
Review on the Vibration Mechanism of Drill String During Natural Gas Exploitation

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Abstract: Gas hydrate, also known as combustible ice, is a pollution-free and clean energy source with huge reserves, so it is widely recognized as an energy source to replace oil. In the process of drilling and exploitation, a large amount of gas is generated by the decomposition of hydrate, which leads to the transformation of the single fluid (drilling fluid) into gas-liquid two-phase flow in the annulus. The constant change of the characteristic parameters of gas-liquid two-phase flow will aggravate the vibration frequency of the drill string. Combustible ice as sediment cement exist, can affect the strength of the sediment, and induce the occurrence of geological hazards, such as underwater landslides, and technical conditions for the present mining cost is too high, so it is necessary to in-depth analysis of the phenomenon, this paper introduced the research present situation and the drill string mechanics when there is a gas liquid two phase flow in the annulus, The research status of the influence of annulus fluid on drill string vibration is aimed to review the relevant literature on the influence of annulus fluid on drill string vibration, and to provide reference for the study of drill string dynamics in gas hydrate drilling and production.

Keywords: Natural Gas Hydrate (NGH), Drillstring, Dynamics, Multiphase Flow, Fluid-Structure Interaction

1. Introduction

Natural gas hydrate is a kind of gas hydrate, which is a solid crystalline substance formed by small molecular gases such as methane, ethane or carbon dioxide and water under low temperature and high pressure. It has the characteristics of large resources, wide distribution and shallow burial degree. Most of the known natural gas hydrates in the world are distributed at the edge of the ocean, and the global natural gas hydrate resources are about $2.1 \times 10^{16} \text{m}^3$, which is about twice of the world's proven oil and gas reserves. It is found that 1m^3 Natural gas hydrate (NGH) can release 164m^3 natural gas and 0.8m^3 water in standard condition. Due to the rapid development of science and technology in recent years, traditional oil and gas resources are being rapidly consumed, resulting in an increasingly serious global energy shortage. Natural gas hydrate reserves are abundant, which can replace traditional oil and gas resources to solve the problem of energy

shortage in the future. Many countries attach great importance to the exploration and development of natural gas hydrate [1-6]. However, in our country, the reserves of gas hydrate resources are abundant, mainly concentrated in the area of South China Sea, but there is a long way to realize large-scale exploitation. Therefore, the effective exploitation and utilization of gas hydrate are of great significance to alleviate the problem of energy shortage in China. In order to increase the contact area between the well and the gas hydrate reservoir and improve the production efficiency, drilling horizontal Wells is a common and effective way to exploit gas hydrate. The drilling process of offshore natural gas is relatively complex, which requires the establishment of a continuous channel from the continental shelf to the deep-sea reservoir for production operations, oil and gas analysis, reservoir monitoring, etc. Figure 1 is a schematic diagram of gas hydrate development using horizontal Wells.

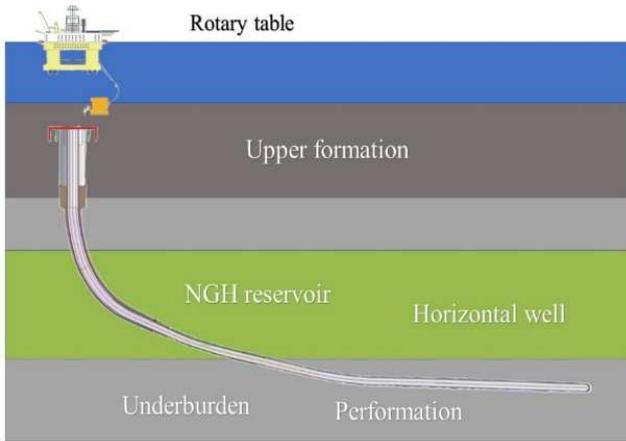


Figure 1. Diagram of horizontal drilling of gas hydrate.

At present, the research of drilling string vibration in horizontal Wells is mainly focused on the experimental or finite element simulation study of the influence of the fluid characteristics of drilling fluid in the string of vertical Wells on the vibration of the drill string, and mainly focuses on the natural frequency of the drill string and the factors affecting the natural frequency, while the research on the vibration motion characteristics of the drill string in horizontal sections is insufficient. The influence of fluid flow in annulus on drill string vibration cannot be ignored, especially when gas hydrate is mixed into drilling fluid, gas-liquid two-phase flow, and its fluid characteristics have more complex influence on drill string lateral vibration. In order to accelerate the exploitation of new energy and reduce drilling losses, the influence of gas-liquid two-phase flow in horizontal annulus on lateral vibration of drill string will be focused on in the future, so as to provide theoretical guidance for downhole vibration research of drill string.

