Research Article

Effect of Annular Gas-Liquid Two-Phase Flow on Dynamic Characteristics of Drill String

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Natural gas hydrate (NGH) is a kind of new type green energy source with giant reserves which has been thought of highly by energy explorers in the world. However, NGH breaks down to produce some natural gas that enters the annulus and flows together with the drilling fluid. The gas-liquid two-phase flow can have an impact on the work of the drill string. Therefore, it is important to study gas-liquid two-phase flow in the annulus on the dynamic characteristics of the drill string. In this article, taking a single drill string as the research object, a fluid-structure coupled finite element mathematical model of two-phase flow in the annulus and drill string is established based on computational fluid dynamics and computational structural dynamics theory. The finite element numerical simulation method is used to analyze the influence of drilling fluid and natural gas in the annulus on the dynamic characteristics of the drill string. The simulation analysis shows the following: (1) The motion of drilling fluid or natural gas in the annulus will reduce the natural frequency of the drill string, and the drilling fluid has a greater impact on the natural frequency of the drill string. (2) When single-phase drilling fluid flows in the annulus, the displacement peak in different directions, maximum equivalent stress, and strain of the drill string increase with the increase of the drilling fluid flow velocity or pressure, and the drilling fluid pressure has a more significant effect. (3) When the gas-liquid two-phase fluid flows in the annulus, the displacement peak, maximum equivalent stress, velocity amplitude, and acceleration amplitude of the drill string all increase with the natural gas flow velocity and natural gas content increase, and the natural gas flow velocity has a more significant effect.

1. Introduction

Energy plays an important role for social stability and national construction. In recent years, there is an increasing demand for energy in various fields, which led to decreasing or even near depletion of oil and gas resources on land. Therefore, various countries have turned their attention to the ocean. Marine resources are very rich, but it is estimated that the exploitation rate of marine resources is only around 30% and a large amount of energy is waiting to be developed [1]. In ocean resources, natural gas hydrate (NGH) is a kind of new energy that has high energy density, wide distribution, cleanliness, and low pollution. It is predicted that China's NGH reserves in the South China Sea exceed 10 billion tons [2].

Various countries have actively participated in the NGH exploitation, but there has been a situation of high input and

low output, and the marine environment has been polluted. During the drilling process, drilling engineering is a key technology for hydrate exploitation. As shown in Figure 1, the drill string is an indispensable pipe tool; its working environment is filled with drilling fluid and subjected to various loads, which accelerates the fatigue failure of the drill string. When the drill string encounters NGH, NGH breaks down to produce some natural gas that enters the annulus and flows together with the drilling fluid, which exacerbates the damage to the drill string. Therefore, it is of great significance to study the influence of fluid-structure interaction on dynamic characteristics of drill string, which provides safety guidance for NGH exploitation.

Fluid-structure coupled theory is a discipline formed by the combination of fluid mechanics and structural mechanics. At present, the phenomenon of fluid-structure interaction has existed in many fields, and the study of fluid-

FIGURE 1: Working environment of the drill string.

structure interaction has broad application prospects. At present, research methods are mainly focused on three aspects: theoretical research, experimental analysis, and numerical simulation. Scholars have studied dynamic characteristics of the drilling string under fluid-structure interaction from different angles. Chang et al. [3] and David Ytrehus et al. [4] investigated the effect of different types of drilling fluids on the vibration characteristics of the drill string. Salehi and Moradi [5], Tran et al. [6], Ma et al. [7], and Chen et al. [8] studied the effects of density, flow rate, frequency, and other parameters of drilling fluid on the drill string vibration characteristics. Cao et al. [9] studied the interaction between the internal fluid and the string of oil and gas wells. Yang et al. [10] studied the influence of drilling fluid on drill string vibration by experiments and numerical simulation methods. The above-mentioned scholars only studied the influence of the fluid inside the drill string on the drill string, ignoring the effect of fluid movement inside the annulus on the drill string. Kootiani and Samsuri [11], Sayindla et al. [12], and Liu and Zhang [13] analyzed the influence of the types and properties of drilling fluid in the annulus on pressure drop by numerical methods. Yang et al. [14] analyzed the effect of annulus drilling fluid on the drill string lateral vibration by numerical simulation technology. Khajiyeva et al. [15, 16] established a mathematical model of drill string vibration and analyzed the gas velocity influence in the annulus on drill string vibration. Feng et al. [17] studied the influence of annulus fluid characteristics on annulus pressure to protect deep well casings. The above-mentioned scholars analyzed the effect of gas or liquid in the annulus on the drill string but ignored the impact on the drill string when both gas and liquid fluids are present in the annulus. Kiran et al. [18], Sorgun et al. [19], and Zhao et al. [20] analyzed the effect of gas-liquid two-phase flow in the annulus on pressure loss by experimental and numerical methods. Zhou et al. [21] conducted a numerical simulation analysis on the motion law of gas-liquid two-phase flow in the annulus. Xie et al. [22] developed a mathematical model to numerically analyze the gas-liquid two-phase flow in the wellbore. The above-mentioned scholars studied the fluid characteristics of the gas-liquid two-phase flow in the annulus without considering the impact of the two-phase flow on the drill string.

