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Characterization of Vibration Pattern and Axial Vibration in Ultra-deep Straight Wells

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Abstract

With the development of oil and gas exploration to ultra-deep and extra-deep fields, the drilling depth increases year by year, and the downhole drilling column exhibits extremely complex dynamics under uncertain loading and environmental conditions downhole, which directly affects the drilling efficiency and safety. Drilling accidents such as wear and fatigue failure of the drill pipe caused by axial vibration result in direct economic losses and increase additional drilling costs. Therefore, in this paper, a well body structure in Sichuan Shuangyuishi block is selected as the research object, and a whole-well drilling column dynamic model is established to calculate the axial vibration characteristics and vibration patterns. The results show that: the larger drilling pressure makes the transverse vibration vibration node sink, and the stability of the drilling tool decreases; the frequency of the drill pipe increases with the increase of the stiffness, and increases with the decrease of the drilling pressure; the trend of axial force reduction from the wellhead to the drilling tool combination is relatively smooth, and the change amplitude is relatively small, and the trend of the axial force reduction is obviously intensified after entering into the drilling tool combination; at the position of the wellhead, the beating amplitude of the node of the drilling column is relatively large However, the vibration frequency is lower compared with the lower BHA; the vibration intensity becomes more and more intense from the top to the bottom.

Keywords

Vibration; Drilling Column Dynamics; Vibration Pattern Analysis.

1. Introduction

0[2]Oil and gas is a key strategic resource for economic and social development. With the development of drilling technology in recent years, China's oil and gas resources exploration is gradually moving towards ultra-deep (well depth between 6000m and 9000m) and extra-deep wells (well depth greater than 9000m) [1] (-) ([3]) . However, the drilling column faces extremely severe challenges in the downhole operating environment: with the increase of well depth, the vibration problem of the drilling column during drilling becomes more and more prominent, which can lead to problems such as drill bit tooth damage and column failure, as shown in the selected figure, and the vibration has gradually become an important factor restricting the drilling efficiency and quality. Therefore, the establishment of a full-well drilling column dynamics model that can truly reflect the dynamic characteristics of the whole well when the drill bit breaks the rock and drills is an urgent problem in the field of drilling tool dynamics research.

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(a) Drill tooth damage[25] (b) Drill pipe failure[25] (c) Drill pipe puncture leakage[3]

Fig. 1 Hazards of vibration

The core of drill string dynamics is vibration and its control. The basic forms of vibration in a drill string include axial, torsional and transverse vibration. These three types of vibration can exist separately or be coupled with each other to form more complex vibration. Many scholars at home and abroad have studied the dynamics of the drilling column: from a single axial vibration[1-7], torsional vibration[8-10], transverse vibration[11-13] modeling, to the development of a complex model of the coupling of the two or three types of vibration to study the vortex[14,15]) , viscous slip vibration ([16]) and so on; also focusing on different dynamical models, such as: the concentrated mass method ([17-19]), the finite element method ([20-22]) , multi-body dynamics ([23.24]) and other methods.

However, the dynamic behavior of the drilling column during the drilling process is less described in the existing studies, which is mainly limited by many factors such as the structure of the well body, the variety of drilling tool combinations, the drilling parameters, the complexity of the interaction between the drilling tool and the wall and the rock at the bottom of the well, etc. In this paper, we established the dynamics model of the full-well drilling column, computed the dynamics model of the full-well drilling column and the hydrostatic model, and analyzed the axial vibration and the oscillation pattern. The results provide an important reference for risk prediction of drilling operations.

2. Full-well Drilling Column Dynamics Established

2.1. Kinetic Modeling

In the study of the full-well drilling column dynamics model, the following conditions are assumed: the drilling column is simplified as a homogeneous beam with multiple cross-sections, each of which is in the shape of a circle; the contact interface between the drill bit and the rock at the bottom of the well is assumed to be the boundary condition at the bottom end, and the rock eigenstructural model is adopted as the Drucker-Prager model; the yielding behaviors of the rock are simulated in the calculations and the rock units are deleted after they reach the yielding limit; Since the strength of the drill bit is much stronger than that of the rock at the bottom of the well, the drill bit is simplified as a rigid body, and the damper is simplified as a combined spring and damper model to facilitate the solution in numerical calculations.

This paper is to establish the dynamical equations of ultra-deep well drilling[25] column system through Hamilton's principle, which is the relationship between kinetic and potential energies of a mass in motion and the work done on the mass by the nonpotential force:

$$\delta\int_{\Delta t}(T-V)\mathrm{d}t+\int_{\Delta t}\delta W\mathrm{d}t=0 \qquad (1)$$

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When δdenotes the variational operator; T denotes the total kinetic energy of the system; W denotes the total potential energy of the system; t denotes the work done by the nonpotential forces; and denotes time.

The T-V term in the above equation is the Lagrangian function term (L), and in a continuous system, the dynamic displacement and corner variables of the drilling column are u(z, x, y, t) and θ(z, x, y, t), respectively, through which the kinetic and potential energy as well as the nonpotential work of the system can be directly expressed. In the finite element, the drill column is viewed as a geometrical ensemble that includes the individual drill column units. The continuous variables in the model are replaced by the nodal variables (Ui) of the individual drill column units. The substitution is obtained:

$$\int_{\Delta t}\left[-\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\partial L}{\partial \dot{U}_i}\right)+\frac{\partial L}{\partial U_i}+F_i\right]\delta U_i=0 \tag{2}$$

When F_i denotes the generalized non-have power.