With the development of drilling technology, experts at home and abroad have done a lot of research on the influence of annulus fluid on drill string vibration, including theoretical analysis, experimental analysis and numerical simulation analysis, and achieved good research results [7-10]. However, most of the current studies focus on the influence of single-phase flow in the annulus of vertical Wells on the drill string, and do not consider the influence of multi-phase flow on the drill string vibration. However, in the actual engineering of drilling horizontal Wells to extract natural gas hydrate, there is not only drilling fluid but also some gas in the annulus of the drill string. Therefore, the flow system in the annulus is a gas-liquid two-phase flow composed of gas phase and liquid, and the dynamic characteristics of the drill string are more complex under the interaction of gas-liquid two-phase flow. Therefore, it is still an important topic to consider multiphase flow when studying the dynamic characteristics of lateral vibration of drill string. Further research may be needed to supplement the influence of gas-liquid coupling in the annulus of horizontal Wells or other multiphase flows on the vibration of drill string.

2. Research Status of Drill String Mechanics

In the development process of drill string mechanics, after continuous research and improvement by scholars, several typical research methods are finally formed: classical differential equation method, energy method, finite difference method, longitudinally curved continuous beam method and finite element method. The research process has experienced from linear analysis to nonlinear analysis, from static analysis to dynamic analysis. The above methods are summarized in the following table.

Table 1. Summary of methods.

Research method
Classical differential equation method
The energy method
Finite difference method
Continuous beam method with vertical and horizontal bending
Finite element method

2.1. Classical Differential Equation Method

The classical differential equation method was first used in the study of drill string mechanics. Its idea is to establish the classical differential equation of the elastic force problem of drill string by using the analytical method of material mechanics and obtain the analytical solution by using the assumption conditions. This method is simple, intuitive and practical, which is of great significance for understanding the structure and design of drill string. With the development of drilling technology, people put forward higher requirements for wellbore trajectory control, which requires a more accurate calculation method. However, when many factors are considered, the established differential equation is complicated and it is difficult to obtain the analytical solution. This method has been used in the early research of drill string mechanics.

The earliest internationally recognized research paper on drill string mechanics was published by Lubinski in 1950 [11]. He used the classical differential equation method to study the statics of drill string, defined the critical bit weight of drill string, obtained the expression of contact force at the contact position between drill string and borehole wall through calculation, and proposed the "secondary bending drill string theory". Later, he and Woods proposed the "pendulum drill string theory", which pointed out that without the bit pressure at the bit, the lateral direction of the drill string was only affected by the transverse component of the drill collar weight between the drill string and the upper cut point, so that the drill string tended to be affected by the additional bit pressure [12].

Lubinski and Wiliamson used the classical differential equation method to predict and analyze the bottom hole assembly (BHA), where the hole curvature is constant and there is no bending moment on the bit, and the BHA combination structure determines the force on the bit independent of the formation [13]. However, this method is not applicable to all Wells in practice, and the effect of the

upper drill string on the drill collars must be considered in the design of the BHA.

2.2. The Energy Method

The energy method uses the energy principle to model and solve the problem, but the equation obtained by the energy method is complicated and difficult to obtain the solution because the boundary conditions need to be introduced. Therefore, this method is limited in use.

Walker studied BHA with the energy method, gave the calculation equation of BHA, and gave the solution satisfying the upper boundary conditions of the drill bit in the case of introducing the inclination Angle of the drill bit [14]. However, the boundary conditions could not be applied to the upper tangent point because this method could not be used to determine the upper cutting position of the drill string, so the results had errors. For example, the calculated lateral displacement of 120 feet of drill string 83cm is obviously not in accordance with the reality. Wu used the energy method to study the spiral buckling of the drill string and assumed that the drill string was of equal pitch after buckling [15]. He believed that as the torque of the drill string increased, its critical buckling load decreased, and the direction of torque determined the direction of the screw. Yu Yongnan studied the buckling problem of drill string by energy method, and described the lateral displacement of drill string after buckling with sinusoidal function [16]. This model comprehensively considered factors such as drill string gravity and well inclination Angle, and gave sinusoidal buckling critical load of drill string by ignoring higher-order terms. Lv Yingmin et al., in order to study the buckling problem of horizontal section drill string, regarded the drill string as an elastic foundation beam, assumed that the stratum reaction force on the drill string was proportional to the lateral displacement of the drill string, and calculated the critical buckling load of horizontal section drill string by energy method on the premise of giving engineering calculation method [17].

2.3. Finite Difference Method

Finite difference method (FDTD) is a widely used approximate numerical method in mechanics. The principle is to establish the differential equation of drill string mechanics from the basic equation of elasticity, and then replace the derivative function in the equation with the difference scheme, so that the solution of the differential equation can be transformed into the operation of the difference equation. The finite difference method is more convenient to consider the hole and nonlinear term constraints. Because of its high computational speed, high precision and easy programming, it has become possible to be applied in the field of petroleum engineering.

Bradly, Fischer et al. used the finite difference method to calculate the transverse displacement and analyze the two-dimensional force and deformation of the drill string [18]. The results show that this method can well simulate various complicated situations in the drilling process. There is an

obvious linear relationship between the force at each point on the drill string and the drill collar. At the same time, the factors affecting well inclination are also given. They point out that the well deviation is caused by the bending of the drill string, and the resultant force Angle on the bit is the drilling trend of the drill string, which points out the direction for the research of well trajectory prediction.