In recent years, the studies on the influence of gas-liquid two-phase flow in the annulus on the dynamic characteristics of the drill string are rare. Therefore, taking a single drill string as the research object, fluid governing equations and structural governing equations are established based on

fluid dynamics and structural dynamics theory, and the fluid and structure motion equations are derived by using Galerkin finite element method. The calculation results are transferred on the interface between the fluid domain and the structural domain to ensure that the boundary conditions of the coupling surface are met and then numerical simulation methods are used to build a finite element calculation model and analyze the effects of two fluids in the annulus, drilling fluid and natural gas, on the dynamic characteristics of the drill string.

2. Fluid-Structure Coupled Finite Element Mathematical Model

2.1. Model Description. The fluid in the annulus and the drill string structure are regarded as the research object in this paper. The fluid in the annulus includes drilling fluid and natural gas. Therefore, a fluid-structure coupled model of the drill string system is established. In order to study the influence of gas-liquid two-phase flow on drill string dynamics, the model needs to be simplified by making the following assumptions [23–25]: (1) the drill string is a homogeneous, prismatic, and isotropic circular pipe; (2) the drill string is coaxial with the wellbore, both are annular in cross section, and the wellbore is considered adiabatic; (3) the gas-liquid two-phase fluid is uniformly mixed, and the chemical change and phase change of both are not considered. The boundary conditions at both ends of the drill string that is parallel to the ground are fixed constraints. It is assumed that the drilling fluid flow direction is the z -direction, the vertical direction of the ground is the y -direction, and the direction perpendicular to the drill string and parallel to the ground is the x -direction, as shown in Figure 2.

The research on the interaction between the fluid in the annulus and the drill string is a typical fluid-structure interaction problem. The motions of fluid and structure need to meet their respective equations, and then the equations of the fluid domain and the structure domain are combined to derive the fluid-structure coupled equation. The parameters at the fluid-solid coupled surface need to meet the conservation of boundary conditions.

2.2. Fluid Control Equations. The natural gas decomposed by NGH enters the annulus and flows together with the drilling fluid. According to the amount of gas in the annulus, different gas-liquid two-phase flow patterns are formed in the annulus. There are two states of fluid flow in the annulus: the drilling fluid flowing alone and the drilling fluid and natural gas flowing together. The above both types of fluids obey the laws of physical conservation. In the flow field analysis, considering the problems of calculation accuracy and calculation speed, the Euler-Euler multiphase flow model and the standard k - ε turbulence model are used to solve the mathematical problem of the annulus air-liquid two-phase flow. It is assumed that the two fluids are incompressible, the physical parameters of the two fluids are constant, and the

FIGURE 2: A simplified model of the drill string system.

heat transfer between them is not considered. Therefore, the control equations of the two fluids are shown as follows [26].

Continuity equation of the gas phase:

$$\frac{\partial(\rho_g \alpha)}{\partial t} + \frac{\partial(\rho_g \alpha v_g)}{\partial x} = 0. \quad (1)$$

Continuity equation of the liquid phase:

$$\frac{\partial[\rho_l (1 - \alpha)]}{\partial t} + \frac{\partial[\rho_l (1 - \alpha) v_l]}{\partial x} = 0. \quad (2)$$

Mixed momentum equation:

$$\begin{aligned} \frac{\partial}{\partial t} [\rho_g \alpha v_g + \rho_l (1 - \alpha) v_l] + \frac{\partial}{\partial x} [\rho_g \alpha v_g^2 + \rho_l (1 - \alpha) v_l^2] \\ + \frac{\partial p}{\partial x} + f + [\rho_g \alpha + \rho_l (1 - \alpha)] \cdot g = 0. \end{aligned} \quad (3)$$

The equations for the other two directions can be obtained in the same way and are not described here.

Gas-liquid mixing density equation:

$$\rho = \rho_g \alpha + \rho_l (1 - \alpha). \quad (4)$$

The fluid in this paper is turbulent, and the standard $k-\varepsilon$ turbulence model is applied. This model has been applied to most engineering problems and has good convergence. The constraint equations are as follows:

$$\begin{aligned} \frac{\partial(\rho k)}{\partial t} + \nabla(\rho v k) &= \nabla \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \nabla k \right] + P_k - \rho \varepsilon, \\ \frac{\partial(\rho \varepsilon)}{\partial t} + \nabla(\rho v \varepsilon) &= \nabla \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \nabla \varepsilon \right] + \frac{\varepsilon}{k} (C_{\varepsilon 1} P_k - C_{\varepsilon 2} \rho \varepsilon), \\ \mu_t &= C_\mu \rho \frac{k^2}{\varepsilon}. \end{aligned} \quad (5)$$

The above-mentioned continuity equations, momentum equations, and turbulence equations form the control equations for gas-liquid two-phase flow. The control equation of gas-liquid two-phase flow is discretized by Galerkin finite element method to obtain the fluid motion equation. The pressure values of the fluid on different positions of the outer wall of drill string can be obtained by solving the motion equation above, which provides fluid pressure and other data for the subsequent fluid-structure interaction analysis.