Further expansion of the above equation gives

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\partial T}{\partial \dot{U}_i}\right)-\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\partial V}{\partial \dot{U}_i}\right)-\frac{\partial T}{\partial U_i}+\frac{\partial V}{\partial U_i}=F_i \tag{3}$$

The discrete assembly of the drilling column system based on the finite element theory leads to the establishment of a three-dimensional multi-degree-of-freedom drilling column dynamics model of the drilling column in ultra-deep wells, as shown below

$$M\cdot\ddot{U}+C\cdot\dot{U}+K\cdot U=F \tag{4}$$

When, M C and K are the mass matrix, damping matrix and stiffness matrix of the drilling column system, respectively; $\ddot{U}$, $\dot{U}$, U and F are the acceleration matrix, velocity matrix, displacement matrix and load matrix of the drilling column system, respectively.

2.2. Boundary Conditions

In the process of processing the wellhead boundary conditions, the constraint characteristics in the actual drilling well should be fully considered. The wellhead turntable restricts the lateral displacement of the drill pipe. In the numerical model, in order to accurately simulate this constraint, the lateral displacement degrees of freedom and rotation degrees of freedom at the node of the drill pipe located at y=0 are fixed. In addition, during the cutting process of the drill bit, with the dynamic change of the wellbore position, the whole drill column moves downward in the vertical direction gradually. Therefore, the displacement degrees of freedom of the nodes of the drill column in the y-direction at the wellhead remain unconstrained. Meanwhile, in order to more realistically simulate the pulling effect of the drilling platform on the drilling column, an appropriate external force F is applied in the negative direction of the y-axis, which is used to characterize the pulling and holding effect of the platform's large hook on the drilling column.

For rock drill interaction, the main ontological models reflecting the plastic mechanical properties of rock are the Mohr-Coulomb (Mohr-Coulomb) model and the Drucker-Prager (Drucker-Prager) model . Both models reveal the damage mechanism of rock materials under compressive shear in drilling engineering. However, the former does not consider the intermediate principal stress among the three principal stresses, and thus is only applicable to low peripheral pressure conditions. In contrast, the latter model[25] is modified and expanded

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on the basis of the Mohr-Coulomb model and the Mises criterion, which not only introduces the influence of the intermediate principal stresses on the damage characteristics of the rock, but also takes into full consideration of the role of the surrounding pressure. Therefore, this model is selected for the study in this paper. Its mathematical expression is as follows:

$$f = \alpha I_1 + \sqrt{J_2} - K = 0 \tag{5}$$

when I_1 is the first invariant of stress, J_2 is the second invariant of stress, α and K are rock material related parameters.

The damage mode of rock at the bottom of the well in drilling engineering is mainly shear damage, and the initial equivalent plastic strain at the time of damage is assumed to be a function of the shear stress ratio and the shear strain rate in the numerical calculation of finite elements:

$$\bar{\varepsilon}_s^{pl} = f(\theta_s, \dot{\bar{\varepsilon}}^{pl}) \tag{6}$$

$$\theta_s = \frac{q + k_s p}{\tau} \tag{7}$$

When, τ is the rock shear strength; p is the equivalent stress, Pa;

The damage variable D is a variable that describes the degree of damage to a plastic unit and has a variety of expressions. The damage variable D increases in the range of 0 to 1 during the damage process, and at the time of complete failure of the unit, the damage variable D = 1. It is expressed as follows:

$$D = 1 - \frac{E'}{E} = \begin{cases} 0 & (\varepsilon \le \bar{\varepsilon}_0^{pl}) \\ 1 - \dfrac{\sigma}{\bar{\sigma}} & (\varepsilon \ge \bar{\varepsilon}_0^{pl}) \end{cases} \tag{8}$$

When, E' is the modulus of elasticity of the rock unit after the occurrence of damage, Pa; ε is the strain of the rock unit; σ is the stress of the rock after the occurrence of damage, Pa; $\bar{\sigma}$ is the stress of the rock without damage, Pa.

2.3. Model Validation

Using the pre-processing module of the finite element software, the three-dimensional models of the drill column, well wall and rock were established and meshed with three-dimensional beam units, rigid shell units and hexahedral solid units, respectively, and the finite elements of the system are shown in Fig. 2 below after assembling the drill bit, the drill column, the well wall and the rock model. In order to verify the accuracy of the finite element model, this study compares the simulation results with the experimental data in the cited article. The experimental data show that the average value of the longitudinal acceleration of the drill pipe ranges from 1g to 1.7g, and the maximum instantaneous value is more than 10g. In order to make sure that the simulation conditions are consistent with the experiments, this simulation establishes a finite element model with the same drilling tool combination as the experiments (drill bit + 8.46 "stabilizer + 7 "damper + 7 "collars + 6.25 "collars + 5 "rods), and obtains the acceleration curves for the collars at a distance of 2m from the drill bit. curve at a distance of 2 meters from the drill bit.

In the whole rock breaking process as shown in Figure 3 below, the PDC cutting teeth continuously alternate into the rock, the front cutting teeth carry out the initial cutting, while the rear cutting teeth further break the residual rock chips finely to ensure uniform cutting and improve the rock breaking efficiency. With the continuous rotation of the drill bit, the cutting teeth repeat the process of pressing in, shearing, breaking and removing rock chips, which finally realizes the stable advancement of the drill bit and efficient drilling.

