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Experimental and numerical study of drill string dynamics in gas drilling of horizontal wells

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A B S T R A C T

The combination of gas drilling and horizontal well has been considered as an effective technique for the exploitation of low permeability reservoirs to protect reservoir, enlarge drainage area and increase production. Given the currently inadequate understanding about drill string dynamic characteristics in gas drilling of horizontal wells, a theoretical model of drill string dynamics is established in this paper. The nonlinear dynamics equations are derived to study the motion state of drill string. Meanwhile, an experimental apparatus is developed according to similarity principle, and the kinetic characteristic of drill string is investigated based on the simulation experiment. Particular attention is focused on the lateral vibration which results from the impact and frictional interaction with wellbore constraint. The effect of weight on bit and rotary speed on drill string motion pattern is also discussed based on experimental results. Finally, the buckling and contact of drill string are analyzed through finite element simulation study. The results indicates that the contact force between wellbore and drill string is relatively large and helical buckling of drill string can be caused without the lubrication and damping effects of drilling fluid in gas drilling. The work presented in this paper can provide theoretical foundation and technological basis for drill string dynamics analysis and drilling parameter optimization in horizontal wells drilled with gas.

1. Introduction

Gas drilling is an underbalanced drilling technology using air, nitrogen or natural gas as circulating medium. As a widely-applied technique, gas drilling has shown its superiority in drilling rate improvement, reservoir discovery and formation protection (Lian et al., 2012). The combination of gas drilling and horizontal well technique can effectively protect reservoir, enlarge drainage area and increase production of oil and gas wells (Sun et al., 2008; Han and Yan, 2009). Therefore, drilling horizontal well with gas has recently been considered as an innovative technique for the exploitation of low permeability reservoirs. However, when gas is used as circulating medium, some problems related to friction and vibration of horizontal drill string happen frequently. These problems seriously restrict the effect of trajectory control and drilling speed improvement.

Researches on drill string dynamics have been conducted from various perspectives. Lubinski (1950) presented systematic analyses on the stress and deformation of drill string and the critical conditions of drill string buckling were also investigated based on the theory of elastic stability. His work laid the foundation for the study of drill string mechanics. Dykstra (1996) established the dynamical equations of drill string based on Hamilton principle and his research provide a reference for further study on dynamic characteristics in both vertical and curved borehole. Menand et al. (2008) presented how the drill string rotation affected the critical buckling load. Through the comparison of an advanced model for drill string mechanics with an experimental setup enabling to reproduce the buckling in wellbore, they found that the critical helical buckling load of a rotating pipe is 50% of the one obtained from non-rotating pipe. Ertas et al. (2013) developed a general drill string mechanics model to analyze the axial and torsional vibrations and provide vibration indices. Huang et al. (2015) proposed an automatic generalized quasi-static model of drill string system and provided an inversion model to revise the model parameters.

To analyze the drill string dynamics in horizontal wells, different models were established and various experiments were carried out. Omojuwa et al. (2012) established the theoretical model for friction, torque, buckling and vibration of drill string in horizontal

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wells; he worked out the distribution of axial force and torque along drill string using the dynamic equations. Wilson and Heisig (2015) presented a detailed analysis of the fully coupled, three-dimensional, nonlinear behavior of drill string under induced vibrations and specific focus was given to the dynamic characteristics of drill string in horizontal wells. However, in the previous models and experiments, drill string dynamics in gas drilling of horizontal wells hasn't been fully studied.

In this paper, a nonlinear dynamics model was established to investigate the motion behavior of drill string. Meanwhile, according to similarity theory, an experiment was designed to study the kinetic characteristic of drill string in gas drilling of horizontal wells. A finite element model was also established and the buckling and contact of drill string was analyzed.

2. Theoretical model of drill string dynamics

The dynamics of drill string belongs to the category of rotor dynamics which mainly discusses the vibration, equilibrium and stability of rotary systems (Zhang, 1900). The drill string is generally simplified as a segmented, homogeneous and uniform-section beams bearing variable loads.

2.1. Assumption

The assumptions in the derivation are shown as follows:

1. Drill string is regarded as elastic beam with homogeneous geometric characteristics and material properties.
2. The stiffness of threaded connections and local notches is neglected.
3. The effect of temperature on material properties is neglected.