2.3. Structural Control Equations. The structural vibration equation is the basis for deriving the structural motion equation. The vibration equation of the drill string is established according to Hamilton's principle [27, 28], which is as follows:

$$\int_{t_1}^{t_2} \delta(T - V) dt + \int_{t_1}^{t_2} \delta W dt = 0. \quad (6)$$

Both ends of the drill string with the length of L are fixed constraints. The kinetic energy of the drill string is expressed as follows:

$$T = \int_0^L \frac{1}{2} m \left(\frac{\partial y}{\partial t} \right)^2 dz. \quad (7)$$

The potential energy of the drill string system mainly includes the following two parts.

Potential energy V_b generated by the bending of the drill string:

$$V_b = \int_0^L \frac{1}{2} EI \left(\frac{\partial^2 y}{\partial z^2} \right)^2 dz. \quad (8)$$

Potential energy change V_o generated by annular fluid pressure:

$$V_o = \int_0^L \frac{1}{2} PA \left(\frac{\partial y}{\partial z} \right)^2 dz. \quad (9)$$

Therefore, potential energy of drill string system is obtained as follows:

$$V = \int_0^L \frac{1}{2} EI \left(\frac{\partial^2 y}{\partial z^2} \right)^2 dz + \int_0^L \frac{1}{2} PA \left(\frac{\partial y}{\partial z} \right)^2 dz. \quad (10)$$

The forces subjected by the drill string mainly include the damping force and the additional lateral force of the annulus fluid. The additional lateral force of the annulus fluid is expressed as follows [28]:

$$F_l = C_M m_o \left(\frac{\partial y}{\partial t} + v \frac{\partial y}{\partial z} \right)^2, \quad (11)$$

where C_M is the additional mass factor, which mainly reflects the effect of the diameter size of annular fluid domain on F_l .

$$C_M = \frac{D^2 + d_o^2}{D^2 - d_o^2}. \quad (12)$$

Therefore, the virtual work done by forces on the drill string is expressed as follows:

$$\delta W = \int_0^L \left(F - F_l - c \frac{\partial y}{\partial t} \right) \delta y dz. \quad (13)$$

The boundary conditions of the drill string with fixed constraints at both ends are expressed as follows:

$$y(0) = y(L) = y'(0) = y'(L) = 0. \quad (14)$$

Substituting (7), (10), and (13) into (6), considering the boundary conditions, and using integral by parts, the following equation is obtained:

$$\int_{t_1}^{t_2} \int_0^L \left[(m + C_M m_o) \frac{\partial^2 y}{\partial t^2} + (C_M m_o v^2 + PA) \frac{\partial^2 y}{\partial z^2} + 2C_M m_o v \frac{\partial^2 y}{\partial z \partial t} + EI \frac{\partial^4 y}{\partial z^4} + c \frac{\partial y}{\partial t} - F \right] \delta y dz dt. \quad (15)$$

Therefore, after simplification process, the vibration differential equation of the drill string is expressed as follows:

$$EI \frac{\partial^4 y}{\partial z^4} + (C_M m_o v^2 + PA) \frac{\partial^2 y}{\partial z^2} + c \frac{\partial y}{\partial t} + (m + C_M m_o) \frac{\partial^2 y}{\partial t^2} + 2C_M m_o v \frac{\partial^2 y}{\partial z \partial t} = F. \quad (16)$$

The basis for the study of structural dynamics properties is the structural equations of motion. The Hermite interpolation function and the Galerkin finite element method are used to discretize the vibration differential equation, and finally the motion equation of the structural unit is obtained [27]:

$$M_e \ddot{d}_e + C_e \dot{d}_e + K_e d_e = G_e, \quad (17)$$

where M_e , C_e , and K_e are the mass, damping, and stiff matrices of the drill string unit; d_e and G_e are the displacement and load at the node of the drill string unit.

The motion equation of structural units is transformed into the motion equation of the whole structure by way of combination:

$$M \ddot{d} + C \dot{d} + K d = G, \quad (18)$$

where M , C , and K are composed of corresponding element matrices and d and G are the total displacement and total load of the drill string.

2.4. Fluid-Structure Coupled Motion Equation. According to the governing equations of fluid and structure, the finite element method is employed to solve the fluid-structure interaction dynamics problem.

Based on the continuity equations, momentum equations, and turbulence equations of the fluid, the Galerkin finite element method is used to discretize the above equations to obtain the motion equation of the fluid element [29, 30]:

$$H_e P_e + F_e \dot{P}_e + E_e \ddot{P}_e = F_a, \quad (19)$$

where H_e , F_e , and E_e are stiff, damping, and mass matrices of fluid element.

The motion equation of fluid units is transformed into the motion equation of the whole flow field by way of combination:

$$HP + F\dot{P} + E\ddot{P} = F_a, \quad (20)$$

where H , F , E , and B are composed of corresponding element matrices.