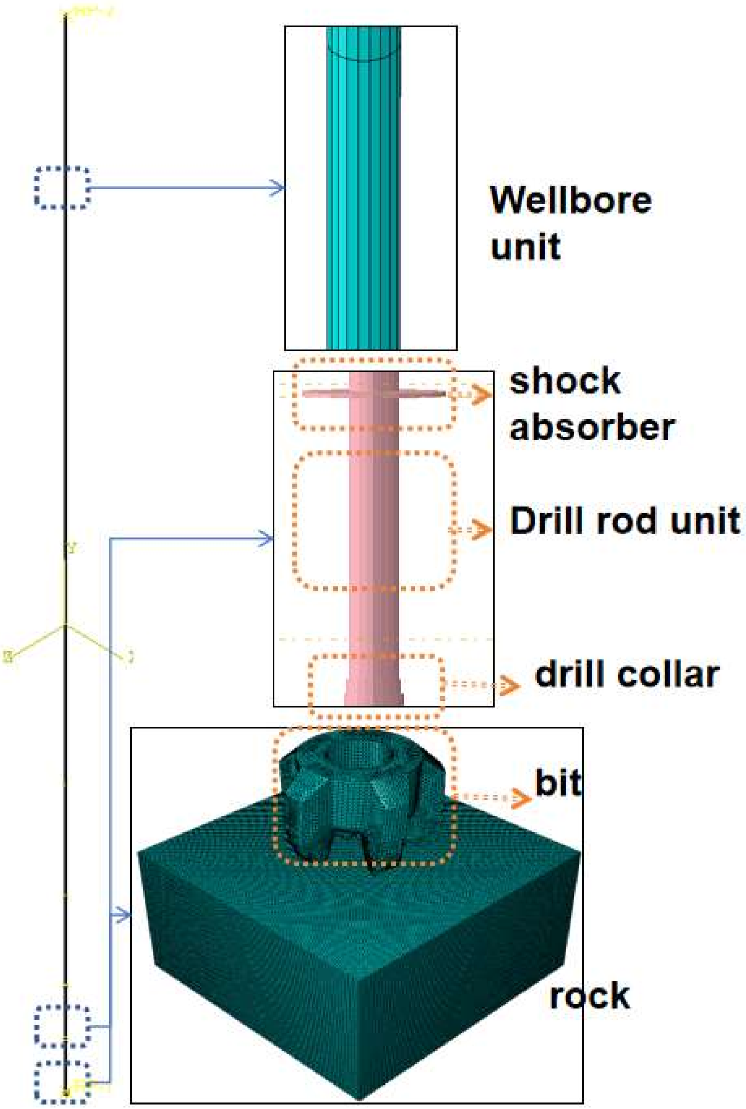

Fig. 2 Finite element model of the whole well drilling column

According to the results in Fig. 4, the acceleration curve of the drill collar shows that its average acceleration is 1.87 g, and the maximum instantaneous acceleration is 7.51 g. Although the maximum instantaneous acceleration obtained by the simulation is slightly lower than the experimental value, its average acceleration is within the range of the experimental data, which fully verifies the accuracy of the simulation model and the reliability of the analysis results. It can be seen that the finite element simulation can accurately reproduce the dynamic response of the drilling column subjected to the drilling process, which provides an effective numerical analysis tool for the further study of the mechanical behavior during the drilling process.

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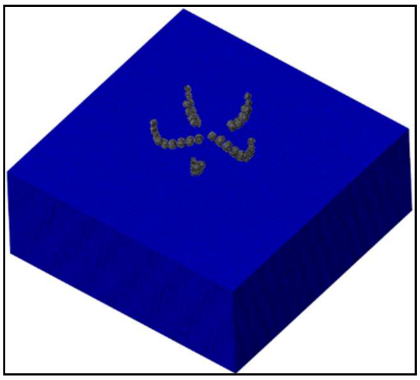
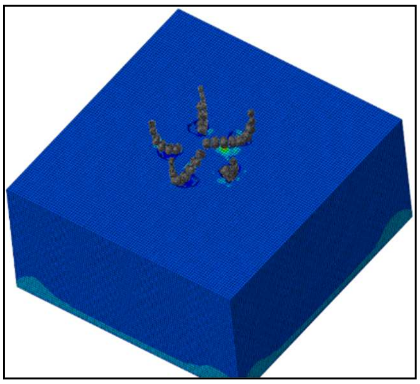
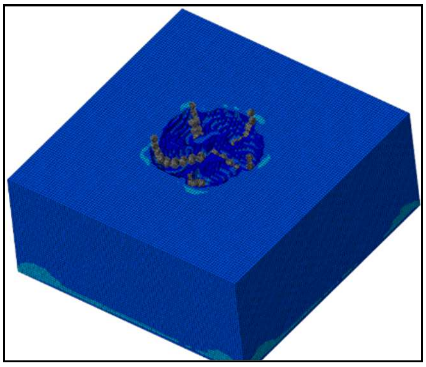


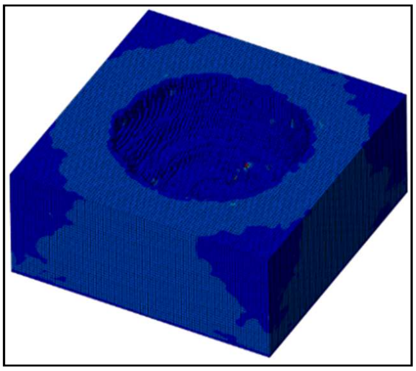
(a) Drill teeth begin to contact the rock



(b) The drill teeth start cutting the rock

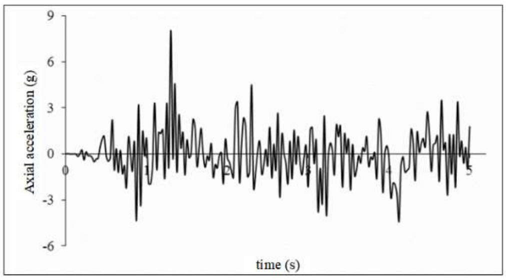


(c) The drill starts drilling

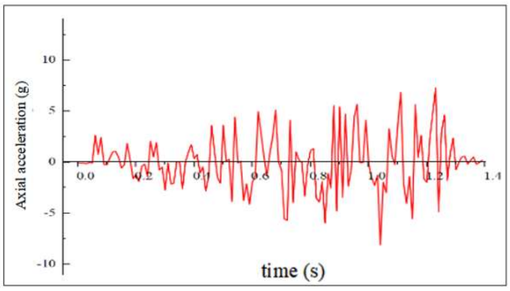


(d) Post-drilling rock map

Fig. 3 Drill bit crushing rock



(a) Experimental data



(b) Simulation data

Fig. 4 Comparison of experimental and simulation data

3. Modal and Vibration Analysis

Simplifying the drilling column into a vibrating beam model as shown in Fig. 5, the axial force of the drilling column, due to the effects of gravity and the interaction between the drill bit and the rock, is

