Vibration Law of Vertical Submarine Pipeline Based on Numerical Simulation

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Abstract. Due to the special working environment of the vertical submarine pipeline, the experimental research is difficult, so this paper makes a numerical simulation study on the turbulence vibration response of the vertical submarine pipeline based on Fluent software. It solves the vibration law of vertical submarine pipeline under different working conditions, and analyzes and discusses the vibration law of the vertical pipeline on the seabed. By establishing the geometric model of the vertical submarine pipeline based on the similarity principle, the flow field distribution law and the vibration law of the vertical submarine pipeline are obtained. When comparing the results of numerical analysis with the experimental results, the selected physical mathematical models are valid, with a margin of error of not more than 10 percent. Therefore, the vibration law and the movement law of the surrounding flow field of the vertical pipeline under different wall thickness, length, incoming flow velocity, different constraints and whether or not to add vibration absorber are analyzed. The results show that the vibration shape of the vertical pipeline is “8” shape under the action of incoming flow.

Keywords: Vertical Submarine Pipeline; Numerical Simulation; the Shock Absorber

1. Introduction

In the subsequent multidimensional analysis, the following patterns were observed: the thickness of the wall is proportional inversely proportional to the length of the tube, and the length of the tube is proportional to the length of the tube, and the flow rate is proportional to the length of the tube. Moreover, studies have shown that emission reduction units can reduce pipeline vibrations and that bandwidths can help the pipeline function effectively.

With the country’s rapid social and economic development, demand for oil is increasing. China’s near-sea water is relatively shallow, mostly less than 200 meters, with a continental shelf area of about 1.4 million square kilometers. China’s coasts are rich in hydrocarbon resources, and the seabed environment with good oil and gas reserves provides favorable conditions for oil and gas exploitation. As a result, the offshore oil industry is developing rapidly, with a large number of pipelines being laid on the seabed and implemented [1], and the stability of the pipelines anchored on the seabed has become one of the main issues in ocean development [2]. It is of practical engineering significance to study the movement law and failure conditions of this part of pipelines. A geometric model of vertical submarine pipeline based on similarity principle is established, to obtain distribution patterns and vibrations of
pipelines anchored on the seabed. The results of the numerical analysis are compared with the experimental results, particularly with regard to the range of pipeline vibrations and the frequency of decreased persuasive movement. The comparison results show that the numerical analysis results are in good agreement with the experimental results, and the error is less than 10%. Therefore, the vibration law and the motion law of the surrounding flow field of the vertical pipe under different wall thickness, length, incoming flow velocity, different constraints and whether vibration absorbers are added or not are analyzed.

Pu Jinjing [3] of Ocean University of China analyzed the causes of submarine pipeline suspension, vortex-induced vibration of pipeline suspension, response of seabed soil support properties to vortex-induced vibration of submarine pipeline suspension, comprehensive coupling effect of external flow field, submarine pipeline and seabed soil support properties. The method adopted is mainly the combination of numerical analysis and experiment, and finally the vibration failure condition of the pipeline is obtained and the corresponding solution is proposed. Hu Jiashun of Dalian University of Technology [4] focused on the key scientific and technical issues in the vibration analysis of submarine suspended spans pipelines and the identification of structural states and cracks. Theoretical and experimental studies are carried out systematically, and a numerical model is established to simulate the boundary conditions of suspended span pipelines with three-way soil spring constraints. The effects of parameters such as boundary soil properties, external environmental load, axial force and suspended span length on the natural frequency of the structure are discussed. Secondly, according to the internal characteristics of the frequency structure of the suspended pipeline, the feature vector sensitive to the structural state is constructed, and a state identification method of the suspended pipeline based on Kernel Discriminant Analysis (KDA) is proposed. Finally, a model test of state identification of suspended pipelines is carried out, and the effectiveness of the method is verified by model test data.