He Huashan based on the analysis of the problems existing in the drill string model, an improved model is given, and the use of the discrete finite difference method and considering rigid influence on the rigidity of the drill string, the drill string with soft model of drill string comparison, points out that the soft drill string model is only applicable to borehole trajectory is smooth curve, but drill collar rigid effect more apparent, ordinary drill pipe rigidity effect can be neglected [19]. Finally, the formulas for calculating the torque and lateral force under two different conditions are given. The results show that the soft drill string model can reflect the actual situation more accurately. Hard drill string model cannot accurately simulate downhole conditions.

2.4. Continuous Beam Method with Vertical and Horizontal Bending

The vertical and horizontal bending continuous beam method treats the drill string as the vertical and horizontal bending continuous beam, constructs the nonlinear equations by using the three moment equation, and obtains the deformation and force of the drill string by solving it. An example shows that compared with the traditional calculation method, the calculation result of this method is accurate and reliable. And can meet the requirements of engineering accuracy; At the same time, it has the advantages of high calculation accuracy and simple operation. This method of calculation is so fast that it can be carried out by ordinary microcomputer.

White House in 1977 Brazil for the first time put forward the crossbar bending continuous beam theory (BHA) to solve the problem of the force and deformation [20], and to take n lower root stabilizer drill combination for one dimensional analysis of the target, based on the vertical and horizontal bending deformation superposition principle of continuous beam from the stabilizer on the continuous conditions between two root cross beam and the tangent point on the boundary conditions on three bending moment equation. The method can be divided into two parts: 2D and 3D, where 3D analysis refers to the decomposition of a complex 3D problem into two simple 2D problems, that is, the calculation is carried out in the oblique Angle plane or azimuth Angle plane. The corresponding differential equations are deduced, and the internal force and displacement values of each section are obtained by numerical calculation, so as to determine the relative position relationship between each section. An example is given for verification. The results show that the method has high calculation accuracy and efficiency. Later, Su Yiniao et al. used this method to solve the joint problem of bending joint and downhole dynamic drilling tool, and analyzed the action law of each factor on the lateral force of

the bit by using the established model [21]. The results showed that the joint length of the lower part, the elbow Angle and the device Angle had the best effect.

2.5. Finite Element Method

The finite element method is one of the approximate numerical calculation methods widely used in solid mechanics. Specifically, the drill string is decomposed into beam elements and a series of calculations are made. Finally, the algebraic equations with the unknown node displacements are obtained. The physical concept of finite element method is clear, simple and practical.

Firstly, Millheim established the mechanical analysis model of BHA with finite element method, analyzed it with beam element, and introduced clearance element to simulate the contact between drill string and borehole wall [22]. This model abandons the assumption of upper tangent point, but does not consider the geometric nonlinear deformation of drill string. This analysis method has been successfully applied to study the stress of drill collar and drill pipe under various drilling conditions. In addition, Millheim also made a deep discussion on wellbore stability under drilling fluid. He noted that the trajectory of the bit determined the amount of lateral force it was subjected to. Millheim published several papers successively, which established the status of finite element method in the study of drill string mechanics.

3. Research Status of Drill String Vibration

Many experts and scholars at home and abroad have studied and analyzed various problems in drill string vibration for a long time, and put forward many mechanical models of drill string vibration and research methods of drill string vibration. However, due to the gap between these theories and the actual situation, there are more or less some errors or deficiencies in the application. The basic research contents are as follows.

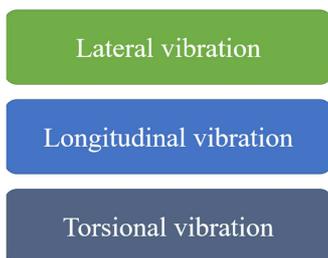


Figure 2. Type of drill string vibration.

3.1. Research Status of Lateral Vibration of Drill String

In 2000, G. OMS, B. E. Kamman-Reihartz analyzed the feedback effect of Newton fluid in drilling fluid in the process of rotating eccentric drill string drilling [23]. G. Hisig, etc., derived the transverse vibration model of drill string to study the collision vibration law of drill string and drill wall, and obtained the natural frequency of transverse vibration of drill