$$F_y = \rho g A(l - y) - F(l) \tag{9}$$

When ρ Equivalent density of the drill column, kg/m3; A Cross-sectional area of the section of the drill column, m2; l Length of the drill column, m; $F(l)$ Axial force at the bottom of the drill column, N; F_w Magnitude of the drilling pressure value, N

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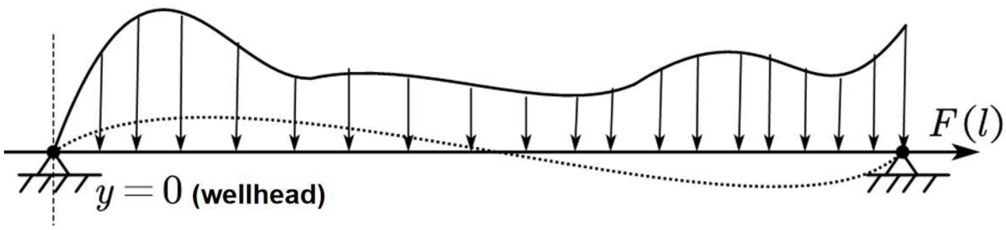

Fig. 5 Bending vibration of the drill pipe

According to the above mechanical model, the length of the drilling column is selected as 10250m, and the combination of drilling tools and material parameters are shown in Table 1 to analyze the influence of the axial force of the drilling column on the frequency of the drilling column and the vibration pattern of the drilling column. ×When gravity is not considered, the drill pipe is a gravity-free rod, and the 1st order vibration frequency of the drill pipe is 4.19 10-4rad/s, which is very soft. When gravity is considered, the axial force on the drill pipe is a variable axial force along the course, which will have a large effect on the overall stiffness of the drill pipe and the lateral self-oscillation frequency. Figure 6 demonstrates the first 10 order frequencies versus different values of gravity. Considering the axial force increases the self-oscillating frequency of the drill pipe in general, and the 1st order vibration frequency of the drill pipe is 10.57 10-2rad/s, which is an increase of 252.27 times as compared to the frequency when gravity is not considered for the drill pipe.

Table 1. Drilling tool combinations used for modal analysis

Drilling tool sets				Material parameters	
name (of a thing)	Outer diameter/mm	Inner Diameter/mm	Length/m	name (of a thing)	(be) worth
driller	215		0.34	Density of drill pipe	7860kg/m^3
drill rod	139.7	121	10097	gravitational acceleration	9.8m/s^2
drill collar	165	82	400	Modulus of elasticity of drill pipe	2.1e11N/m^2

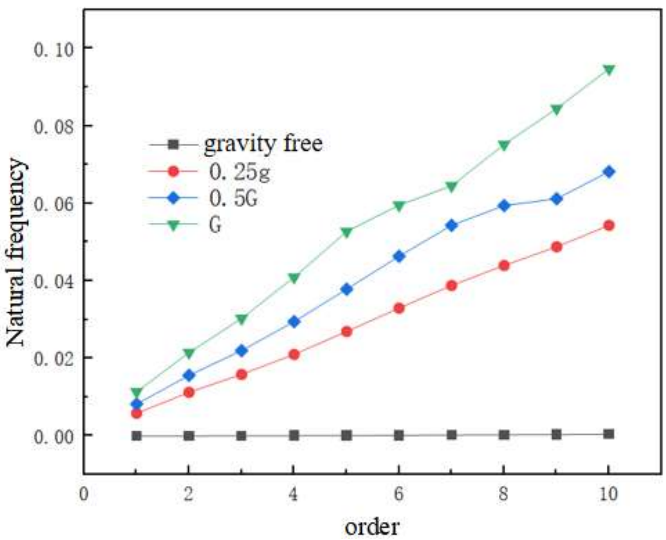

Fig. 6 Effect of gravity on the frequency of each order of the drilling column

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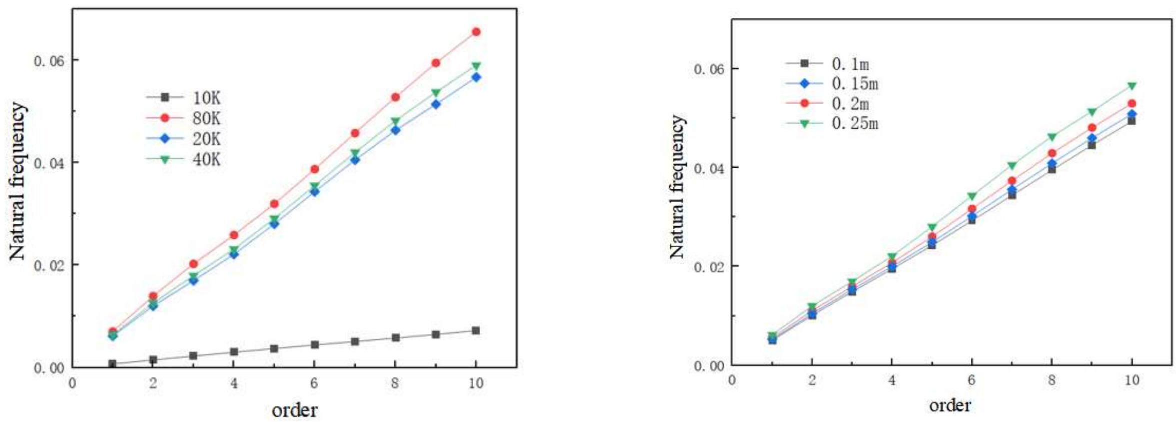
With other conditions unchanged, the intrinsic frequency is calculated when F(l) is 10kN, 20kN, 40kN and 80kN respectively, and the frequency of each order is obtained as shown in Fig. By observing the frequency changes under different drilling pressures, it is found that when the mass of the drilling column system and the stiffness conditions of the drilling tool combination remain unchanged, reducing the drilling pressure can effectively improve the system's ability to resist deformation, which in turn reduces the probability of system instability. This shows that the reduction of drilling pressure has a positive effect on the mechanical stability of the drilling column, which helps to reduce the amplitude of lateral vibration of the column, thus improving the safety of drilling operations.