Wu Xin [5] of the Institute of Mechanics, Chinese Academy of Sciences studied the coupling interaction force between pipe and soil of submarine pipelines by numerical analysis method, and compared the vibration law of pipelines under different load conditions when the pipelines are constrained by soil.

Sudhakar & Vengadesan (2012) [6] conducted in-depth research on the vortex at the tail of the cylinder and the lift and drag on the surface of the cylinder. Some foreign scholars use Cartesian coordinates and immersed boundary method to solve the two-dimensional N-S equation. Calculations show that the three-dimensional vortex provides accurate enough simulation results. Foreign scholars Sunghan & Wilson (2013) [7] used LES for 3D numerical simulation on forced oscillation of cylinders, and successfully found two forms of “2S” and “2P” vortex shedding. Saltara (1998) [8] used the discrete vortex method (DVM) and large eddy simulation (LES) models to numerically simulate the single-degree-of-freedom vibration of a cylinder at Reynolds number 1000. Taar-holder (2000) [9] simulates the forced vibrations of the 2.4×104 cylinders in Reno using models of hurricanes and restricted values. Some foreign scholars use Cartesian coordinates and immersed boundary method to solve the two-dimensional N-S equation. Calculations show that the three-dimensional vortex provides accurate enough simulation results. Guilmineau and Queutey, based on the Reynolds stress equation and k-turbulence model, have carried out numerical analysis of single-degree-of-freedom vibration with Reynolds numbers in the range of 900~15×10³ by 2D finite volume method. Compare the results of selected mathematical and physical models with the experimental results of the research literature. The overall error is controlled within 10% from the three aspects of pipeline vibration amplitude and pipeline stress and pipeline vibration shape, It is proved that the selected mathematical and physical model is effective [10].

2. Governing equation

Based on the flow law of vertical pipelines in shallow sea, the commercial software is used to carry out numerical calculation on the research object. The governing equation is as follows:

2.1. Mass conservation equation
\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho \cdot u)}{\partial x} + \frac{\partial (\rho \cdot v)}{\partial y} + \frac{\partial (\rho \cdot w)}{\partial z} = 0
\]  

(1)

Where \( \rho \) — fluid density \((\text{kg/m}^3)\);
\( t \) — Time \((\text{s})\);
\( u, v, w \) — velocities \((\text{m/s})\) in the \( x, y, \) and \( z \) directions, respectively.

In the analysis, the solution is carried out according to the steady state, and all variables are independent of time, so in the actual processing process, the \( t \) term in the equation can be omitted.

2.2. Momentum conservation equation

\[
\frac{\partial (\rho \cdot u)}{\partial t} + \frac{\partial (\rho \cdot u^2)}{\partial x} + \frac{\partial (\rho \cdot u \cdot v)}{\partial y} + \frac{\partial (\rho \cdot u \cdot w)}{\partial z} = F_x + \frac{\partial p}{\partial x} + \frac{\partial}{\partial x}\left[ \mu \cdot (\frac{\partial u}{\partial x}) - 2 \cdot \frac{\partial}{\partial x} \cdot \frac{\partial v}{\partial x} \right] + \frac{\partial}{\partial y}\left[ \mu \cdot (\frac{\partial u}{\partial y} + \frac{\partial v}{\partial y}) \right] + \frac{\partial}{\partial z}\left[ \mu \cdot (\frac{\partial u}{\partial z} + \frac{\partial v}{\partial z}) \right]
\]

(2)

Where \( \mu \) — viscosity \((\text{Pa/s})\) of the fluid;
\( F_x \) — mass force in the direction of the \( x \) axis \((\text{N})\);
\( \nabla \) — Laplace operator.

The analysis uses the flowing two-way pairing to update fluid networks based on rules and restructuring, and transmits force and displacement data via the continuous-flow coupling interface.

