

# Dynamic Behavior Analysis of Drilling String in Horizontal Section of Deep-Sea Gas Well

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**Abstract.** In this paper, a mathematical model of axial vibration of drill string near drill bit in horizontal well under natural gas is established considering the effects of gravity, load and fluid on drill string system. Based on the developed drilling string dynamic test platform, the axial vibration experiments of drilling string system under different gas content and gas flow rate are carried out. The experimental results show that the axial vibration of drill string is more serious and the vibration amplitude increases with the increase of air flow velocity and gas content.

**Keywords:** Natural gas hydrate; Dynamic behavior; Horizontal well; Two-phase flow; Simulation experiment.

## 1. Introduction

With the rapid development of China's industry and science and technology, the demand for energy in various industries is also growing rapidly. However, the reserves of fossil energy that have been explored and discovered in the world are very limited, and the exploitation of existing resources is difficult and the utilization rate is low, and the use of fossil energy will bring many environmental problems. Optimizing the energy structure and realizing low carbon emission is the key to China's green sustainable development. As a widely alternative clean energy, natural gas has attracted much attention, and its proportion in the energy system of various countries is increasing. The South China Sea is rich in natural gas hydrate resources and is an important area for future oil and gas exploration and development<sup>[1]</sup>. Because of the thin gas reservoir, the use of drilling horizontal Wells can increase the contact area between the wellbore and the reservoir to improve the mining efficiency<sup>[1-7]</sup>.

In the process of drilling horizontal Wells to exploit natural gas hydrate, the natural gas hydrate will decompose and produce a large amount of gas. The gas will enter the space between the drilling string and the wellbore with the flow of drilling fluid, making the fluid in the annulus change from unidirectional liquid flow to complex gas-liquid two-phase flow. Horizontal well drilling is a key oil and gas exploration technology, and its drilling efficiency and drilling quality affect the cost and benefit of oil and gas exploration. However, in the process of horizontal well drilling, the vibration of drill string is always one of the important factors affecting the drilling efficiency and quality. Drill string vibration refers to the unstable movement of the drill string during drilling, which may be caused by the uneven friction between the drill string and the wall or the imbalance of the drill string itself. Drill string vibration can also damage drilling tools and wellbore equipment, increasing drilling costs<sup>[8]</sup>.

In this paper, through reasonable simplification, the drillstring axial vibration model is established, and the influence of internal and external fluids on near-bit drillstring system is analyzed according to the finite element discrete theory and the relevant theories of fluid mechanics. The influence law of fluid on horizontal well drill bit axial vibration is illustrated by finite element simulation and experimental verification.

## 2. Drill string axial vibration model

### 2.1. Work done by gravity

When establishing the mathematical model of the bit axial vibration, the influence of gravity on the drill string system cannot be ignored, and its expression is as follows:

$$F_{G-el} = \int_0^L \rho g A u dx \quad (1)$$

$\rho$  is the material density of rotary drill string, unit;  $A$  is the cross-sectional area, unit;  $L$  is the total length of the drill string system, unit;  $g$  is the acceleration of gravity, unit.

Gravitational variational form:

$$\delta F_{G-el} = \int_0^L \rho g A \delta u dx \quad (2)$$

The finite element method is used to discretize it, and the vector form is obtained:

$$\delta F_{G-el} = \int_0^1 N_u^T \rho g A l_e d\xi \quad (3)$$

### 2.2. Execution end load

In this paper, the form of the executive end action is simplified as the cutting and friction of the bit on the rock, and its expression is as follows:

$$T_{AR} = T_q + T_f, F_{AR} = F_q + F_f \quad (4)$$

Where, the subscript and respectively represent the cutting action and friction action.  $T_q = \frac{1}{2} \varepsilon_b r_b^2 d$ ,  $F_q = \zeta_b \varepsilon_b r_b d$ ,  $r_b$  is the bit radius,  $\zeta_b$  is the cutting factor,  $\varepsilon_b$  is the maximum contact load,  $d = A_n \left( u(t)|_{x=x_n} - u(t-t_n)|_{x=x_n} \right)$  is the depth of cutting.

The number of cutting edges at the execution end is  $A_n$ , and the cutting process diagram is shown in Figure 1.