Considering the effect of stiffness change on the frequency of each order of drill pipe, the stiffness of drill collar in the lower part of the drill column system can be adjusted by changing the thickness of drill collar section. Taking F(l) = 80kN as the working condition, the different drill pipe order frequencies are calculated when the wall thickness of the drill collar is 0.1m, 0.15m, 0.2m and 0.25m, respectively, as shown in Fig. The analysis results show that with the increase of the wall thickness of the drill collar, the frequency of the drill pipe gradually increases at the same modal order. Specifically, when the wall thickness of the drill collar is 0, the 1st order frequency of the drill pipe is 0, indicating that the system is in a completely flexible state at this time, which is prone to violent transverse vibration. However, when the wall thickness of the drill collar is increased by 0.15 m, the 1st order frequency of the column becomes 4.24×10^{-2} rad/s, indicating that the system stiffness is significantly improved. With the further increase of wall thickness, the overall stiffness of the drill collar is further enhanced, and the 1st order frequency continues to increase, indicating that the ability of the system to resist transverse deformation is also improved accordingly.



(a) Effect of the magnitude of F(l) on the frequency of each order of the drilling column

(b) Effect of collar stiffness on the frequency of each order of the drill column

Fig. 7 Effect of drilling pressure and stiffness on frequency

The following figure illustrates the distribution of vibration modes for two full-well drilling columns in 1st to 3rd order transverse modes for the case of no weight rod and WOB=10KN. In the case of neglecting the gravity effect, the 2nd order mode of the drilling column exhibits a centrosymmetric distribution with one node (at the intersection with the vertical axis), while the 3rd order mode exhibits two nodes. At this time, the shape of the vibration mode is mainly influenced by the stiffness of the drill column itself and the external excitation. When the drill column buckled under the axial force, the vibration pattern changed significantly. Compared with the vibration pattern of the drill pipe when there is no gravity or when it is only subjected to lower pressure, the vibration pattern after buckling is fundamentally changed by the axial

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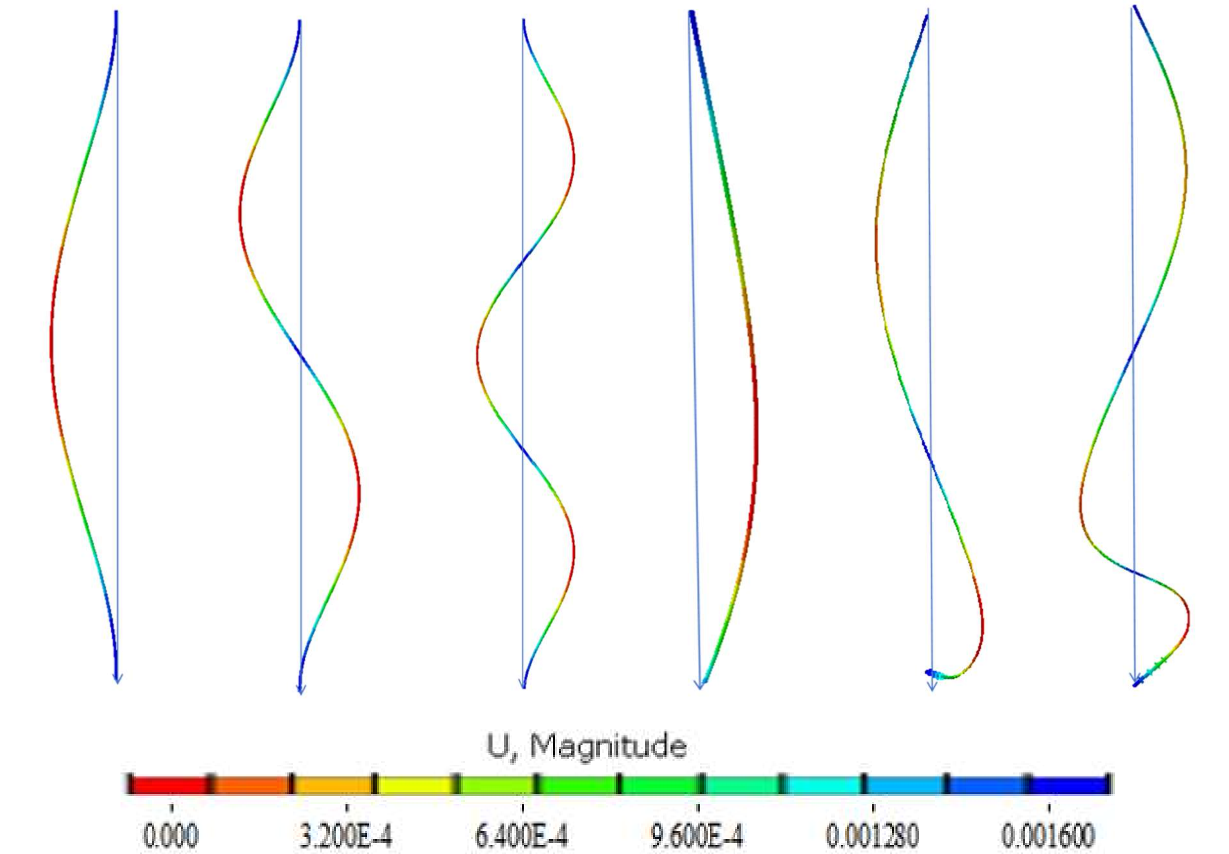
force, and the original shape of the vibration pattern is altered. In particular, the node positions of the first 3 steps of the vibration patterns sunk significantly, and the more the bottom of the drill column was subjected to the axial compression force, the more significant the amount of sinking was.