2.3. Moving grid governing equation

When the grid is regarded as different control bodies and the integral of generalized scalar \( \Phi \) is introduced, the conservation equation can be expressed as follows:

\[
\frac{d}{dt} \int_V \rho \Phi dV + \int_{\partial V} \rho \Phi \left( \vec{u} - \vec{u_g} \right) \cdot \vec{n} dA = \int_{\partial V} \Gamma V \Phi \cdot dA + \int_V S_{\Phi} dV
\]

(3)

Where \( \rho \) — fluid density, \( \vec{\mu} \) — speed vector, \( \vec{u_g} \) — moves mesh speed, \( \Gamma \) — dispersal factor, \( S_{\Phi} \) — source element, \( \partial V \) — limit of mesh control cell \( v \)

The derivative of the rear half-fraction gap of the first order of time can be obtained:

\[
\frac{d}{dt} \int_V \rho \Phi dV = \frac{(\rho \Phi V)^n - (\rho \Phi V)^{n+1}}{\Delta t}
\]

(4)

The \( n \) and \( n+1 \) of the equation represents different time layers. \( V^{n+1} \) on the \( n+1 \) layer are calculated by the following equation:

\[
V^{n+1} = V^n + \frac{dV}{dt} \Delta t
\]

(5)

Where \( dV / dt \) — controls the temporal conductivity of the unit. To ensure the continuity of the internal mesh of the control body, the deviation of the control body from time can be calculated by the following formula:

\[
\frac{dV}{dt} = \int_{\partial V} \vec{u_g} \cdot dA = \sum_{j} u_{g,j} \cdot \vec{A}_j
\]

(6)

In the equation \( n_j \) — controls the number of surface grids in the cell. \( \vec{A}_j \) — surface area vector \( j \).

Point multiplication \( u_{g,j} \cdot \vec{A}_j \) is calculated by the following equation:
\[
\frac{\delta V_j}{\Delta t} = u_{g,j} \cdot A_j
\]  

Where \( \delta V_j \) — the volume of space of control body area \( j \) swept by the volume area during the time interval \( \Delta t \).

All variables in the equation are similar to the momentum equation and are weighted by the mass of different phases. There is only one governing equation.

3. Numerical analysis and research

3.1. Geometric models
The geometric domain is created according to the actual size of the vertical pipeline by 3D modeling software catia. The geometric model is created by means of assembly, which is divided into fluid domain and structure domain. Subsequent output stp format import grid software. The geometric model is shown in the following figure. This paper analyzes the flow field distribution law under different pipe lengths, wall thicknesses and geometric models with or without vibration absorbers. It can be seen from Figure 1 that the model is the geometric model used in the numerical analysis and calculation in this paper. Entrances are considered to be entrances to speed, and exports are a source of pressure. The outer wall of the border is calculated as a symmetrical border, which primarily eliminates the effect of non-frontier seismic movements on the movement of internal computational fluids. Through the functioning calculations in the workshop, the force and movement between the liquid and steel surfaces are transferred, and the coupling processing is carried out using the conditions at the limits of the interface. remesh and smooth are used for mesh updating.

![Geometric model of pipeline](image)

Figure 1. Geometric model of pipeline

3.2. Grid division
Workbench meshing is used to grid geometry, which is mainly divided into fluid domain and solid domain. In figure 2, fluid networks and buffaloes are as follows:

Hybrid grid is the division of computing domain, which uses structured grid to execute external computing domain and unstructured grid to execute internal computing domain. The computational accuracy and speed are mainly considered comprehensively. The dynamic grid deformation adopts tetrahedral grids with better coordination. The total number of grid cells is 660,000, the total number of cells is 694,000, and the average grid quality is above 0.8. For the grid distribution of submarine riser, hexahedral grid is used to divide the geometric domain of submarine pipeline. For the calculation accuracy and speed, the grid quality is expected to be consistent. Considering the calculation speed, 37,500 are the total number of grid elements and 254,000 grid nodes, and the outer wall surface of
pipeline and the inner wall surface of fluid are coupled through interface to transmit data.