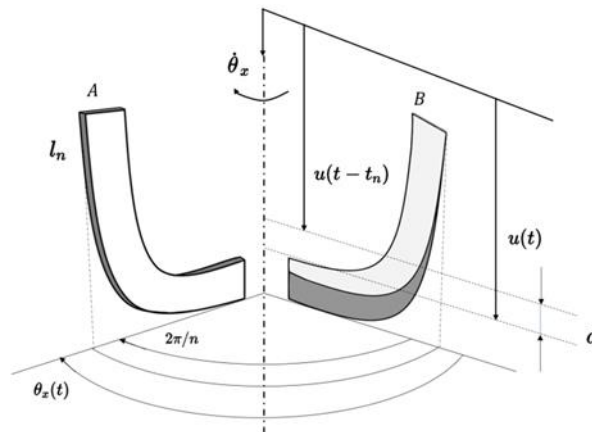


**Fig. 1** Schematic diagram of cutting process

The variational of the executing unit yields:

$$\delta E_{AR-el} = N_u^T F_{AR} \Big|_{x=L} + N_{\theta_x}^T T_{AR} \Big|_{x=L} \quad (5)$$

### 3. Fluid effects on drill string systems

The flow of fluid inside the drill string system is shown in Figure 2. The circulation process is that the liquid flow starts from the external water tank, enters the left drill string system entrance by pressurizing the pump, flows through the bottom of the drill string and returns to the annular space.

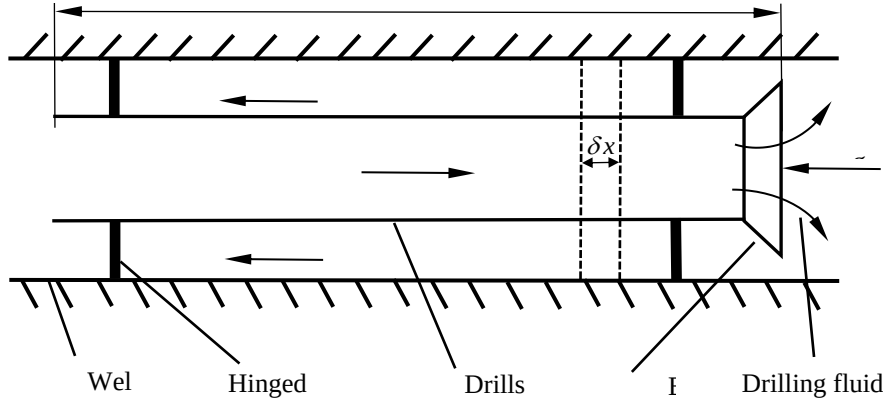


**Fig. 2** Schematic diagram of drill string system near the bit in annulus

Where,  $R_h$  represents the inner diameter of the shaft wall,  $R_e$  represents the outer diameter of the drill string,  $R_i$  represents the inner diameter of the drill string.

As shown in Fig. 3 and 4 below, they represent the external and internal flow force diagram of the horizontal drill string system respectively:

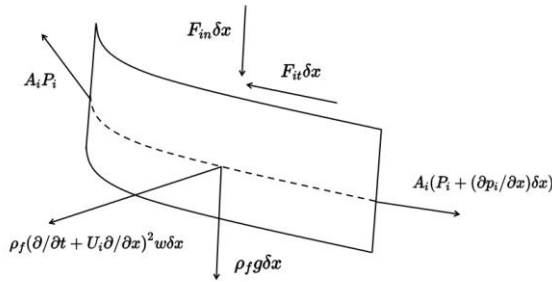


**Fig. 3** External flow force

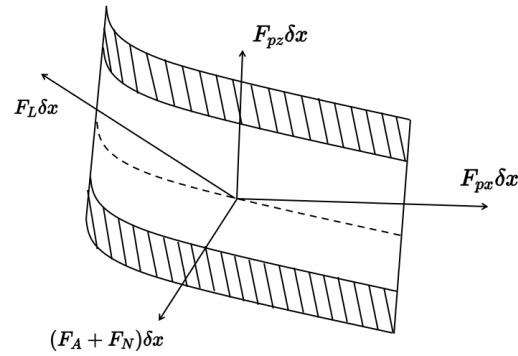


**Fig. 4** Internal flow force

The axial force generated by the drilling string system under the influence of internal flow is as follows <sup>[9]</sup> :

$$F_{z-in} = M_f \left( \frac{\partial^2 w}{\partial t^2} + 2U_i \frac{\partial^2 w}{\partial x \partial t} + U_i^2 \frac{\partial^2 w}{\partial x^2} \right) + A_i \frac{\partial}{\partial x} \left( p_i \frac{\partial w}{\partial x} \right) \quad (6)$$

$$F_{z-ex} = D_x \rho_f A_e \left( \frac{\partial w}{\partial t} - U_{ex} \frac{\partial w}{\partial x} \right) \left( \frac{\partial w}{\partial t} - U_{ex} \frac{\partial w}{\partial x} \right) - A_e \frac{\partial}{\partial x} \left( p_e \frac{\partial w}{\partial x} \right) + f_z + F_L \frac{\partial w}{\partial x} \quad (7)$$

Where,  $D_x = \frac{(D_h / D_e)^2 + 1}{(D_h / D_e)^2 - 1}$  represents the diameter coefficient,  $U_i$  represents the internal flow

rate, unit  $m/s$ ;  $U_{ex}$  represents external flow rate, unit  $m/s$ ;  $f_z$  represents frictional viscosity, unit  $N$ ;  $\rho_f$  represents stands for liquid density, unit  $kg/m^3$ .