(a) First order without weight bars | (b) Weightless rod second order | (b) Weightless bar third order | (b) 10K first order | (b) 10KN second order | (b) 10KN third order

Fig. 8 Comparison of vibration patterns between gravity free and 10KN drilling pressure

4. Axial Vibration Characterization

4.1. Axial Force Simulation

On the basis of the previous drilling tool combination, the axial vibration force response curve was calculated, as shown in Fig. 5-1. The prediction of axial force at each key point position of the drill column has a certain guiding role in evaluating the drilling safety. The mean value of axial tension at the wellhead position is 1256.51kN, and the instantaneous drilling pressure fluctuates significantly with time due to the randomness of the drill bit-rock formation contact interaction, the mean value of the drilling pressure is 97.79kN, and the amplitude is 56.22kN, the average value of the axial force at the position of drill collar at 40m away from the bit is -44.68kN, and the amplitude is 56.22kN. The average value of the axial force at the collar position at 40m is -44.68kN, and the amplitude of axial force fluctuation is 27.18kN, and the percentage of transient values in the bad interval is 38.72%, which shows that the axial force fluctuation at the collar is serious, and the reduction of the percentage of transient values in the bad interval can reduce the vibration intensity of the lower BHA.

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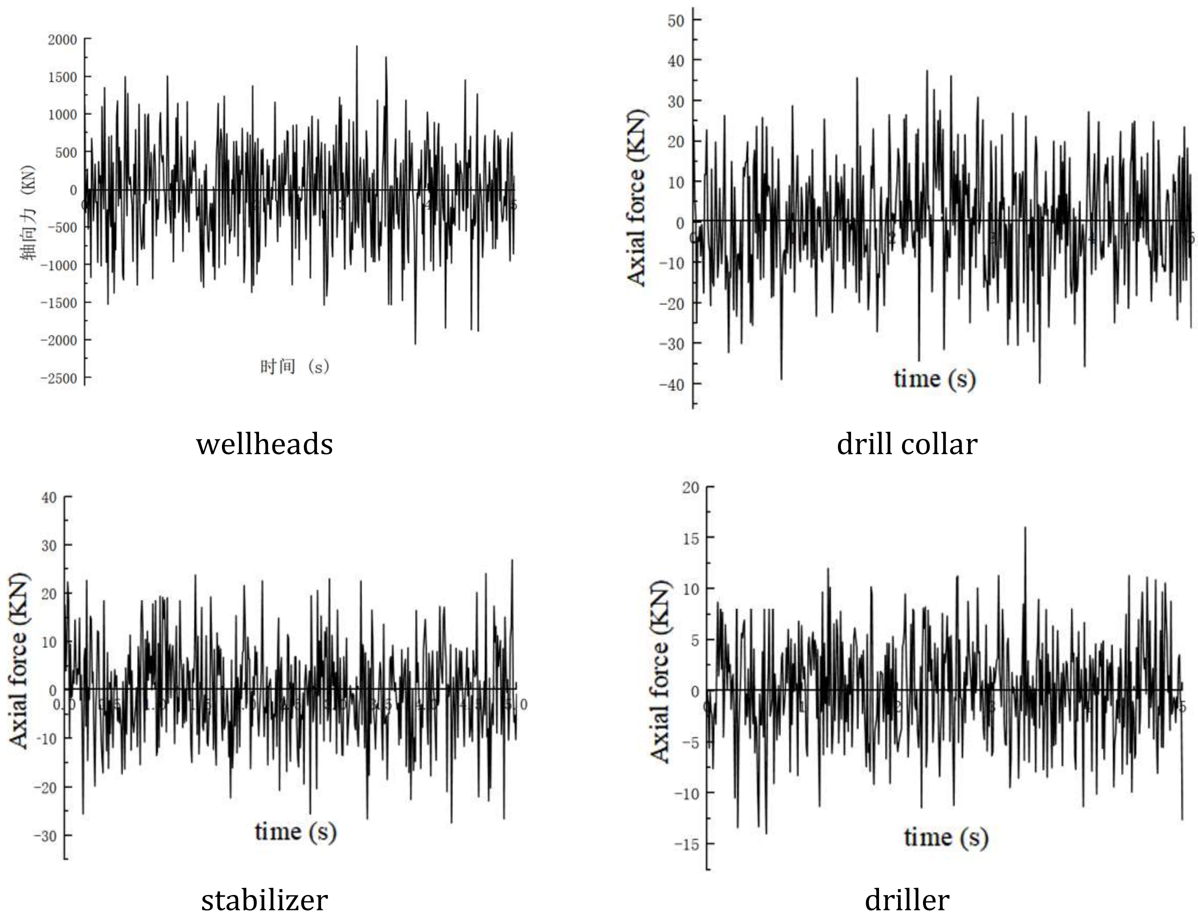

Fig. 9 Axial force curves at different positions

The axial force distributed along the length of the drill column and the axial force amplitude are shown in Figure 5-2. From the figure, it can be seen that the trend of axial force can be divided into two regions. Between 0 and 9,850 meters, the trend of axial force reduction is relatively smooth and the change amplitude is relatively small. This stage is mainly affected by the stiffness of the column itself, drilling pressure and formation pressure and other factors, resulting in a relatively flat rate of axial force reduction. Between 9850 m and 10250 m, the trend of axial force reduction accelerates significantly, indicating that in this depth range, the external pressure and formation deformation effect on the drill pipe are more significant, resulting in a significant increase in the rate of axial force reduction.