![Grid scale distribution model](image)

**Figure 2.** Grid scale distribution model

### 3.3. Solve settings

Analysis and problem solving are carried out through workstations, and the problem is divided into two parts: single fluid and structural unit. In view of single-stage flow, transient flow and seawater medium, the Fluent solver is used to solve this problem. Parameters refer to water characteristics and set gravity direction. The inlet adopts speed inlet and the outlet adopts pressure outlet. The inlet speed is 3000 Reynolds, and the outlet is treated under stable pressure in high direction. The wall surface is considered to be symmetrical boundary sym except the bottom surface, two fluid calculation domains, internal and external. Interactor is used in the middle area for data transfer. The fluid structure coupling surface adopts dynamic grid technology, and the wall surface contacting with the solid region of the pipeline is selected, considering as dynamic grid, and fsi-system coupling is selected for node and force transmission. The internal fluid region is initialized in the whole area, and the total analysis time is 10s considering the influence of inlet flow rate. 1000 is the set number of iterations, and the vibration law of the pipeline within 10 seconds is also taken into account. In the subsequent analysis, the maximum deformation of the pipeline and the flow field distribution law in the surrounding area are mainly considered. The post-treatment adopts cfd-post treatment. The transient structure is used to analyze and discuss the vibration of the pipeline. In this example, the two ends of the pipeline are fixed and restrained. The outer wall of the pipeline is coupled with the system coupling surface, which transmits the force and displacement with the pressure mapped to the wall of the pipeline by fluid calculation. The time and structure of this combination coincide with the time of liquid. This systematic combination is used to understand and analyze the whole analysis system and get close results and conclusions.

### 3.4. Results discussion

The numerical analysis results are compared with the experimental results in the literature, and the vibration amplitude and vortex frequency in the downstream direction of the pipeline are compared with the experimental results, thus verifying the selected mathematical model and physical model. It can be confirmed that the mathematical and physical model is selected effectively and has good calculation effect, and the error is relatively small and controlled below 10%. The following figure 3 shows the effectiveness of this type.
The main objects of numerical analysis are different flow rates, different pipe thicknesses, pipe lengths, pressures, reaction distributions and change modes, and the following results are obtained by calculation. The following figure 4 shows the flow field distribution at different sections of the vertical pipeline. It can be seen from the figure that the seawater forms vortex at the wake, which is the factor affecting the vibration of the pipeline. The following is a comparative analysis of the stress and strain of the pipeline under different working conditions.

The following Table 1 shows the stress and strain of vertical pipelines under different Reynolds numbers, different pipeline lengths, different wall thicknesses and different constraint conditions. It can be seen from the table that the stress and strain of submarine vertical pipeline are in positive proportion to Reynolds number, in positive proportion to pipeline length and inversely proportional to pipeline wall thickness. The two-end hinge method is better than the two-end soil method and the two-end complete restraint method.

**Table 1. Stress and Strain of Pipeline under Different Working Conditions and Loading Conditions of Vibration Absorber**

| Condition                      | Pipe Length | Wall thickness | Constraint mode              | Reynolds number | Stress (Pa) | Strain (m) |
|--------------------------------|-------------|----------------|-------------------------------|-----------------|-------------|------------|
| Default operating condition    | 20          | 4.5            | Fixed at both ends           | 3000            | 1.55E+0    | 0.445      |
| Reynolds number                 | 20          | 4.5            | Fixed at both ends           | 6000            | 2.87E+0    | 1.127      |
| Length variation                | 15          | 4.5            | Fixed at both ends           | 3000            | 2.15E+0    | 0.248      |
| Wall thickness variation        | 20          | 3              | Fixed at both ends           | 3000            | 3.35E+0    | 3.586      |
| Constraint change               | 20          | 4.5            | Both ends hinged Soil at both ends | 3000           | 9.96E+5    | 0.413      |