When the drill string is in contact with the annulus fluid, there is an interaction between fluid and drill string on the contact surface, where F_a is the load of the drill string on the fluid [31]:

$$F_a = -\rho B \ddot{d}. \quad (21)$$

Substituting equation (21) into equation (20), the following equation is obtained [32]:

$$HP + F\dot{P} + E\ddot{P} + \rho B \ddot{d} = 0. \quad (22)$$

Considering the fluid-structure interaction problem, G in equation (18) includes the load F_0 of the annulus fluid on the drill string and other loads F_1 . Therefore, equation (18) is transformed into

$$M \ddot{d} + C \dot{d} + K d + F_0 + F_1 = 0, \quad (23)$$

where [31]

$$F_0 = -B^T P. \quad (24)$$

Substituting equation (24) into (23), the following equation is obtained [30]:

$$M \ddot{d} + C \dot{d} + K d - B^T P + F_1 = 0. \quad (25)$$

The essence of the fluid-structure interaction problem is to solve equation (22) and (25), and the coupled equation is as follows:

$$\begin{bmatrix} E & \rho_a B \\ 0 & M \end{bmatrix} \begin{bmatrix} \ddot{P} \\ \ddot{d} \end{bmatrix} + \begin{bmatrix} F & 0 \\ 0 & C \end{bmatrix} \begin{bmatrix} \dot{P} \\ \dot{d} \end{bmatrix} + \begin{bmatrix} H & 0 \\ -B^T & K \end{bmatrix} \begin{bmatrix} P \\ d \end{bmatrix} + \begin{bmatrix} q \\ F_1 \end{bmatrix} = 0. \quad (26)$$

The above equation shows that the unknown quantities include drill string displacement and fluid pressure. The parameters of drill string displacement and fluid pressure are obtained by solving the above equation and transferred to each other on the coupling surface for fluid-structure interaction dynamics study.

2.5. Data Transfer between Fluid-Structure Coupling Interfaces. When analyzing fluid-structure interaction problem, the key is the information transfer between fluid-structure coupling interfaces. There are 2 types of fluid-solid interaction: one is that the coupling effect only occurring at

the contact surface between fluid and structure, and the other is that the coupling effect occurs at the overlap between fluid and structure. The coupling type in this paper belongs to the former one. The load transfer process of the coupling interface is shown in Figure 3.

The movement of fluid and structure on the coupling interface needs to meet displacement and force balance:

$$\begin{aligned} D_f &= D_s, \\ T_f &= T_s. \end{aligned} \quad (27)$$

During the data transfer process between fluid-structure coupling interfaces, the pressure on the inner surface of the annulus fluid needs to be transferred to the outer surface of the drill string. The transfer equation is as follows:

$$\tau_s = H_1 \tau_f. \quad (28)$$

And then the drill string is deformed under annulus fluid pressure, which will be fed back to the fluid through the following equation:

$$d_f = H_2 d_s. \quad (29)$$

The data transfer between fluid and structure on the interface is realized through the above displacement and stress equations, and then the fluid-structure coupling dynamics problem is studied.

The partitioned coupling method is used by the solution of the fluid-structure interaction. The fluid domain equation and the structure domain equation are solved by the above method, and the calculation results of the fluid domain and the structure domain are exchanged through the coupling surface. The analysis steps of the partitioned coupling method are as follows:

- (1) Assign initial boundary conditions such as inlet velocity and outlet pressure of the two-phase fluid in the annulus
- (2) Solve the fluid domain and get the fluid pressure
- (3) Transfer the fluid pressure load to the structure through the coupling surface and solve the structural domain to obtain the structural displacement
- (4) Transfer the structural displacement to the fluid through the coupling surface to get the deformation of the fluid domain and then recalculate the fluid domain to update the fluid pressure
- (5) According to the above calculation steps, keep repeating the calculation until the fluid pressure load and structural displacement meet the calculation error

3. Numerical Simulation and Analysis

The finite element calculation model is established, as shown in Figure 4. The model includes structure domain and fluid domain. The inlet boundary of the annulus fluid domain is defined as the velocity inlet, the outlet boundary of the annulus fluid domain is defined as the pressure outlet, and the outer surface of the drill string and the inner surface of

FIGURE 3: Data transfer diagram between fluid and structure.

FIGURE 4: Finite element calculation model.

the fluid domain are defined as the coupling surfaces. A single drill string is selected as the structural model, and the fluid in the annulus includes drilling fluid and natural gas. The structure and fluid main parameters are listed in Table 1, and other fluid parameters and specific parameters of the boundary conditions are determined according to specific working conditions.

The numerical simulation analysis involves the coupling problem of fluid and solid, so it is necessary to mesh the fluid domain and the structural domain. The grid number affects the final result of numerical simulation, so different grid numbers are selected for grid independence test in this paper. When the drilling fluid flow rate is 4 m/s, the mesh independence of the numerical model is verified by taking the maximum equivalent stress of the drill string as the evaluation index [33].

