CSCanada
Advances in Petroleum Exploration and Development
Vol. 6, No. 2, 2013, pp. 23-27
DOI:10.3968/j.aped.1925543820130602.1762

ISSN 1925-542X [Print]
ISSN 1925-5438 [Online]
www.cscanada.net
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Research on BHA Load Transfer Considering Drill String Transverse Vibration

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Supported by National Science and Technology Major Project (2011ZX05021-006)

Received 21 October 2013; accepted 5 December 2013

Abstract

With increasing difficulty of reservoir development and harsh geological conditions, higher drilling technology meets lots of challenges, especially in the large displacement wells and ultra-deep wells. For Limit Extension Well, not only good drilling equipment is needed, but also drilling technology and basic theory are acquired. Bottom hole assembly (BHA) load transfer rule has important influence on Limit Extension Well. Therefore, on the basis of previous research, BHA load transfer rule is studied which considers the influence of drill string transverse vibration, and sensitivity analysis based on affecting factors of BHA load transfer rule. Research results show that transverse vibration of drill string has greater influence on the axial force and torque transfer. With the increase of friction coefficient and azimuthal variation, friction and torque of BHA increases linearly; with the increase of weight on bit (WOB), friction and the rate of torque of BHA also goes up. The application of model considers drill string transverse vibration, which will not underestimate values of loads like previous dynamic models. It will support optimal BHA design and prevent early drill string failures. Therefore, the influence of transverse vibration cannot be ignored on load transfer in large displacement wells.

Key words: Drill string; Transverse vibration; Bottom hole assembly; Load transfer; Limit extension well

Yan, T., Wang, P., & Zhang, Q. (2013). Research on BHA Load Transfer Considering Drill String Transverse Vibration. *Advances in Petroleum Exploration and Development*, *6*(2), 23-27. Available from: http://www.cscanada.net/index.php/aped/article/view/j.aped.1925543820130602.1762
DOI: http://dx.doi.org/10.3968/j.aped.1925543820130602.1762

INTRODUCTION

With the increasing number of horizontal, large displacement horizontal and complex wells, it requires drilling equipment and drilling technology higher and higher for petroleum engineering. With the increasing drilling depth, not only advanced equipment is needed, but also the drilling technology and basic theory are acquired. BHA design optimization is very different compared with conventional design analysis, especially for large displacement horizontal well. It needs to consider more complex influence factors, such as optimize well track to reduce the friction torque, optimize drilling parameters to avoid serious drill string buckling, etc[1-4]. In addition, BHA vibration has great influence on BHA stress and drill string fatigue damage. Many scholars put forward a series of prediction methods to prevent drilling tool damage, but few scholars study the effects of the BHA load transfer rule under the condition of the BHA transverse vibration[5-9]. On the basis of predecessor's studies, this paper study the movement of BHA load transfer rule considering BHA transverse vibration, which can be used to BHA design and optimizing, to provide the basic theory for reducing drill tool fatigue damage and drilling cost, to provide technical support for improving oil and gas well limit extension, to increase oil and gas production in signal well.

1. LOAD TRANSFER MODEL

Momentum theory is applied to reveal rule that inertial force and contact force of load transfer caused by transverse vibration along the borehole. BHA friction torque, buckling, vibration are considered in the model. Integrated axial force and torque transfer equation are corrected by considering additional contact coefficient of buckling degree and transverse vibration degree. Buckling analysis contains sinusoidal buckling and spiral buckling. Additional contact coefficient contains intermittent contact analysis between drill string and wellbore during transverse vibration. The comprehensive mechanics equations can be used for sensitivity analysis with different boundary loads and wellbore parameters. The model of load transfer is proposed to optimal BHA design in Limit Extension Well.

1.1 Fundamental Assumptions

(1) Sliding drilling or combined drilling mode;
(2) BHA is homogeneous and isotropic;
(3) BHA has linear elastic deformation property;
(4)Transverse vibration is considered in BHA dynamic analysis on the influence of the axial load and torque;
(5) BHA is considered as many near-straight sections.