The following Figure 5 shows that, firstly, due to the force entering seawater, the maximum
deformation and the maximum pressure distribution are in the calculation field. The following figure shows that the maximum deformation occurs in the middle of the vertical underwater pipeline, and the maximum stress occurs at both ends of the vertical underwater pipeline. The positions of maximum stress and strain in soil confinement and hinged confinement are different from those in fixed confinement. When both ends of the pipeline are confined by soil, the maximum stress is located at both ends of soil confinement, the magnitude of stress is small relative to the fixed restraint at both ends, and the main reason is that soil restraint has different restraint effects on the wall surface of the pipeline in the direction of soil depth. Compared with completely fixed restraint, the displacement position can be properly released at the wall surface of the pipeline. Therefore, a similar phenomenon occurs. The maximum deformation occurs at the same position as the fixed restraint at both ends and is also the midpoint position in the length direction of the pipeline. When the two-end constraint is changed to the two-end hinged constraint, the maximum stress position appears at 1/4 of the two ends of the pipeline, and the maximum strain is the same as the two-end fixed constraint.

![Figure 5. Distribution Law of Stress and Strain in Pipeline](image)

Through numerical analysis, it can be found that the main reason for pipeline vibration is the vortex formed after the pipeline when the ocean current flows through the pipeline section. The vortex caused the 8 shaped vibration of the pipe. The shock absorber is designed to reduce the formation of eddy current. The main purpose is to reduce the flow by reducing the position of the pipe section and thus the turbulence level. The shock absorber is mainly designed to eliminate the vortex at the tail end, because the boundary plate falls into the turbulent flow of the cylinder. Therefore, the shock absorber needs to be set to streamline type to eliminate the vortex at the tail. The periodic eddy current in the tail is the main cause of pipeline vibration. Therefore, the design of the shock absorber can effectively eliminate the swing of the pipe and reduce the stress. Here, the tail angle is selected to be 60 degrees. In figure 6, the structure of the vibration absorber is as follows:
The following figure 7 shows the distribution law of vibration amplitude and internal stress of submarine vertical pipeline with or without seismic absorber. The range of vibration and internal pressure is reduced after installing shock absorber equipment. The main reason is that adding shock absorber can effectively eliminate the eddy current at the end of the pipeline, which is the main cause of vibration. The following Table 2 shows that, by loading the shock absorber, the maximum stress and strain of the pipeline are significantly reduced.

So the addition of shock absorber can reduce the vibration amplitude and internal stress of submarine vertical pipeline. Adding energy can effectively reduce vibration. Therefore, the vibration absorber can effectively eliminate the vibration amplitude of the vertical pipeline in the seabed.

| Is the vibration absorber loaded | Maximum stress | Maximum strain |
|----------------------------------|----------------|---------------|
| Not Load                         | 1.55E+06       | 0.445         |
| Load                             | 5.53E+05       | 0.096         |

4. Conclusion
(1) The vortex induced vibration and stability analysis of submarine vertical pipeline are simulated by numerical analysis method. The vibration and flow field distribution of submarine vertical pipeline under different inflow velocity, pipe wall thickness, In order to verify the accuracy of the selected mathematical and physical models, it is necessary to calculate the pipe length and set the pipe end limit. Compared with the experimental results in the literature, less than 10% error exists between the actual calculation and the experimental results. The validity of the selected mathematical and physical model has been verified here.
(2) The vibration level of pipeline is inversely proportional to wall thickness, directly proportional to its length, and directly proportional to water flow velocity. The vibration amplitude of the pipeline is the smallest when the two ends of the pipeline are connected. When the soil constraint is large, the pipeline vibration amplitude is maximum.

(3) According to the vortex shedding phenomenon in the downstream of the pipeline, it can be found that the inducement of the pipeline vibration is the vortex generated at the tail of the pipeline. Therefore, if the vortex at the tail can be effectively eliminated, the amplitude of the pipeline vibration can be effectively reduced. According to this principle, the shock absorber is designed to reduce the boundary layer shedding phenomenon and achieve a smooth transition. Through numerical analysis and calculation, it can be seen that the vibration of the pipeline can be reduced the vibrator can effectively reduce the vibration phenomenon of pipeline, and has good engineering application value.

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