As shown in Table 2, as the grid number increases, the maximum equivalent stress of the drill string gradually tends to converge. By comparing the change trend of the result, the mesh number of 256845 is selected for subsequent numerical calculation. If the grid number continues to increase on the basis, the effect on the calculation result is relatively small; i.e., grid independence has been satisfied [34].

The selection of time step size will also affect the calculation result. Taking the above mesh number 256845 as the mesh model, 0.1 s, 0.05 s, 0.01 s, 0.005 s, and 0.001 s are selected for time-independent test. The results show that the change trend of the results obtained from the time step test is similar to that from the grid number test and both gradually converge. Therefore, based on comprehensive consideration of computing resource and accuracy, the calculation time step in this paper is 0.005 s.

3.1. Modal Analysis of Drill String under Fluid-Solid Coupling.

Modal analysis is the basis for studying the structural dynamic characteristics. The modal analysis helps researchers know the structural modal parameters, provides a reliable basis for the analysis of the structural dynamic characteristics, and prevents the structure from resonating.

TABLE 1: Fluid and structure parameters.

	Parameter names	Value
Structure parameter	Density (kg/m^3)	7850
	Length (m)	9
	Outer diameter (mm)	115
	Wall thickness (mm)	8
	Elastic modulus (GPa)	210
	Poisson's ratio	0.3
Fluid parameter	Drilling fluid density (kg/m^3)	1200
	Drilling fluid viscosity (Pa·s)	0.001
	Natural gas density (kg/m^3)	0.75
	Natural gas viscosity (Pa·s)	1.15×10^{-5}

TABLE 2: Grid independence verification.

The total number of elements	108354	151864	201034	256845	305983
Maximum equivalent stress	0.41585	0.42256	0.42598	0.42687	0.42691

It can be known from the statement in Section 2.2 that there are two states of fluid flow in the annulus: the drilling fluid flowing alone and the drilling fluid and natural gas flowing together. Therefore, in order to analyze the effect of fluid-structure interaction on the modal characteristics of drill string, numerical simulations are performed for modal problems under three cases of no coupling, liquid-solid coupling, and gas-liquid-solid coupling, respectively. As shown in Table 3, the first six orders natural frequencies are extracted separately for discussion and analysis.

The modal analysis results include the natural frequency and mode shape of the structure. Firstly, the natural frequency of the drill string is analyzed under the above three cases. As shown in Table 3, the adjacent two-order frequencies are almost equal due to the constraint and shape symmetry of the drill string structure. From Table 3, the natural frequency of the drill string under liquid-solid coupling is lower than that under no coupling. The reason is that the movement of the drilling fluid in the annulus creates pressure on the outer wall of the drill string, which causes the mass of the drill string to increase and subsequently the natural frequency to decrease. As the modal order number increases, the difference rate between the natural frequencies of the drill string under the above two coupling actions gradually decreases, indicating that the effect of drilling fluid on low-order natural frequencies is greater than that of high-order natural frequencies. Drilling fluid motion is aggravated by the vibration of the drill string under higher-order modes, which makes the drill string vibrate more violently and subsequently makes the frequency of the drill string vibration increase. Therefore, as the modal order number increases, the difference between the natural frequencies under liquid-solid coupling and no coupling gradually decreases. The natural frequency of drill string under gas-liquid-solid coupling is less than that under no coupling but more than that under liquid-solid coupling. The gas-phase natural gas entering the annulus replaces part of the liquid-phase drilling fluid, and the density of natural gas is much less than that of drilling fluid. So, compared with the action of drilling fluid, the action of natural gas exerts less pressure

on the outer wall surface of the drill string and adds less mass to the drill string, with a consequent reduction in the overall coupling effect on the drill string after gas-liquid mixing. Therefore, the natural frequency under gas-liquid-solid coupling is between the natural frequency of the drill string under no coupling and liquid-solid coupling. As the modal order number increases, the difference between the natural frequencies under gas-liquid-solid coupling and liquid-solid coupling gradually increases. It suggests that natural gas has a greater impact on the higher-order natural frequencies than the lower-order natural frequencies and the reason is the same as the analysis of drilling fluid factor above.

The mode shapes of the above three cases are compared and analyzed after numerical simulation. The mode shapes of the drill string structure are not affected by the fluid-solid coupling, but there is a tiny increase in the mode shape amplitude due to the fluid-solid coupling. Therefore, the mode shape without coupling is extracted for discussion and analysis. Due to the symmetry of the drill string structure, the 1st, 3rd, and 5th order modes vibrate in the Y - Z plane, while the 2nd, 4th, and 6th order modes vibrate in the X - Z plane. The mode shapes on the two planes are the same, but the vibration directions are perpendicular to each other. Therefore, the 1st, 3rd, and 5th order mode shapes in the Y - Z plane are extracted and normalized, as shown in Figure 5. According to Figure 5, the mode shape of the drill string structure is dominated by bending vibration, and as the modal order increases, there are more and more bending parts. The 1st order mode shape has one curved part, the 3rd order mode shape has two curved parts, and the 5th order mode shape has three curved parts. As the modal order number increases, the natural frequency of the drill string increases, which causes the drill string to vibrate more intensely and makes mode shape more complex, so the number of bending areas also increases.