string [24]. Bernd Schmalhors *et al.* optimized the BHA by analyzing the coupling force between drill tools, taking into account the lateral dynamic pressure of the drill string under the action of drilling fluid [25]. Due to the wide variation of inclination Angle in horizontal Wells, the eccentricity of horizontal section of drill string is more serious, friction exists between drill string and borehole wall, and the force of downhole drill string is complicated. The drill string is prone to eddy movement and often has violent transverse vibration, leading to the fatigue failure of drill string. If the vibration reduction measures are not taken in time, the drill pipe will be broken or stuck, and other malignant accidents will even cause major accidents. In addition, with the rapid development of petroleum industry, oil and gas exploration and development is becoming more and more difficult. Therefore, a drilling string vibration model close to the actual drilling conditions is needed to analyze and study the solid-liquid coupling lateral vibration of horizontal well drilling string. In 2003, Liu Weikai established a mechanical model for analyzing the longitudinal vibration of drill string in deep Wells, and used three-dimensional dynamic finite element method to analyze the vibration of drill string to obtain the longitudinal vibration equation of drill string system and derive the calculation formula for the fatigue fracture of drill string, thus providing a theoretical basis for the evaluation and prediction of the fatigue strength of drill string [26]. In 2006, Alsaklen established a finite element model to analyze the force of the drill string system, and then optimized and adjusted the BHA [27]. This model is more suitable for the real working conditions of the drilling construction site, and has practical theoretical reference significance for drilling construction. 2007 Han Chunjie and Yan Tie drill string lateral vibration during drilling engineering based on the actual situation [28], mechanics model is established and analyzed considering the axial force under column transverse free vibration change rule, for calculating natural frequency of the drill string lateral vibration model and analysis of drill string lateral maximum deflection and bending stress variation law with the drill string lateral vibration frequency. In order to provide a theoretical basis for drilling construction, Hu Zhongwei analyzed and established the vibration frequency equation and summarized its mechanical variation law through the longitudinal, transverse and torsional vibration theory of drill string, and proposed the resonance variation law on this basis [29]. In 2011, Fu Lei analyzed the unstable conditions of the departure of the drill string from steady motion based on the flexible multi-body dynamics theory and chaos theory [30]. Based on the vibration theory -- dynamic gap element theory and considering the nonlinear solid-liquid coupling of drilling fluid, The finite element method was used to construct the transverse vibration and torsion coupling nonlinear dynamic model of vertical flexible multi-body drill string system, and ANSYS software was used to simulate the analysis. The results show that: Considering the coupling effect of drilling fluid, the natural frequency of lateral vibration of drill string will be reduced, but the axial load of drill string will increase its frequency. The axial load of drilling fluid and drill string

system does not affect the natural frequency of torsional vibration, and the larger the drill string or drill collar length, the lower the natural frequency of torsional vibration. ChiLiBin in 2013 proposed the horizontal and vertical section of the solid-liquid coupling mathematical model of transverse vibration of the drill string [31], based on the principle of minimum action eulerian method was applied to segment model of transverse vibration frequency of horizontal and vertical Wells, exploration period of transversal vibration of horizontal and vertical Wells by calculation frequency variation law with time, considering with annular section of horizontal and vertical Wells drilling fluid action, Based on the principle of mechanical balance, the variation law of transverse vibration frequency of vertical section of horizontal well is put forward, and the variation law of solid-liquid coupling transverse vibration frequency of vertical section of horizontal well is obtained. Firstly, the relationship between drill collar axial force and drilling parameters is derived theoretically, which provides a basis for numerical simulation. Then, based on MATLAB language, the corresponding program is prepared, and finally, the effect of drill string length, bit weight, drilling fluid density on lateral vibration frequency is obtained. To sum up, the domestic and foreign scholars on the theory analysis of drill string lateral vibration phenomena have done many work, solution methods mainly include the natural frequency of the differential equation of analytical method, the transfer matrix method, the finite element method and elastic wave method, using the analysis method of each are not identical, but the conclusion given, the analytical mechanics model is roughly same, However, because the derivation process is very complicated and the results are not simplified, the natural frequency calculation of drill string can only be obtained by using software and graphical methods, and the calculation accuracy is relatively low.

3.2. Research Status of Longitudinal Vibration of Drill String

There are three different forms of drill string vibration, one is longitudinal vibration and the other is transverse vibration, which leads to the vibration of drill string. The vibration force is the axial jump force and torsional runout moment of the drill bit during drilling. When drilling in homogeneous soft formations, the bit force or moment run fluctuation is not large, and the string fatigue damage is usually not caused. The fatigue fracture of drill string often occurs when drilling in heterogeneous hard formation only. Field practice has proved that the joints of drill string with fatigue fracture are often accompanied by gluing. It can be concluded that the longitudinal vibration of drill string is the primary factor leading to the failure of drill string. Millheim et al. conducted a systematic study on the vibration of drill string for the first time. Starting from statics analysis and considering various factors such as internal inertial force and friction resistance, they introduced and established the first dynamic three-dimensional finite element model with downhole drilling tools as the research object. However, due to the

limitations of wellbore size and formation conditions, the conclusions of Millheim et al. on the drill string motion law in the drilling process have not been further developed. In 1984, Dunnyevsky analyzed the conditions needed to produce directional well vibration phenomenon and the properties reflected when maintaining steady state vibration of the drill string of tricone bit, and put forward for the first time the argument that the drill string also has vibration when it rotates around its central axis. In 1987, Mitchell and Alien et al. first considered the additional mass caused by drilling fluid and used harmonic finite element analysis to conduct systematic numerical research. They not only clearly pointed out the role of drilling fluid in the research, but also proposed that it was necessary to further study the dynamics of downhole drill string. At the same time, Skaugh et al. took the random view as the starting point to study the relationship between the bit vibration and the longitudinal vibration of the drill string.