2.2. Element displacement vector

A simplified drill string element is shown in Fig. 1. The relevant parameters of the drill string element are divided into two categories, namely nodal DOF (degree of freedom) data and load parameters. In the finite element analysis, nodal displacements are generally taken as the basic unknown variables. The nodal displacement vector of drill string element is expressed as

$$\{\delta_e\} = \left(u_i, v_i, w_i, \theta_{xi}, \theta_{yi}, \theta_{zi}, u_j, v_j, w_j, \theta_{xj}, \theta_{yj}, \theta_{zj}\right)^{\mathrm{T}} \tag{1}$$

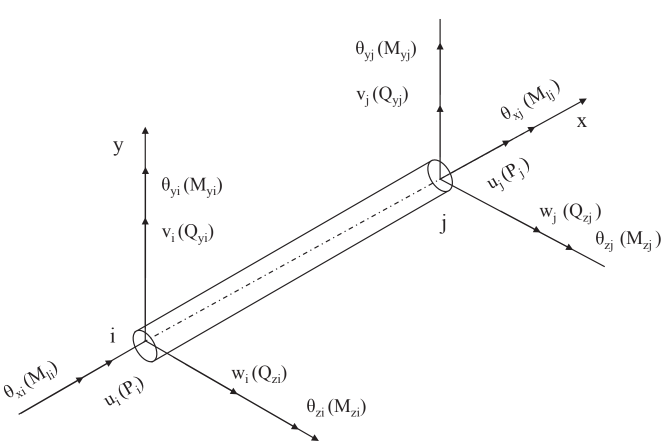

Fig. 1. Drill string element.

where u_i, v_i and w_i are the displacement of node i in x-, y- and z-direction respectively; θ_{xi}, θ_{yi} and θ_{zi} are the rotation angles of node i in x-, y- and z-direction respectively; variables with subscript "j" represent the DOF of node j.

The nodal force vector of drill string element is expressed as

$$\{R_e\} = \left(P_i, Q_{yi}, Q_{zi}, M_{li}, M_{yi}, M_{zi}, P_j, Q_{yj}, Q_{zj}, M_{lj}, M_{yj}, M_{zj}\right)^{\mathrm{T}} \tag{2}$$

where P_i is the axial force of node i; Q_{yi} and Q_{zi} are the shear forces of node i in y- and z-direction respectively; M_{li} is the torque of node i; M_{yi} and M_{zi} are the bending moments of node i in x−y plane and x−z plane respectively; variables with subscript "j" represent the loads of node j.

The generalized displacement vector of drill string element is depicted by

$$\{u_e\} = [N]\{\delta_e\} \tag{3}$$

where $[N]$ is the shape function matrix. For three-dimensional beam element, it can be expressed as

$$[N] = \begin{bmatrix} N_u \\ N_v \\ N_w \\ N_\theta \end{bmatrix} = \begin{bmatrix} N_1 & 0 & 0 & 0 & 0 & 0 & N_2 & 0 & 0 & 0 & 0 & 0 \\ 0 & N_3 & 0 & 0 & 0 & N_4 & 0 & N_5 & 0 & 0 & 0 & N_6 \\ 0 & 0 & N_3 & 0 & N_4 & 0 & 0 & 0 & N_5 & 0 & N_6 & 0 \\ 0 & 0 & 0 & N_1 & 0 & 0 & 0 & 0 & 0 & N_2 & 0 & 0 \end{bmatrix} \tag{4}$$

where $N_1 = 1 - x/l$, $N_2 = x/l$, $N_3 = 1 - 3x^2/l^2 + 2x^3/l^3$, $N_4 = z - 2x^2/l + x^3/l^2$, $N_5 = 3x^2/l^2 - 2x^3/l^3$, $N_6 = -x^2/l + x^3/l^2$

2.3. Equation of motion

Lagrange equation must be satisfied for the discretized drill string system (Dykstra, 1996):

$$\frac{d}{dt}\left[\frac{\partial(T-U)}{\partial\{\dot{\delta}_e\}}\right] - \frac{\partial(T-U)}{\partial\{\delta_e\}} = \{R_e\} \tag{5}$$

where T and U are the element kinetic energy and potential energy, respectively.

$$T = \frac{1}{2}\int_{V_e} \rho\{\dot{u}_e\}^T\{\dot{u}_e\}dV \tag{6}$$

$$U = \frac{1}{2}\int_{V_e}\{\varepsilon\}^T\{\sigma\}dV - \int_{A_e}\{u_e\}^T\{P_A\}dA - \int_{V_e}\{u_e\}^T\{P_V\}dV - \{u_e\}^T\{P_e\} \tag{7}$$

where $\{P_A\}$, $\{P_V\}$ and $\{P_e\}$ are body force, surface force and nodal force vectors, respectively.

Then substituting Eqs. (6) and (7) into Eq. (5), the motion equation of drill string element at local coordinate system is expressed as (Zhu et al., 2012)

$$[M]_e\{\ddot{\delta}_e\} + [C]_e\{\dot{\delta}_e\} + [K]_e\{\delta_e\} = \{R_e\} \tag{8}$$

where $[M]_e$, $[C]_e$ and $[K]_e$ are the mass, damping and stiffness matrixes, respectively.