1.2 Modeling

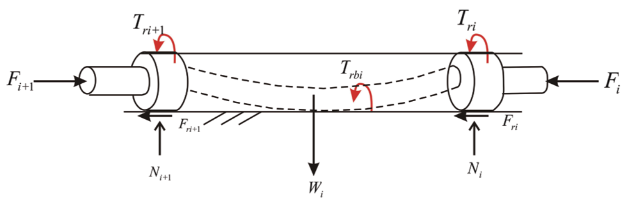

Figure 1
Mechanical Analysis of BHA

$$F_{i+1}-\sum F_{ri}-F_i-P_o(A_o-A_i)+W_i=m_i\frac{\mathrm{d(ROP)}}{\mathrm{d}t} \tag{1}$$

$$F_{ri}=\mu_d(F_{drag}+N_{buckling}+N_{vib}) \tag{2}$$

$$F_{drag}=\sqrt{(F_i\Delta\phi)^2+(W_i)^2} \tag{3}$$

$$N_{buckling}=K_1\frac{r_bF_i^2}{8EI} \tag{4}$$

$$N_{vib}=K_2\omega^2R_oL(m_{fi}+m_{\mathrm{BHAi}}) \tag{5}$$

Where, F_i is the right axial force of BHA, N; F_i is the left axial force of BHA, N; $\sum F_{ri}$ is total friction force of BHA, N; P_o is drilling fluid pressure outside string, Pa; W_i is buoyant weight per unit length of BHA, N; m_i is mass of BHA, kg; A_o is the area from the outer diameter of BHA, m^2; A_i is the area from the inside diameter of BHA, m^2; r_b is the radial clearance between outer diameter of BHA section and wellbore diameter, m; α is inclination($\alpha\approx 90°$), rad; $\Delta\phi$ is azimuth change, rad; ROP is rate of penetrate of the BHA section, m/s; t is time; μ_d is dynamic friction coefficient; F_{drag} is drag force, N; $N_{buckling}$ is additional contact force caused by string buckling, N; N_{vib} is additional contact force caused by transverse vibration, N; K_1 is buckling coefficient of BHA($0\le K_1\le 1$); K_2 is additional contact coefficient caused by transverse vibration ($0\le K_2\le 2$); EI is bending rigidity of BHA, N·m^2; ω is rotation speed of BHA, rad/s; R_o is outer diameter of BHA, m; L is length of BHA, m; m_{fi} is mass of drilling fluid inside and outside string, kg/m; m_{BHAi} is mass of each section of the BHA, kg/m.

1.2.1 Axial Stress Transfer Model Considering Transverse Vibration of String

Take formula (3), (4), and (5) into formula (1), then

$$F_{i+1}=F_i+X+Y+Z \tag{6}$$

Where, $X=m_i\frac{\mathrm{d(ROP)}}{\mathrm{d}t}$ represents the force caused by accelerating of the BHA section during drilling;

$Y=P_o(\mathrm{A_o}-\mathrm{A_i})$represents the stability force which accounts for the hydraulic or piston effect of the drilling fluid on the cross-sectional area of an open-ended tubular;

$$Z=\mu_d\left[\sqrt{(F_i\Delta\phi)^2+(W_i)^2}+K_1\frac{r_bF_i^2}{8EI}L+K_2\omega^2R_oL(m_{fi}+m_{\mathrm{BHAi}})\right]$$

represents separately: BHA drag, buckling force, additional force caused by vibration.

1.2.2 Torque Transfer Model Considering Transverse Vibration of String

In the condition of transverse vibration, BHA torque is consisted of the following four parts: torque-on bit, torque caused by BHA sliding friction, torque caused by BHA inertia, and reaction torque caused by the "stick-slip" movement with drill string transverse vibration[10-12]. As shown in formula (7).

$$T_{i+1}=T_{bit(i)}+T_{f(i)}+T_{in(i)}+T_{m(i)} \tag{7}$$

$$N_i=\sqrt{(F_i\Delta\phi)^2+(W_i)^2}+K_1\frac{r_bF_i^2}{8EI}L+K_2\omega^2R_oL(m_{fi}+m_{\mathrm{BHAi}}) \tag{8}$$

$$\begin{cases} T_{bit(i)}=0.92kD_wW_{\mathrm{b}}^{1.5} \\ T_{f(i)}=-\mu_dN_iR_o \\ T_{in(i)}=I\frac{\mathrm{d}\omega}{\mathrm{d}t} \\ T_{m(i)}=-K_2\mu_d\pi R_o\frac{r_b^2F_i^2}{2EI} \end{cases} \tag{9}$$

$$T_{i+1}=-\mu_d\begin{bmatrix}\sqrt{(F_i\Delta\phi)^2+(W_i)^2}+K_1\frac{r_bF_i^2}{8EI}L \\ +K_2\omega^2R_oL(m_{fi}+m_{\mathrm{BHAi}})\end{bmatrix}R_o+0.92kD_wW_{\mathrm{b}}^{1.5}+I\frac{\mathrm{d}\omega}{\mathrm{d}t}-K_2\mu_d\pi R_o\frac{r_b^2F_i^2}{2EI} \tag{10}$$

Where, $T_{bit(i)}$ is torque-on-bit(refer to bit torque calculation model from Hughes company), N·m; $T_{f(i)}$ is friction torque, N·m;$T_{in(i)}$ is reaction torque caused by transverse vibration (relative to the drill bit torque), N·m;$T_{m(i)}$ is additional torque caused by buckling, N·m; D_w is well diameter, m; W_b is weight on bit, N; I is moment of inertia of BHA section, m^4.