The above discussion about natural frequencies and mode shapes is further analyzed. The action of different fluids will all cause the natural frequency of the drill string structure to decrease but the vibration amplitude to slightly increase. The reason is that the movement of different fluids

TABLE 3: The natural frequency of the drilling string under fluid-structure coupling.

Order	Natural frequency (Hz)			Change rate	
	Uncoupled	Fluid-solid coupling	Gas-liquid-solid coupling	Former two (%)	Later two (%)
1	8.904	8.026	8.028	9.86	0.02
2	8.905	8.026	8.028	9.87	0.02
3	24.471	23.659	23.668	3.32	0.04
4	24.471	23.658	23.667	3.32	0.04
5	47.783	46.986	47.008	1.67	0.05
6	47.783	46.987	47.009	1.67	0.05

FIGURE 5: Different mode shapes of drill string without coupling.

exerts a force on the outer wall of the drill string, subsequently increasing the additional mass of drill string. So, when the density, viscosity, velocity, and other physical parameters of the drilling fluid or natural gas change, the pressure on the outer wall of the drill string and the additional mass of drill string are also altered, resulting in a change in the natural frequency and amplitude of the drill string structure.

3.2. Influence of Drilling Fluid in the Annulus on Drill String Dynamic Characteristics. When the drill string is not in contact with NGH, only the drilling fluid flows in the annulus. In different environments, the drilling fluid flow velocity and pressure are variable, which has different degrees of influence on the drill string dynamic characteristics. Therefore, the numerical simulation is used to analyze the change law of some drill string dynamic characteristics with drilling fluid flow velocity and pressure.

The effect of drilling fluid velocity on the displacement peak of the drill string is first analyzed, as shown in Figure 6. The peak combined displacement and Y-direction displacement peak are much larger than the displacement peaks in the other two directions, and curves of the peak combined displacement and Y-direction displacement peak with drilling fluid flow velocity almost coincide. The above

FIGURE 6: Variation curve of displacement peak in different directions with drilling fluid velocity.

analysis shows that the vibration direction of drill string is mainly the Y-direction, and the vibration in the other two directions has little effect on the drill string and can even be ignored. As shown on the upper left corner of Figure 6, the X-direction and Z-direction displacement peak curves are enlarged to facilitate clear comparison. From Figure 6, as the velocity increases, the displacement peak and its increasing rate in different directions also increase. The above analysis shows that the greater the drilling fluid velocity, the greater the impact on the displacement peak of the drill string and the larger the impact on the Y-direction displacement peak among the three directions. The difference between the X-direction and Z-direction displacement peaks increases with increasing velocity, indicating that the velocity factor has a greater influence on the displacement peak in the Z-direction than in the X-direction.

As shown in Figure 7, the displacement peak in different directions increases almost linearly as the pressure increases. But, from Figure 6, it can be found that the displacement peak in different directions increases almost nonlinearly as the pressure increases and a comparison of the data in Figures 6 and 7 shows that the displacement peak under the influence of drilling fluid pressure is greater than that under

FIGURE 7: Variation curve of displacement peak in different directions with drilling fluid pressure.

the influence of drilling fluid velocity. The above analysis shows that the pressure factor has a greater influence on the drill string displacement peak than the velocity factor. When considering the material strength, it is necessary to focus on the effect of drilling fluid pressure on the drill string.

Figures 8 and 9 show the effects of velocity and pressure of drilling fluid on the maximum equivalent stress and strain of drill string. Comparing Figures 6 and 7 with Figures 8 and 9, it is found that the curves in Figures 6 and 8 present a nonlinear change and the curves in Figures 7 and 9 present a linear change. It shows that, under the influence of pressure or speed, the curve change trend of stress and strain is related to the curve change trend of displacement. Both ends of the drill string are fixed constraints, and other parts are not restricted. Therefore, when the drill string deforms, the maximum equivalent stress and strain of the drill string occur at both ends of the drill string, and the maximum equivalent stress and strain of the drill string will increase as the deformation of the drill string increases. The above analysis results are consistent with the curve change law of the above four graphs.

3.3. Influence of Natural Gas in the Annulus on Drill String Dynamic Characteristics. NGH breaks down to produce some natural gas that enters the annulus and flows together with the drilling fluid. The drill string dynamic characteristics will be affected by the natural gas flow velocity and the natural gas volume in the annulus. Therefore, the effects of natural gas flow velocity and gas volume fraction in annular drilling fluid on the drill string dynamic characteristics, including the maximum deformation, maximum equivalent stress, vibration velocity, and vibration acceleration, are simulated numerically.

FIGURE 8: Variation curve of maximum equivalent stress and strain with drilling fluid velocity.

FIGURE 9: Variation curve of maximum equivalent stress and strain with drilling fluid pressure.