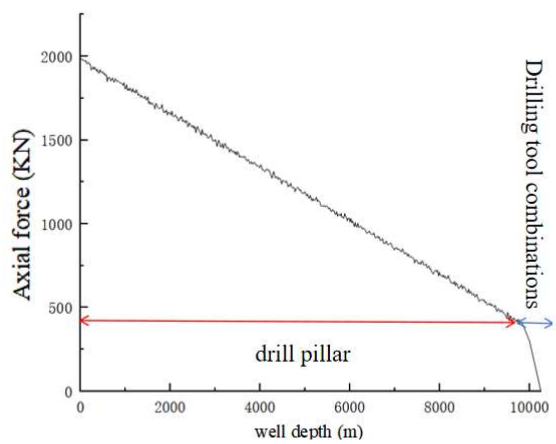

Fig. 10 Distribution of axial force along well depth for the whole well

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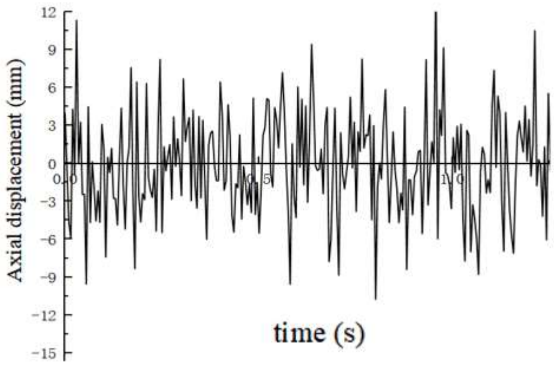
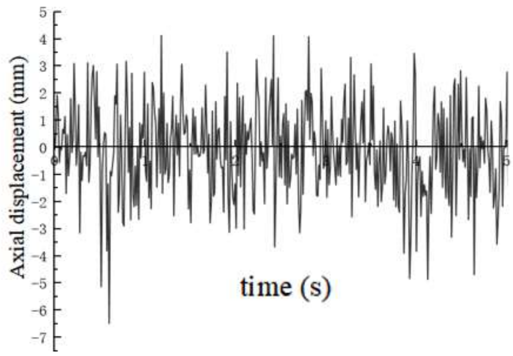
4.2. Axial Vibration Displacement

The axial force is the root cause of the axial motion of the drill pipe, the behavior of the upper tool compressing the lower BHA and the feedback behavior of the lower BHA to the upper compression make the whole tool system in a nonlinear motion state, and the simulation of the vibration displacement of the drill pipe is helpful to increase the understanding of the drasticness of the axial motion of the whole well.

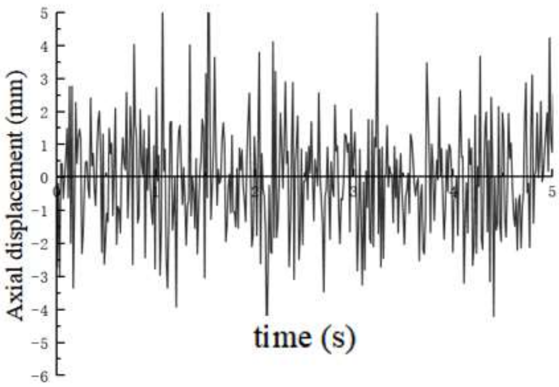
The kinematic characteristics of the drilling tool as a whole determine the axial displacement at the drill bit in the direction of increasing well depth, and the accumulation of axial displacement directly leads to the increase of the length of the well body. Through numerical simulation analysis, the axial vibration displacements of the wellhead, drill collar, stabilizer and drill bit can be obtained, and the relevant results are shown in Figure 5-3. The numerical results show that at the wellhead position, the jumping amplitude of the drill pipe node is relatively large, but its vibration frequency is lower than that of the lower BHA. This phenomenon is consistent with that observed during the actual drilling process, i.e., the up and down vibration of the drill pipe can be clearly felt on the drilling platform. In addition, in the lower BHA, the axial vibration at the drill bit is particularly intense, and its maximum vibration displacement reaches 2.21 mm, indicating that the drill bit is subjected to large fluctuations of force during the rock breaking process.