1.2.3 Application of BHA Dynamic Transfer Rule Considering Transverse Vibration of String

For large displacement wells and horizontal wells, the force of drill string contain: friction force, collision vibration, transverse vibration generated by the "stick-slip" motion of drill string, and the vertical vibration produced by contact collision between the bit and bottom[13-15]. Drill string transverse vibration often occurs at the section of BHA in horizontal well. It has realistic guiding significance to calculate bottom-hole friction under the influence of transverse vibration. Torque dynamic transfer rule can be used to prevent drilling tool damage. Applications of theory research mainly contain:

(1) To design BHA and optimize drilling parameters with axial load and torque transfer rule in Limit Extension Well.

(2) To evaluate the influence of the downhole dynamic events on axial force and torque transfer along the BHA in Limit Extension Well.

(3) To support optimal BHA design and prevent early failures due to drill string buckling and fatigue.

(4) To compute the axial load and torque distribution along the BHA. Calculate the side force according to the stress on the bit and direction of the bit. These provide basic theory for horizontal well borehole trajectory controlling.

2. EXAMPLES ANALYSIS

2.1 Background and Data Preparation

M2 is a horizontal well located in Jilin oilfield of southern part of Song Liao basin. Primary data: survey data in Figure 2, casing program in Table 1, well structure in Table 2. Drilling fluid density is 1078 kg/m^3, weight on bit is 50 kN, rotary speed is 100 r/min, BHA length is 74.7 m, azimuth changes 10°, static friction coefficient is 0.35 that should be obtained from back-calculation using offset well data, dynamical friction coefficient is 0.28, and additional contact coefficient of transverse vibration is 1.0.

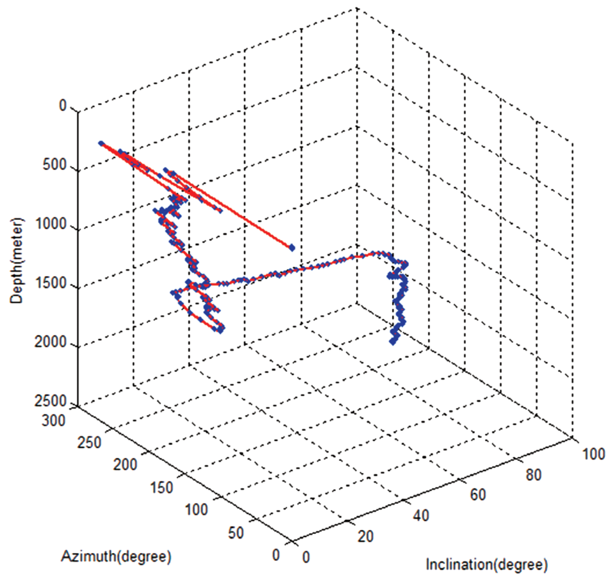

Figure 2
Survey Data 3D Display of M2 Well

Table 1
Casing Program

Wellbore type	Top depth measurement (m)	Bottom depth measurement (m)	Outer diameter (mm)	Inner diameter (mm)
Surface casing	0	152.40	609.60	482.60
Technical casing	152.40	1706.88	311.15	258.88
Open hole	1706.88	2330.00	253.36	—

Table 2
Bottom Hole Assembly

Tool type	Length Li(m)	Out diameter do(mm)	Inside diameter di(mm)	Min yield strength Y(MPa)	Make up torque T(N•m)	Elastic modulus E(MPa)	Linear density ρ'(kg)
Bit	0.3	250.83	—	758	57500	2.06e5	387.31
Screw	8.9	203.20	63.5	758	57500	2.06e5	229.71
Stabilizer	1.5	203.20	63.5	758	57500	2.06e5	229.71
LWD	12.2	203.20	63.5	758	57500	2.06e5	229.71
Collar	9.5	196.85	63.5	758	57500	2.06e5	214.05
Stabilizer	1.5	203.20	63.5	758	57500	2.06e5	229.71
Collar	41.8	196.85	63.5	758	57500	2.06e5	214.05