Xie Zhu Zhuang in 1992, studied the rule of the drill string vibration energy transmission [32], it concluded that the drill string vibration energy in the process of tripping with elastic wave propagation approach, the drill string is located in the lift or lower the initial and the end of the stage, the suspension point stress will change big ups and downs, on stage, the largest difference caused by the velocity wave and stress wave along the pipe under the column to pass, The hoisted steel pipe string of several thousand meters is regarded as an elastic body, and its stress and motion are regarded as a cross-section function. With the increase of dead weight, there is a large stress wave between the lifting stage and the lowering stage, a large elastic wave exists in the lifting stage, and a small elastic wave exists between the lifting stage and the lowering stage. Therefore, the function of this factor should be fully considered in the design, so that the whole well structure can be reasonably optimized; At the same time, the underground accident caused by unbalance should be prevented. A method for calculating the natural frequency of drill string is also presented. Some significant changes of drill string movement and mud pressure caused by the stress change of suspension point are noteworthy. However, its disadvantage is that the effect of internal and external drilling fluid column on drill string is not considered in the elastic wave analysis of drill string. Since the mid-80s of last century, China has formally begun to make a deep analysis of vibration on the level of stress wave. In 1988, Zhao Guozhen and Gong Wei 'an made a detailed analysis on the vibration of drill string, which added a reference for the analysis of the vibration of directional Wells in the future. One of the most influential is the first discovery that the drill string may be the main reason for the fatigue failure of the drill string rod along the wall of the reverse jitter of the reverse movement. The discovery was also highly praised by the American Petroleum Institute. It was not until THE Publication of Li Helin and Li Pingquan's work on the failure analysis and research of petroleum drill string in 1999 that the latest development in the scientific research and failure analysis of drill string was achieved in China.

Afterwards, Kuang Yuchun et al. focused on the longitudinal vibration of drill string. In the process of research,

they first calculated the total mass and the total stiffness of the system by using the finite element method, and obtained the longitudinal vibration equation of the drill string by combining Newton's law. The boundary conditions at the end of the actual drill string theory are obtained by constructing the physical model of the interaction between the bit and the rock, and the vibration differential equation is solved by using the Houbolt digital model solution method. At the same time, they also specially designed the simulation software for this research and carried out a large number of simulation experiments. Through analyzing and sorting out some series of results of simulation experiments, they also made further discoveries. In the process of research, they regarded the drill string rod as a homogeneous elastic straight rod, and established the differential equation of dynamic vibration form of the drill string rod according to the theoretical basis of vibration mechanics. Through the ANSYS simulation study, the characteristics of the longitudinal vibration of the drill string and the effect of the position of the shock absorber on the longitudinal vibration movement of the drill string are obtained. The results show that, according to the characteristics of the system, the proper placement of shock absorber can reduce the longitudinal vibration of the drill string, and then reduce the occurrence rate of the drill string failure accident.

In short, most of the current domestic and foreign researchers focus on the longitudinal and transverse vibration characteristics caused by drilling string, and also consider the variation characteristics of multiple vibrations superimposed together, transient or harmonic response, etc. Theoretically speaking, these methods have certain limitations; Therefore, it is very important to analyze the dynamics and optimize the design of drilling equipment and its components. On the other hand, with the continuous development of modern science and technology, vibration testing technology is becoming more and more mature. At the same time, from the perspective of research field, in recent years, foreign countries tend to study the mechanism and characteristics of vibration drilling in the cutting process, and domestic more inclined to study the application and development of vibration drilling in petroleum machinery, drilling engineering and other fields.

3.3. Research Status of Torsional Vibration of Drill String

The torsional vibration of drill string was first discovered in the rotary table torque measurement in 1980. Since then, the torsional vibration of drill string has been studied at home and abroad. The main contents include the theoretical analysis of the torsional vibration model of drill string, the analysis of the in situ operation conditions of drill string torsional vibration, etc. 1. The theoretical analysis of torsional vibration of drill string firstly carries out mechanical modeling of drill collars, and then uses Laplace transform to solve the displacement and stress distribution rules of each node. However, due to the complex drilling conditions, the results cannot fully meet the actual engineering needs. In 1982, Belokobyl *et al.* proposed a single degree of freedom concentrated mass torsional pendulum model for the first time, taking the relationship

