, which will lead to waste of resources. The schemes obtained from the independent dual-pipe model and multi-pipe model are highly close, which confirms the correctness of independent dual-pipe model scheme. Compared with the multi-pipe model, the independent dual-pipe model is easier to model, the calculation speed is faster, and the convergence is better. Therefore, the independent dual-pipe layout scheme can be utilized.

Figure 7. Comparison of Different Centralizer Layout Schemes.

3.2. Dynamic responses of TTR pipe-in-pipe system considering centralizers
In this section, three cases are studied to investigate dynamic response of TTR pipe-in-pipe system, which are specified as follows.

Case A: TTR pipe-in-pipe system without centralizer
Case B: TTR pipe-in-pipe system considering equidistant centralizers layout scheme
Case C: TTR pipe-in-pipe system considering independent dual-pipe centralizers layout scheme

As shown in figure 8 (a) (b) (c) and (d) (e) (f), it can be seen that the stress response of independent dual-pipe centralizers layout scheme is the smallest that indicates the best mitigation vibration effect. What’s more, the stress response fluctuates intensely at the beginning. This is because that the inner pipe is in silent and the outer is excited by outside loads simultaneously which indicates enormous state differences. Comparing figure 8 (a) (d), (b) (e) and (c) (f), there is not much difference between the stress response of outer pipe and inner pipe.

Figure 8. 3D Stress Response of Outer Pipe and Inner Pipe in all Three Cases.
The root-of-mean-square (RMS) Mises stress responses of outer pipe and inner pipe which are to eliminate the effect of non-stationarity in all three cases are presented in figure 9. Peak stress response happens at the top end of riser in all cases which indicates it is a “dangerous stress region”. Besides, RMS Mises stress response of the independent dual-pipe centralizers layout scheme is the smallest both in outer pipe and inner pipe, and reduces 30.65% and 14.34% compared with those without centralizer and equidistant centralizers layout scheme respectively. Combining the conclusion gained from figure 8, it is clear that the independent dual-pipe centralizers layout scheme has the best vibration mitigation effect.

![Figure 9. RMS Mises Stress Responses of Outer Pipe and Inner Pipe.](image)

4. Conclusions

In this paper, independent dual-pipe model and multi-pipe model considering centralizer are built for dynamic analysis. A novel centralizer layout scheme based on the ADFM is generate via the independent dual-pipe model. Another layout scheme based on multi-pipe model is provided for comparison. Result illustrates that the independent dual-pipe scheme is precise and economic. Dynamic analysis of a typical TTR pipe-in-pipe system considering the independent dual-pipe layout scheme is implemented via ABAQUS. Stress and displacement responses are discussed and compared with non-centralizer scheme and equidistant layout scheme. Results demonstrate that independent dual-pipe layout scheme has the best vibration mitigation effect.

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