The viscous force is:

$$F_L = \frac{1}{2} C_f \rho_f D_f U_e^2 \quad (8)$$

$$f_z = \frac{1}{2} C_f \rho_f D_f U_e \left( \frac{\partial w}{\partial t} - U_e \frac{\partial w}{\partial x} \right) \quad (9)$$

Where,  $C_f$  represents damping coefficient,  $D_f = \frac{4A_e}{\pi(D_h + D_e)}$  represents liquid and mass diameter, unit  $m$ ;  $A_e$  represents the size of the outflow area in units  $m^2$ .

The pressure distribution function is:

$$p_i = \rho_f g x + p_{\text{pump}} \quad (10)$$

$$p_e = \left( \rho_f g + \frac{F_L D_e}{A_e D_h} \right) \quad (11)$$

The finite element method is used to discretize it, taking the displacement vector and the second derivative of time as the mass matrix of the fluid:

$$M_{F-\text{el}} = \int_0^1 (M_f + D_f \rho_f A_e) (N_w^T N_w + N_v^T N_v) l_e d\xi \quad (12)$$

The first derivation of displacement to time is the element damping matrix:

$$C_{F-\text{el}} = \int_0^1 \left[ 2(D_f \rho_f A_e U_e - M_f U_i) (N_{\theta_y}^T N_{\theta_y} + N_{\theta_z}^T N_{\theta_z}) + \left( \frac{1}{2} C_f \rho_f D_e U_e + k \right) (N_w^T N_w + N_v^T N_v) \right] l_e d\xi \quad (13)$$

The first term of displacement against time is taken as the stiffness matrix:

$$K_{F-\text{el}} = \int_0^1 (A_e p_e - M_f U_i^2 - A_i p_i - D_f \rho_f A_e U_e^2) (N_w^T N_w + N_v^T N_v) \frac{1}{l_e} + \int_0^1 \left( A_e \frac{\partial p_e}{\partial x} - A_i \frac{\partial p_i}{\partial x} \right) (N_{\theta_y}^T N_{\theta_y} + N_{\theta_z}^T N_{\theta_z}) l_e d\xi \quad (14)$$

The remaining terms are work done by equivalent liquid flow, whose vector is:

$$\delta F_{F-\text{el}} = \int_0^1 \left( M_f g - A_i \frac{\partial p_i}{\partial x} - \frac{1}{2} C_f \rho_f D_e U_e^2 \right) N_u^T l_e d\xi \quad (15)$$

Discretize the equation of motion:

$$M\ddot{q}_e + C\dot{q}_e + Kq_e = F \quad (16)$$

Where,  $M$  represents the element mass matrix,  $C$  represents the element damping matrix,  $K$  represents the element stiffness matrix,  $F$  represents the element force vector.

Since the kinetic energy and strain energy generated by the rotation of the drill string system are not considered, hence:

The force vector in the equation of motion (16) is equal to the combination of gravity and linear force,  $F = F_g + F_{nl}$  <sup>[10]</sup>

$$F_g = \delta F_{G-\text{el}} \quad (17)$$

$$F_{nl} = \delta F_{F-\text{el}} + \delta E_{AR-\text{el}} \quad (18)$$

4. Numerical simulation analysis

In this section, the influence of the fluid characteristics of annular fluid on the dynamic behavior of a horizontal drilling string system is explored by changing the velocity and gas content of annular fluid. The parameters of the drilling string system and fluid used in the study are shown in Table 1 below.