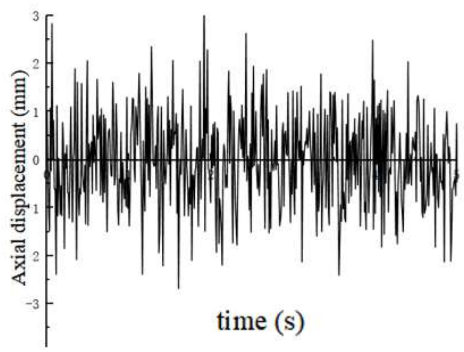
wellheads



drill collar



stabilizer



driller

Fig. 11 Axial displacement curves at different positions

4.3. Axial Strength Simulation

Reducing the large hook load to pressurize the lower drilling tool and creating drilling pressure at the drill bit is the source of axial vibration of the whole system, and the prerequisite for creating axial force and acceleration at each position of the drill column. Analyzing the axial vibration characteristics of the system at the key points using transient dynamics methods can assess the severity of the axial vibration and the risk of the lower BHA being exposed to axial vibration, and the acceleration of the axial vibration is one of the parameters reflecting the characteristics of the axial vibration. The axial acceleration is also one of the parameters that characterize the axial vibration. The performance of axial acceleration is usually based on the grading method of Baker Hughes in the U.S., in which the root-mean-square (RMS) value of the vibration acceleration is expressed as a multiple of the gravitational acceleration to measure the vibration level: when the root-mean-square value is in the range of 0-2.0g, the tool is in the safe vibration level, and it performs well downhole and operates smoothly; in the range of 2.0g-5.0g, the tool is in the moderately severe level, and then the monitoring of the tool needs to be strengthened to avoid the risk of the lower BHA in axial vibration. For 2.0g-5.0g, the drilling tools are in the moderate vibration level, and it is necessary to strengthen the monitoring of the drilling tools to avoid the vibration intensification; when the rms value is more than 5.0g, the drilling tools are in the severe vibration level, and it is highly probable that a drilling accident will occur, so it is recommended to apply damping measures before continuing drilling.

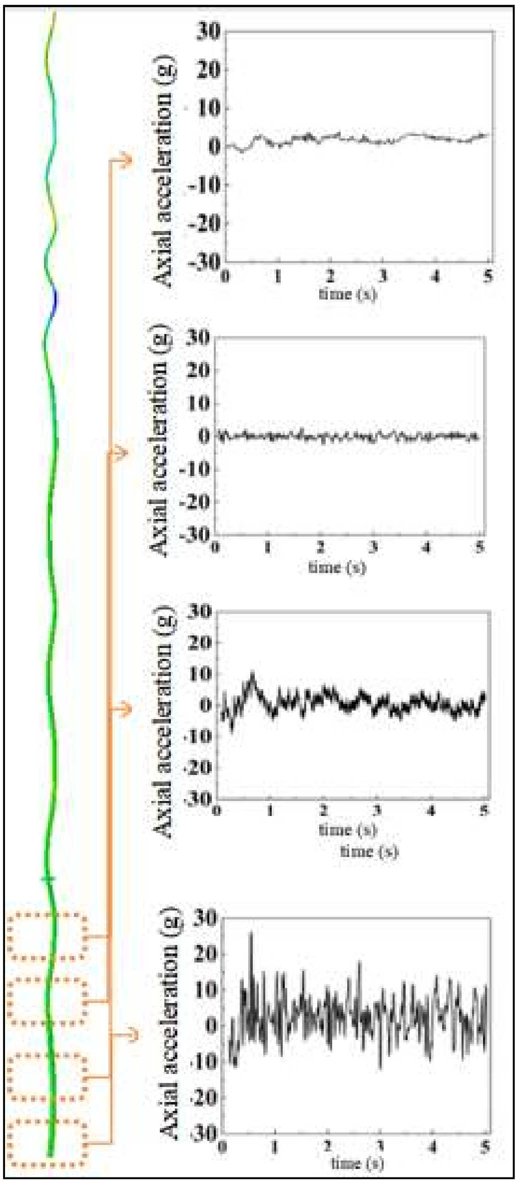


Fig. 12 Axial vibration intensity at each position

Fig. 12 shows the transient values of axial acceleration at each point from the corresponding position of the drill bit. the axial vibration intensities of the armature, 11'' drill collar, 12'' damper and PDC drill bit are 0.93 g, 3.74 g, 3.62 g and 3.98 g. The overall vibration intensities of the drill column from the drill bit upwards are rapidly decaying.

5. Conclusion

In this paper, the deep well vibration pattern as well as the axial vibration characteristics are calculated and analyzed by establishing the whole-well dynamics model and hydrostatic model, and the following conclusions are drawn:

(1) The axial force of the drill column significantly affects its vibration characteristics. When gravity is not taken into account, the stiffness of the drill pipe is low and shows greater flexibility; after gravity is taken into account, the axial force enhances the overall stiffness. Under the condition that the mass and stiffness of the drill pipe remain unchanged, reducing the drilling pressure can effectively improve the system stiffness, reduce the risk of instability, and reduce the amplitude of lateral vibration, thus improving the safety of drilling wells. In addition, increasing the wall thickness of the drill collar can significantly improve the stiffness of the drill column and increase the intrinsic frequency of each order.

(2) The vibration mode of the drill column is significantly affected by the axial force. Under the condition of no gravity, the 2nd order mode is centrosymmetric distribution with 1 node, and the 3rd order mode has 2 nodes, which is mainly affected by the rigidity of the drill column and external excitation. When the column is flexed by the axial force, the shape of the vibration mode is fundamentally changed, and the node position of the first 3-order mode is obviously sunk, and the larger the axial compression force is, the more significant the amount of sinking is.

(3) The average value of axial tension at the wellhead is 1256.51kN, the average value of drilling pressure at the drill bit is 97.79kN, and the average value of axial force at the drill collar position is -44.68kN, indicating that the force fluctuation at the drill collar is serious; The change of axial force along the depth of the well shows a two-phase characteristic, and the rate of decrease is obviously accelerated below 9850m, and it is more significantly affected by the effect of formation pressure and deformation; the vibration of the wellhead position is larger in magnitude but lower in frequency, while the lower BHA vibration is more intense. The vibration amplitude at the wellhead is larger but the frequency is lower, while the vibration at the lower BHA is more intense, and the maximum vibration displacement of the drill bit reaches 2.21mm, indicating that the force fluctuates greatly during the rock-breaking process, which is in line with the actual drilling phenomenon; the vibration acceleration at the corrector, drill collar, damper and drill bit is 0.93g, 3.74g, 3.62g and 3.98g, respectively, and the vibration at the drill bit is the strongest, and it is rapidly decaying upward along the drill column. According to the Baker Hughes classification standard, the drill collar, vibration damper and drill bit are in the moderately severe vibration level, which needs to be strengthened and monitored to reduce the risk of drilling accidents.

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