3.3.1. Influence of Natural Gas Flow Velocity on Drill String Dynamic Characteristics. First, the drilling fluid flow velocity is controlled to 2 m/s, and the volume ratio of drilling fluid to natural gas is controlled to 9:1 by control variable method, and then the influence of different flow rates of natural gas on the dynamics of the drill string is studied. The variation law of peak combined displacement and maximum equivalent stress of the drill string with natural gas flow velocity is expressed in Figure 10. As shown in Figure 10, both drill string peak combined displacement and maximum equivalent stress increase with increasing natural gas flow velocity, and the increasing rate of both increases. The above analysis shows that the greater the flow velocity of natural gas, the greater the impact on drill string displacement and equivalent stress. A comparison of Figure 10 with Figures 6 and 8 shows that the gas flow velocity has a greater effect on

FIGURE 10: Variation curve of peak combined displacement and maximum equivalent stress with natural gas velocity.

the drill string dynamic characteristics than the drilling fluid flow velocity. Analysis of the reasons for this shows that as the flow velocity of natural gas in the annulus increases, the fluid motion in the annulus becomes more intense, resulting in greater fluid forces on the outer wall surface of the drill string, so the deformation increases and the equivalent force increases.

Figure 11 shows the variation law of the velocity amplitude of drill string in the three directions with the natural gas flow velocity. From Figure 11, as the gas velocity increases, the velocity amplitude in the Y-direction is much greater than that in the Z-direction and X-direction, with velocity amplitude in the Z-direction being slightly greater than that in the X-direction. The above analysis shows that the drill string vibrates most violently in the Y direction. The results of the simulations at both ends of the velocity amplitude curves in three directions in Figure 11 are extracted and compared. The increasing rate of the data at both ends of the X-direction velocity amplitude curve is 42.9%. The increasing rate of the data at both ends of the Y-direction velocity amplitude curve is 122%, and the increasing rate of the data at both ends of the Z-direction velocity amplitude curve is 118%. The above analysis shows that the natural gas flow velocity has the greater influence on the increasing rate of the velocity amplitude in the Y-direction than that in the other two directions but the increasing rate of the velocity amplitude in the three directions always increases with the increase of the natural gas flow velocity.

Figure 12 shows variation law of drill string acceleration amplitude with natural gas velocity in different directions. As shown in Figure 12, acceleration amplitude in the Y-direction is two orders of magnitude larger than that in the X-direction and Z-direction, and acceleration amplitude in the X-direction is slightly larger than that in the Z-direction. The comparative analysis of Figures 11 and 12 further proves that the drill string's main vibration direction is the Y-direction. The curves of acceleration

FIGURE 11: Variation curve of velocity amplitude in different directions with natural gas velocity.

FIGURE 12: Variation curve of acceleration amplitude in different directions with natural gas velocity.

amplitude with velocity in X- and Z-directions are enlarged, as shown on the lower right corner of Figure 12. According to the comparison of the two magnification curves, the X-direction acceleration amplitude increases almost linearly, and the increasing rate is nearly unchanged. However, the Z-direction acceleration amplitude increases nonlinearly. The increasing rate of the acceleration amplitude in the Z-direction increases with the increase of the natural gas flow velocity, which is the same as the changing trend of the acceleration amplitude in the

FIGURE 13: Variation curve of the peak combined displacement and maximum equivalent stress with natural gas fraction.

FIGURE 14: Variation curve of velocity amplitude in different directions with natural gas fraction.

Y-direction. The above analysis shows that gas flow velocity has the greatest effect on Y-direction acceleration, the followed effect on Z-direction acceleration, and the least effect on X-direction acceleration.

3.3.2. Influence of Natural Gas Volume Fraction on Drill String Dynamic Characteristics. First, the natural gas flow velocity is controlled to 3 m/s, and the drilling fluid flow velocity is controlled to 2 m/s by control variable method, and then the influence of different natural gas volume fraction on the dynamics of the drill string is studied.

As shown in Figure 13, the variation law of the drill string peak combined displacement and the maximum equivalent

stress with the natural gas volume fraction is simulated. It can be seen from Figure 13 that as the natural gas volume fraction increases, the peak combined displacement and maximum equivalent stress of drill string both increase linearly. The change trend of the curve in Figure 13 is different from that in Figure 10, and the values on the two curves in Figure 13 are both smaller than those on the two curves in Figure 10. The above analysis shows that the natural gas flow velocity has a greater influence on the displacement and stress of drill string than the natural gas volume fraction. Analysis of the reasons for this shows that as the natural gas volume fraction increases, the share of drilling fluid will correspondingly decrease, which makes the flow energy of the two-phase flow and the additional forces on the outer drilling wall surface decrease.

FIGURE 15: Variation curve of acceleration amplitude in different directions with natural gas fraction.

FIGURE 16: Variation curve of X- and Z-direction acceleration amplitude with natural gas fraction.