between the torsional vibration of the drill string and the friction torque on the bit as the research object [33]. In 1986, Halsey *et al.* used a LWD measuring instrument with a depth of 1000 meters to measure the data on the bit to analyze the coupling between the axial vibration and torsional vibration of the drill string [34]. In 1987, Dawson *et al.* proposed to use the torsional pendulum model to represent the friction torque between the drill string and the borehole wall, and regarded the drill string speed as a function [35]. When the rotary speed exceeded a certain critical value, the drill string would experience torsional vibration. In 1988, Kyllingstad *et al.* obtained the equivalent moment of inertia of drill string on the basis of the torsional pendulum model and considered the difference between drill pipe and drill collar at the same time, regarded the BBIT match as a concentrated mass flywheel, and concluded that the torsional vibration frequency of drill string was less than the natural frequency of the system, and the higher the rotary speed, the lower the torsional frequency of drill string. Because of this theoretical assumption, there are large errors in the research results. Therefore, it is necessary to further study the interaction between drill string and casing during drilling [36]. In 1991, Lin *et al.*, based on the torsional pendulum model, comprehensively considered the viscous damping of drilling fluid and analyzed the torsional vibration law of drilling string caused by factors such as viscous damping, rotary speed and natural frequency of drilling string system [37]. In 1991, Dufeyte *et al.*, after 3,500 hours of field measurement, found that stick-slip vibration occurred in more than half of the drilling process, and concluded that the maximum ratio of bit speed to turntable speed in the slippage stage was 10 [38]. The result is known as the stick-slip theory. After that, Hoek *et al.* proved the correctness of this theory through experiments and numerical simulation, and proposed measures to improve the drilling rate. And the country has not seen this aspect of the report. In 1992, Brett *et al.* [39] proposed a torsional pendulum model with two free and concentrated masses (referred to as torsional pendulum model) based on the torsional pendulum model. The conclusion is that the larger the bit pressure is, the blunter the bit is and the smaller the drill string velocity is, the easier the torsional vibration is. Pavone developed a technology to increase the frequency of downhole sampling and measurement in 1994 [40], and proposed two effective methods to control the torsional vibration of drill string, which were tested by simulation. In 2004, Navarro *et al.*, based on the torsional pendulum model with two free concentrated masses, obtained the dynamic equation of drill string by using friction torque models at different bits, and analyzed the torsional vibration law of drill string caused by viscous damping, formation texture and drill string length [41, 42]. The results show that the drill string has a large longitudinal displacement because of the viscous effect. When there is a certain gap between drill collar and borehole wall, the horizontal bending of drill string will occur. Therefore, we must pay attention to the stability of drill string. In addition, in 2007, this scholar proposed a multi-free concentrated mass torsional pendulum model to analyze the influence of torque, weight on bit and other

drilling parameters on torsional pendulum vibration of drill string by comprehensively considering the difference of drill tools [43]. In 2011, Rudat et al. completed the research on torsional vibration drilling parameters optimization of drill string using the single-DOF concentrated mass torsional pendulum as the model [44]. Through the analysis of two important factors affecting the torque coefficient and the natural frequency of torsional vibration, it is found that the torque coefficient is mainly controlled by the drilling fluid density; The torsional frequency is determined by bit speed, formation conditions and the intensity of stimulation during drilling. Omojuwa studied the torsional vibration law of drill string in viscous damping environment in 2011 and came to the conclusion that the larger the viscous damping coefficient of drilling fluid, the more difficult the torsional vibration of drill string is [45]. However, in the drilling process, viscoelastic fluids (such as salt water) will have a great impact on drill collars due to high downhole temperature, high pressure, frequent changes in borehole trajectory, and low viscosity and high density of drilling fluid. Highlights the sea and others in full consideration of the environmental impact and the structure characteristics of the drill string [46], on the basis of a with the working condition is more consistent with the torsional vibration model of the drill string, the conclusion shows that from top to bottom of the drill string vibration intensity is increased, and at the bottom of the resonance amplitude is far greater than at the top of the resonance amplitude, when the torque increases when the drill string resonance amplitude also increase, And the resonance amplitude of drill string will change significantly under different damping conditions. The research results provide a reference for the optimization design of downhole tools.

On the one hand, the theoretical analysis of the drill string torsional vibration model has gone from the single-DOF torsional pendulum model to the two-DOF torsional pendulum model to the multi-free torsional pendulum model, and the friction torque on the drill bit becomes more accurate after considering the fluid viscous torque, so as to understand the torsional vibration characteristics of the drill string. On the one hand, with the increase of drill collar length, the drill string axial force increases; At the same time, the uneven distribution of axial stress and radial pressure exists in the rotation direction because the borehole trajectory is not parallel to the wellhead axis. On the other hand, the measurement methods of downhole vibration data of drill string torsional vibration are becoming more and more accurate, and the characteristics of operation conditions of drill string torsional vibration are obtained.