2.2 Calculation Result Analysis

The proposed model is applied to calculate drag and torque of M2 in Jilin oilfield, and BHA axial force and torque transfer along the drill string can be obtained. Considering the bottom drill transverse vibration effect, the additional friction force also increases. At the same time, additional torque increases with consideration of BHA transverse vibration, and it also brings drilling difficulty and drill string fatigue damage. It is observed that the increased percentage of values of torque (minus sign represents negative direction of bit torque) generated during the "vibration" event with respect to the "no vibration" event decreases as the Fi+1 increased (minus sign represents compression load). The calculation results as shown in Figures 3 and 4.

The model above can provide reasonable drilling parameters and proper drilling assembly for drilling operation.

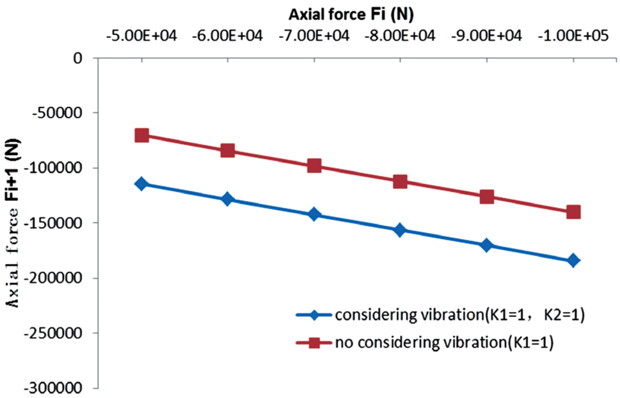

Figure 3
Curve of BHA Axial Force Transfer in M2 Well

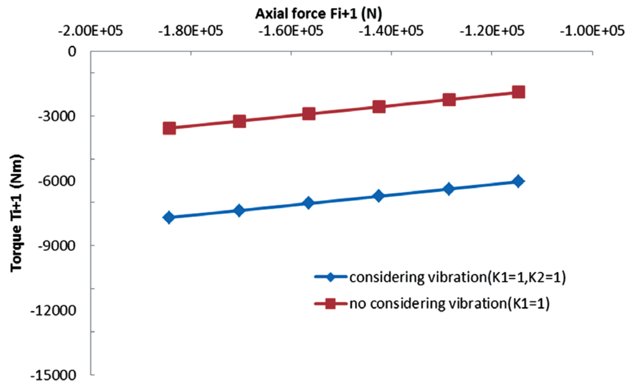

Figure 4
Curve of BHA Torque Transfer in M2 Well

3. SENSIBILITY ANALYSIS

Sensible factors of BHA load transfer include: WOB, linear density of BHA, interspace between BHA and wellbore, dynamic friction coefficient of BHA, azimuth change, etc. Sensitivity analysis can determine axial force and torque transfer rule under dynamic load by changing dynamic parameters, and it provides basic theory for BHA design and mechanics analysis in Limit Extension Well.

The plots Fi versus Fi+1 of for varying friction coefficient and azimuth change along BHA section are displayed in Figures 5 and 7. The curves trend show: with the increase of friction coefficient and azimuth change, the friction force of BHA also increases. It is observed that the percentage of the values of torque increases with the friction coefficient increases.

The plots Ti versus Ti+1 of for varying friction coefficient and azimuth change along BHA section are displayed in Figure 6 and Figure 8. The curves trend show: with the increase of friction coefficient and azimuth change, the torque of BHA also increases. The reduction of the percentage Ti+1 per BHA section with Ti increases is a result of the less effect of drag force when higher axial force transferred to the drill bit.

Azimuth change and friction coefficient impact on torque are more apparent than the axial force. Azimuth change due to geosteering or wellbore placement issues increases the normal contact loads generated from torque and drag which consequently increasing the resultant frictional force and the axial compressive load. The total frictional force generated from torque and drag, buckling and vibration event will increase with the increase of dynamic friction factor of wellbore. The dynamic analysis of the downhole drilling events in Limit Extension Well and their effects on BHA components provides effective methods for predicting the limits of loads, torques and stresses before BHA service failure.

Therefore, to lower friction coefficient and to improve borehole smooth degree are two important aspects for Limit Extension Well.