Figure 14 shows the variation law of velocity amplitude in different directions with natural gas volume fraction. As shown in Figure 14, the three curves present a linear change. Velocity amplitude in the Y-direction is one order of magnitude larger than that in the Z-direction, and velocity amplitude in the Z-direction is one order of magnitude larger than that in the X-direction. A comparative analysis of all the data in Figure 14 and Figure 11 shows that the velocity amplitude in each direction under the action of natural gas content is all smaller than the velocity amplitudes in the corresponding direction under the action of natural gas flow velocity. It is again confirmed that the natural gas flow velocity has a greater impact on the drill string dynamics than the natural gas volume fraction.

Figure 15 shows the variation law of the drill string acceleration amplitudes in the three directions with the natural gas volume fraction. As shown in Figure 15, the three

curves also present a linear change. Comparing the data in Figure 15 with that in Figure 12, the X-directional acceleration amplitudes are nearly the same in both figures, but the Y-directional acceleration amplitude under the natural gas volume fraction is much smaller than that under the natural gas flow velocity. The above analysis shows that the natural gas flow velocity has a much greater influence on the acceleration amplitude in the Y-direction than the natural gas volume fraction. In order to clearly observe the shape of the acceleration amplitude curve in the X-direction and Z-direction, the two curves are redrawn, as shown in Figure 16. The curves of X-direction acceleration amplitude and Y-direction acceleration amplitude show the same changing trend, but there are fluctuations in the Z-direction acceleration amplitude. The gas-liquid two-phase in the annulus flow along the Z-direction (axial direction) and the movement of the fluid has basically the same effect on every

position on the outer wall of the drill string. However, the change of natural gas volume fraction causes the flow field movement to become complicated, which results in a nonlinear variation of the action on each position of the drill string in the Z-direction. Therefore, there are fluctuations in the Z-direction acceleration amplitude.

4. Conclusion

In this paper, a fluid-structure coupled finite element mathematical model of two-phase flow and drill string in the annulus was established by the finite element method, and then the influence of the two-phase flow of drilling fluid and natural gas in the annulus on the dynamic characteristics of the drilling column was investigated by numerical simulation methods. The conclusions were shown as follows:

- (1) Both movement of the drilling fluid and natural gas in the annulus will reduce the drill string's natural frequency and increase the mode shape vibration amplitude, but the drilling fluid has a greater effect on the drill string's natural frequency than the natural gas. As the modal order number increases, the effect of fluid-structure interaction on the drill column's natural frequency decreases.
- (2) When single-phase drilling fluid flows in the annulus, the displacement peak in different directions, maximum equivalent stress, and strain of the drill string increase with the increase of the drilling fluid flow velocity or pressure. However, drilling fluid pressure has a greater effect on the displacement peak, maximum equivalent force, and strain of the drill column than drilling fluid velocity.
- (3) When gas-liquid two-phase fluid flows together in the annulus, the displacement peak, maximum equivalent stress, velocity amplitude, and acceleration amplitude of the drill string all increase with the natural gas flow velocity or natural gas volume fraction increase. However, the above-mentioned drill string dynamics parameters change faster under the natural gas flow velocity. And the natural gas flow velocity has a greater impact on the displacement peak and maximum equivalent stress of the drill string than the flow velocity of the drilling fluid.

Nomenclature

α :	Annular section air content
ρ_g :	Natural gas density (kg/m ³)
ρ_f :	Drilling fluid density (kg/m ³)
ρ :	Gas-liquid mixture density (kg/m ³)
v_g :	Natural gas velocity (m/s)
v_f :	Drilling fluid velocity (m/s)
f :	Fluid friction pressure drop (Pa·m ⁻¹)
k :	Turbulent kinetic energy (m ² /s ²)
ε :	Turbulent dissipation rate
$C_{\varepsilon 1}, C_{\varepsilon 2}$:	Empirical constant
$\sigma_k, \sigma_\varepsilon$:	Turbulent Prandtl numbers
P_k :	Turbulent product

μ :	Dynamic viscosity
μ_t :	Turbulent viscosity
C_μ :	Empirical coefficient of k - ε model
F_a :	Load of drill string on fluid (N)
D_f :	Fluid displacement on the coupling surface (m)
T_f :	Fluid pressure on the coupling surface (Pa)
τ_f :	Pressure after fluid domain calculation (Pa)
d_s :	Displacement of the drill string under fluid pressure (m)
T :	Kinetic energy of drill string system
V :	Potential energy of drill string system
δW :	Virtual work
m :	Mass per unit length of drill string (kg)
E :	Elastic modulus of drill string (GPa)
I :	Moment of inertia of drill string (m ⁴)
P :	Annular fluid pressure (Pa)
A :	Cross-sectional area of fluid domain (m ²)
m_o :	Mass per unit length of fluid (kg)
D :	Inner diameter of wellbore (m)
d_o :	Outer diameter of drill string (m)
F :	Outside force (N)
c :	Damping factor
δ_y :	Virtual displacement (m)
B :	Coupling matrix on coupling plane
F_0 :	Load of fluid on drill string (N)
D_s :	Structural displacement on the coupling surface (m)
T_s :	Structural stress on the coupling surface (Pa)
τ_s :	Structural stress under fluid pressure (Pa)
d_f :	Fluid displacement under structural deformation (m).

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this study.

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