4. Research Status of Fluid-Structure Coupling Vibration Theory of Pipe String

At present, scholars at home and abroad have carried out in-depth research on drill string vibration. Compared with drill string vibration, production pipe string vibration and drill

string vibration have some similarities, but there are also essential differences. For downhole working environment, drilling string vibration will change the pressure distribution in the wellbore to a certain extent. However, it may also lead to casing damage and a series of hazards. Therefore, it is of great significance to study drill string vibration. The vibration of drill string is mainly caused by the rotation of drill pipe and its interaction with the wall and bottom of the hole, while the vibration of production pipe string is mainly caused by the interaction between the pipe fluid and the pipe string, which belongs to typical fluid-solid coupling mechanics. Fluid-structure interaction mechanics is a subject which mainly studies the various behaviors of structures in the flow field, supplemented by the study of the influence of displacement or deformation of structures on the flow field, and the two influence each other. The phenomenon of the interaction between the structure and the fluid often occurs in engineering applications. Fluid-structure coupling vibration of production pipe string is a typical embodiment of this phenomenon in oil and gas resources exploitation.

In 1998, Cai Ya west and others consider fluid dynamic pressure effect on the longitudinal vibration of tubing string [47], the tubing string is established differential equation of longitudinal vibration, hydraulic pressure appear tube was calculated when the tubing string corresponding to the longitudinal vibration of natural frequency, put forward to reduce pipe flow instability can abate the tubing string vibration intensity in order to delay the conclusion of tubing string occur fatigue fracture. In 2005, Yang Ke et al. derived a second-order differential equation with displacement as the basic variable on the basis of the 14-equation model of fluidus-structure coupling for axial vibration of pipelines, considering Poisson coupling, friction coupling and pipeline damping [48]. By solving the equations, the analytical solution of the steady state response of the liquid-filled pipeline under harmonic excitation is obtained. MATLAB software was used to draw the pressure distribution curve. The natural frequency calculated by this equation is verified by experiments, and some characteristics of wave velocity and natural frequency are discussed. In 2006, Deng Yuanzhou first established the governing equation of natural gas flow in the tubing string and the calculation model of the excitation force causing the stimulation of the tubing string, then established the finite element model of transient dynamic response analysis of the tubing string, and finally deduced the mathematical model of fatigue life prediction of the tubing string, and put forward the measures to extend the life of the tubing string [49]. In 2009, Yang Chao and Fan Shijuan used the 14-equation model and the improved characteristic line method to analyze the convection-solid coupling vibration, and took the fluid-solid coupling vibration test of a hydraulic system as an example to prove that the method has high accuracy [50]. In 2014, Ma Yacheng deduced the vibration equation of the simply supported straight pipe at both ends under the action of gas-liquid two-phase flow, obtained the natural frequency calculation expression of the pipe by solving it, and finally discussed the influence of pipe geometry,

material parameters and flow parameters on the natural frequency [51]. In 2015, Fan Honghai *et al.* established the fluid-solid coupling transverse vibration equation of gas production string considering the gravity of the string, and used Galerkin method to solve the equation [52]. The results showed that the influence of the gravity of the string on the vibration characteristics of the string could not be ignored. The theoretical study of fluid-structure interaction dynamics of pipeline has been done for more than 100 years, but the study of fluid-structure interaction dynamics of pipe string is still in the early stage. At present, the finite difference method is mainly used to simulate the fluid flow in the pipe, and the structural parameters of the pipe are optimized according to the calculation results.

In recent years, due to the optimization of commercial software and the improvement of computer performance, computer simulation analysis has become the most important method in the study of fluid-structure coupling vibration characteristics of pipeline. It is worth mentioning that ANSYS Workbench software has obvious superiority in fluid-structure interaction simulation analysis.

In 2004, Zhang Jiangwei conducted an experimental study on the relationship between the natural frequency of the infusion pipeline and the liquid flow rate in the pipeline, and derived the relationship between the flow rate and the natural frequency [53]. In 2006, Liang Feng conducted an experimental study on the vibration characteristics of both ends fixed and one end fixed and one end hinged of the flow transmission pipeline, and obtained the instability regions of multiple flow transmission pipelines and the different motion forms and corresponding frequency segments of the flow transmission pipelines when supported and excited [54]. In 2010, Guo Qing *et al.* established a fluid-structure coupling finite element model of the infusion pipeline in ANSYS software and simulated the fluid-structure coupling vibration of the infusion pipeline under the conditions of different support methods, different pipe lengths and different fluid flow rates [55]. The study showed that the fixed support, shorter pipe lengths and fluid flow rates could reduce the amplitude of the infusion tube. In 2014, Yang Ning verified through experiments that the transverse maximum amplitude of water transmission pipeline containing coarse particles increased with the increase of fluid sand concentration, but the axial vibration amplitude decreased [56]. In 2016, Wang Zeshen found in the test that the steady unidirectional flow of the infusion pipeline caused very little transverse vibration of the pipeline, while the gas-liquid two-phase flow caused more intense vibration of the pipeline cylinder, and the vibration degree was greatly influenced by the gas holdup rate [57]. Based on this, an improved fluid-structure interaction model is proposed, and the simulation results of the model are compared with the experimental results. In the water hammer experiment, the water hammer boost increases with the liquid flow rate and decreases with the liquid gas content. In the same year, Yu Ying established a finite element model of the infusion pipeline with ANSYS software for modal analysis, and simulated the vibration of the pipeline under various