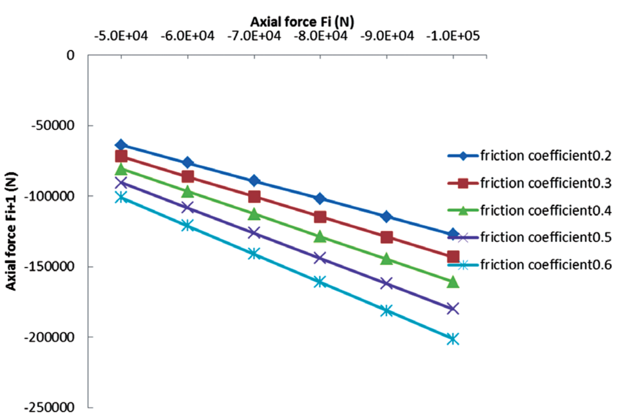

Figure 5
Axial Force Transfer for Varying Friction Coefficient

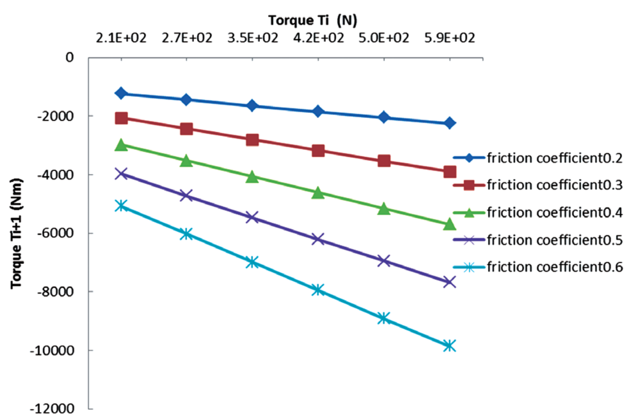

Figure 6
Torque Transfer for Varying Friction Coefficient

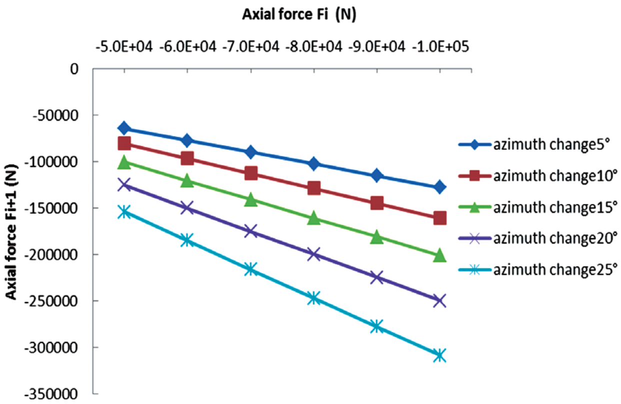

Figure 7
Axial Force Transfer for Varying Azimuth Change

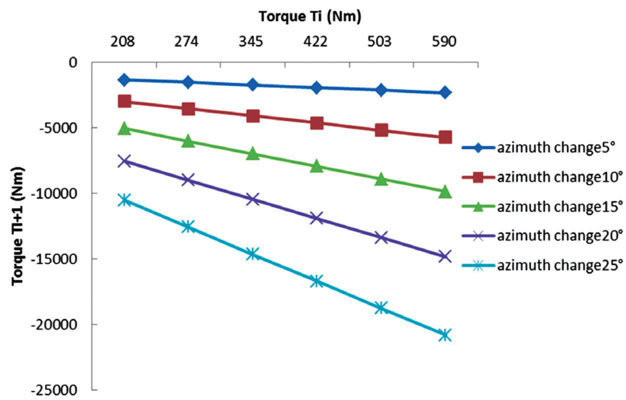

Figure 8
Torque Transfer for Varying Azimuth Change

CONCLUSIONS

Compared with other analysis models, this paper proposes an axial force and torque transfer model that is a comprehensive dynamic prediction and analysis model considering drill string transverse vibration, drill string buckling and contact friction factors. The application of model considers drill string transverse vibration, which will not underestimate values of loads like previous dynamic models. It will be used to optimal BHA design and prevent early failures due to drill string buckling and fatigue.

The force of BHA transverse vibration and additional contact which caused by buckling has great influence on axial force and torque transfer. With increasing change of friction coefficient and azimuth, the friction force and the torque of BHA increase linearly. With increasing WOB, BHA friction force and the torque rate increase. Change of friction coefficient and azimuth has greater influence on torque transfer than friction force transfer.

Axial force and torque transfer rule is quite different among different well types during drilling process, such as complex structure well, extended reach well, etc.

Mathematical model of axial force and torque dynamic transfer is used to calculate drill string load distribution along the wellbore accurately, and it is also known as a comprehensive basic theory for BHA optimization in Limit Extension Well.

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