Table 1. Related parameters of fluid domain and solid domain

|                      | Parameter Names                             | Numerical Value       |
|----------------------|---------------------------------------------|-----------------------|
| Structural parameter | Density (kg/m <sup>3</sup> )                | 7 800                 |
|                      | Length (m)                                  | 10                    |
|                      | Outside diameter of drill string (mm)       | 127                   |
|                      | Wall thickness (mm)                         | 9                     |
|                      | Elasticity modulus (Gpa)                    | 207                   |
|                      | Poisson's ratio (-)                         | 0.3                   |
| Fluid parameter      | Drilling fluid density (kg/m <sup>3</sup> ) | 1 200                 |
|                      | Drilling fluid viscosity (Pa·s)             | 0.001                 |
|                      | Natural gas density (kg/m <sup>3</sup> )    | 0.75                  |
|                      | Natural gas viscosity (Pa·s)                | 1.15×10 <sup>-5</sup> |

4.1. Relationship between gas content in annulus and drill bit axial vibration

The parameter Settings are the same as Table 1, as shown in Figure 5. The changes of peak displacement and maximum equivalent stress of axial vibration of the drill string system with the volume fraction of natural gas in the annulus are simulated. As can be seen from Fig. 5, with the increase of the volume fraction of natural gas in the annulus, the peak displacement and maximum equivalent stress of the axial vibration of the drilling string system increase linearly. Fig. 6 and Fig. 7 respectively show the curves of the velocity amplitude and acceleration amplitude of the axial vibration of the horizontal drilling string system as a function of the natural gas content in the annulus. It can be seen from Fig. 6 and Fig. 7 that with the increasing of gas content in the annulus, the amplitude of axial vibration velocity and acceleration of the horizontal drilling string system are also increasing, and it can be seen from the change curves of the two figures that the two figures both change linearly.

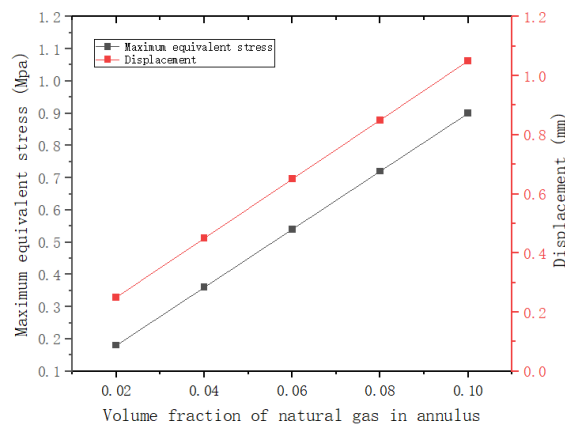


Fig. 5 Peak axial displacement and maximum equivalent stress of drill string system Curve with annular velocity.

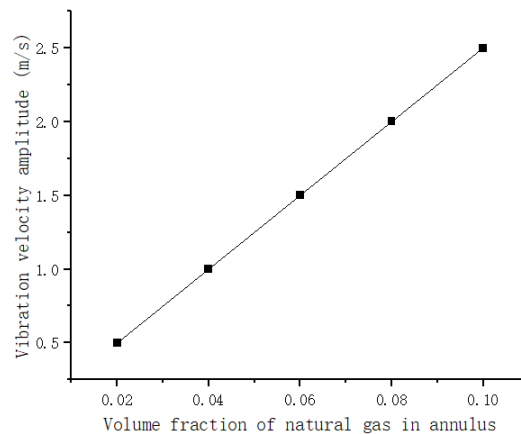


**Fig. 6** The velocity amplitude of axial vibration of the drilling string system varies with the natural gas content in the annulus

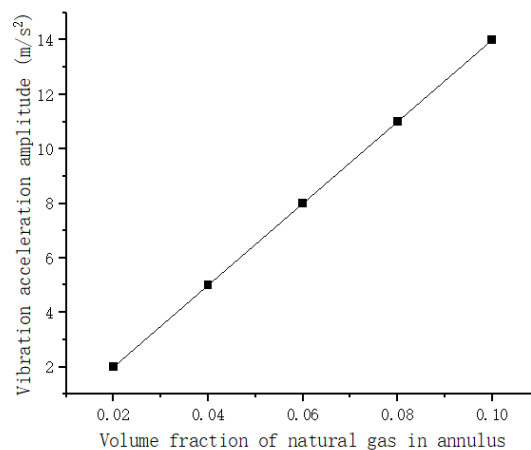


**Fig. 7** Curve of acceleration amplitude of axial vibration of drill string system with the change of natural gas content in annulus

## 5. Simulation experiment and result analysis

### 5.1. Experimental bench system introduction

Based on the similarity criterion <sup>[11]</sup>, a horizontal compression drill string test bench was developed. The overall structure of the test bench is shown in Fig 8:

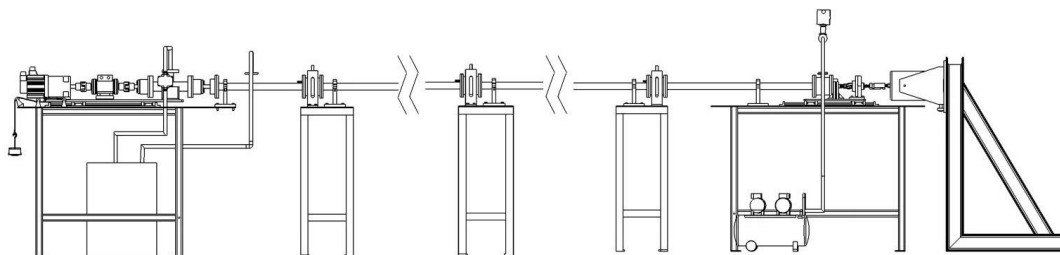
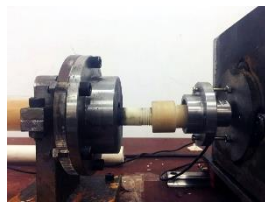


**Fig. 8** Schematic diagram of the experimental device system

The purpose of this test bench is to analyze the buckling characteristics of horizontal rotating drill string under different annular fluid characteristics. The test bench is mainly composed of six systems: drive system, circulation system, pipe column system, loading system, gas-liquid mixing system and test system. The actual picture is shown in Fig 9 and 10.



**Fig. 9** Physical diagram of the overall structure of the experiment



(a) Downhole simulation system



(b) Drill string rotation system



(c) Inspection and pole system



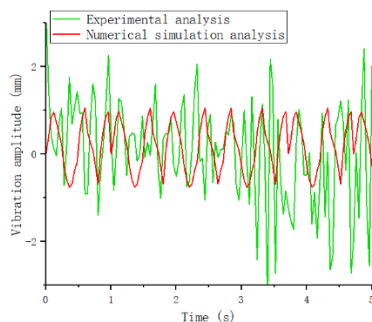
(d) Test system

**Fig. 10** Physical picture of drill string dynamic simulation experimental device for horizontal well

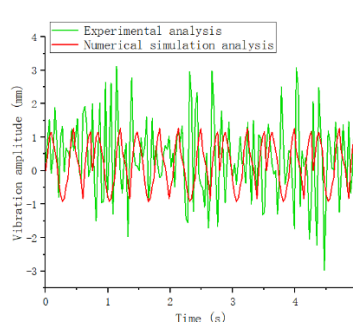
## 5.2. Effect of different annulus gas content on axial displacement of drill string

This section studies the effect of gas content in the annulus fluid on the axial vibration of drilling string when the gas hydrate is decomposed in the drilling of horizontal Wells.

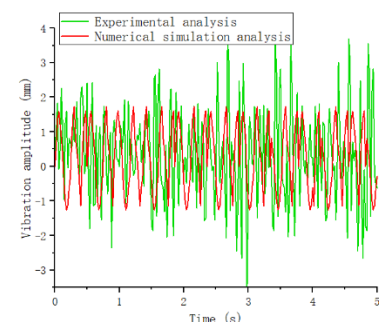
By adjusting the opening of the air pump and ball valve, and observing the gas flow rate in the gas flowmeter, the gas content of the annulus fluid is maintained at a certain value (10%, 20%, 30%), and then the test is carried out and the displacement change curve of axial vibration is measured. By comparing the experimental results under different annular fluid gas content conditions, the effect of annular fluid gas content on drill bit axial vibration is obtained.



a) The gas content of the fluid is 10%



b) The gas content of the fluid is 20%



c) The gas content of the fluid is 30%

**Fig. 11** Axial vibration displacement curve of drilling string under different annulus gas content

By comparison with Fig. 11 (a) -c), it can be seen that with the increase of annulus gas content, the displacement curve value of axial vibration increases, the frequency of axial vibration of the horizontal drilling string system slightly increases, and the amplitude generally shows an increasing trend. The conclusions obtained by the above tests are basically consistent with the numerical simulation results. This is because, with the increase of annulus fluid gas content, the motion characteristics of annulus fluid change, and the effect of annulus fluid on the drill string system becomes more and more complicated, resulting in the axial vibration becomes more and more intense and complex.

## 6. Conclusion

By exploring the influence of natural gas on horizontal well bit axial vibration, this paper established the bit axial vibration model and the drill string system unit stress model, and obtained the following conclusions through numerical simulation and experimental verification:

When gas is present in the annulus, the displacement of axial vibration of the drill string system shows quasi-periodic changes. With the increase of gas content in the annulus, the frequency and amplitude of axial vibration of the drill string system increase slightly and obviously.

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