support modes, lengths, loads and fluid flows [58]. Based on the calculation results, the improvement measures are proposed to solve the problems in the original design scheme and the effectiveness of the improved scheme is verified by experiments. Finally, the numerical simulation results are compared with the theoretical calculated values and the actual measured values. To determine the feasibility of the method adopted. The results show that the natural frequency of wet mode is lower than that of dry mode, and the higher the fluid pressure is, the higher the natural frequency is. The shorter the length of the fixed support, the smaller the flow velocity, the larger the maximum amplitude and the smaller the stress. In 2019, Ding Jiandong selected the injection and production string of a gas storage as the research target and designed a simulation experiment based on the similarity theory to explore the vibration law of gas production string [59]. The fluid flow in the gas production string under different pipe diameters and pressures was simulated in the laboratory, and the displacement curves of each point on the pipe wall during the gas production were filmed and recorded with a high-speed camera. The simulation results show that the vibration of the pipe string can also be caused by gas with stable flow rate. The larger the gas flow rate is, the stronger the vibration of the pipe string is. The vibration of the pipe string is more intense caused by unsteady air flow, and the vibration of the middle section of the pipe string is more intense than that of the two ends. Zhao Jiang established the finite element model of T-shaped infusion tube in ANSYS software and carried out modal analysis and harmonic response analysis through bidirectional coupling method [60]. The natural frequencies and corresponding modes at different flow rates were calculated. At the same time, the influence of various factors on the vibration characteristics of the pipeline was studied by changing the parameters such as wall thickness and diameter. Finally, the corresponding conclusions and suggestions are given based on the numerical simulation results. The results show that, compared with the velocity and density of the fluid, the pressure of the fluid has the most significant effect on the natural frequency of the pipe, and the pipe resonance can be excited by the pulsating fluid in the pipe. In 2020, Molli selected the completion string of horizontal Wells as the research target, carried out tests by simulating the string, used strain gauges to pick up vibration strain data in vibration signal detection, and used modal analysis method for post-processing of data [61]. By analyzing the dynamic response of the string under different gas flow rate and pressure, the influence law of gas flow rate and pressure change on the dynamic characteristic parameters (natural frequency and vibration shape) of the string is discussed. The stress distribution at each point on the bending section is also studied. It is found that in the initial stage of well opening, the vibration of the string will be strong. When the air flow becomes stable, the vibration of the string will gradually decay. The greater the gas flow, the stronger the vibration will be, and the stronger the vibration will be at the bend of the string than at the straight pipe. Xie Dashuai used ANSYS software to construct the finite element model of gas-liquid two-phase

flow pipeline, and used one-way and two-way fluid-structure coupling methods for simulation and analysis [62]. On this basis, the results obtained by the two methods under different working conditions are compared and studied. By changing the pipe length and diameter to simulate different working conditions, the axial and radial forces of each node with time were calculated. The results show that the deformation is the largest in the middle of the pipe section, and the stress is also the largest at the inlet and outlet of the pipe section. Compared with the unidirectional coupling method, the analysis results of the bidirectional coupling method show that the maximum deformation and maximum stress are smaller, and the displacement of the pipe section is larger when the gas hold-up of the pipe section is smaller. At present, universities and institutions have done a lot of research on fluid-structure coupling vibration experiments of flow transmission pipelines, but there are still relatively few fluid-structure coupling vibration experiments of production pipe strings specifically for oil and gas wells. According to the research status over the years, experts and scholars have studied the coupling mechanism between the flow pipe and the fluid, and adopted mechanical analysis methods and energy methods to model different fluid-structure coupling, so as to analyze the dynamic response and vibration characteristics of the flow pipe. However, due to the computational complexity of fluid-structure interaction, fluid-structure interaction theory cannot be applied in practical engineering. Especially for deepwater oil and gas development, the vibration caused by fluid-solid coupling of test string has not been solved.

5. Conclusion

Over the years, the drill string vibration model has evolved from the basic static model to the complex dynamic model of drill string downhole motion prediction. However, due to the lack of in-depth understanding of these models, many practical problems cannot be solved by traditional methods. This paper summarizes the research status and development trend of drill string vibration model at home and abroad. The problems that may be encountered when using different modeling methods under different boundary conditions and damping sources and the corresponding solutions are discussed. Then the drillstring vibration models and their applications in some new drilling technologies are introduced. In the previous research field, people mainly focus on the influence characteristics of annular unidirectional flow (gas and liquid) on drill string vibration, which lays a theoretical foundation for the future establishment of annular air-liquid-fluid-solid coupling drill string vibration model. This paper reviews the simulation analysis of fluid-structure interaction of pipe string and finds that there are still many large and small problems. For example, although the simplified processing reduces the difficulty of simulation to a considerable extent, the simulation results may differ greatly from the actual production situation. The material, size and orientation of the pipe string; The differences in fluid composition, velocity, density, temperature and so on will

result in some differences between the experimental results and the actual string vibration in production. The future research work should be carried out under the premise of closer to the actual production conditions of gas production string.

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