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Optimizating Drilling Operating Parameters With Real-Time Surveillance and Mitigation System of Downhole Vibration in Deep Wells

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Abstract

Torsional vibration is the main bottleneck which leads to low efficiency of rock breaking. According to the characteristics of torsional dysfunctions performance, the paper defines three main types of stick-slip, and analyzed the relationship between ROP and energy from bit. Based on Newton's equations of motion, established frequency domain, single degree of freedom, damped and forced drill string torsional vibration prediction model, with more accuracy for downhole drill string mechanical state description. On this basis, semi-analytical transfer matrix method is adopted to establish drill string response relationship between internal force wave and surface parameters changes in the condition of vibration, which greatly reduce the number of discrete elements and the associated computing time, enabling rapid screening of a large number of design alternatives on a PC. In addition, the response parameters for drillstring stick-slip are integrated into an index (Vibration Strength Estimate, VSE), which is used to quantitatively evaluate downhole stick-slip severity. A three-week pilot test has been conducted in deep wells in Yumen Oilfield in China, with 25% increase of the average ROP and 40% enhancement of the average bit footage compared with offset wells. Validation of field application shows that the downhole torsional vibration evaluation technology is an effective method for further excavate the potential of ROP and reduce drilling cost.

Key words: Stick-slip; Torsional vibration; Transfer matrix; VSE; Quantitative evaluation

INTRODUCTION

With the exploration and development of hydrocarbon reservoirs moving toward more complex formation, non-conventional wells, downhole vibrations have been identified as one of the most significant limiters to damage bits and reduce the rate of penetration (ROP). While there are no definitive, industry-wide statistics on the percentage of NPT associated with vibrations, previous studies have shown that as much 75% of downhole accidents and complexities are associated with vibrations[1]. Therefore, it is essential to establish a simple and effective vibration mitigation scheme in order to achieve better drilling performance.

Conventionally, ROP and MSE are used as the indices to evaluate the drilling performance[2], which have achieved the satisfied ROP and longer bit runs based on keeping a proper relationship between ROP and energy input. However, they can not be utilized to estimate the downhole vibration severity in condition of current drilling technologies and geology, especially in quantification. Based on Newton's equation of motion, an advanced damped forced torsional oscillation model in frequency-domain is developed. The model achieves higher accuracy diagnosis and computational efficiency due to more boundary condition effects combined with a fit-for-purpose rigid model, damping coefficient algorithm and BHA-matching transfer matrices. Additionally, the vibration mitigation principle is demonstrated in detail, conducting a variety of tests to mitigate torsional dysfunctions. The optimization algorithm is applied to a real-time surveillance system automatically estimating the stick-slip severity and guiding the drillers to weaken torsional resonance. The success of pilot test proved that the system can diagnose the inducing factors for torsional dysfunctions, providing useful insights into the judgment of reasonability of drilling parameters.

1. ANALYSIS OF STICK/SLIP AND OPTIMIZAION MECHANISM

During drilling process, the drill string is executed as an important link between surface drilling equipments and the bit. However, the drillstring contacting with the borehole generates friction resistance which results in intermittent mechanical jamming at the bottom of the drill string inducing BHA torsional dysfunctions with a signature as stick/slip. The root causes of the BHA spontaneously stuck are the irregular hole geometry, improper hydraulic/engineering parameters and changing of formation lithology and so forth, while the drillstring buildup torque overcomes the friction, the BHA rotates with the high speed leading to bit torque instantaneously releasing, cutters damaging, strain deformation of thread and drill string fracturing. Based on the characteristics of stick/slip, the torsional dysfunctions are identified three types as following[3]:

(a) Unstable Stick/slip: BHA unsteadily rotates, which rock breaking in condition of lowest-frequency torsional resonance.

(b) Bit/BHA Stall: intermittent mechanical jamming results from too much friction resistance

(c) Synchronous Torsional Dysfunction: Application of periodic external excitation with first-order resonance of the BHA.

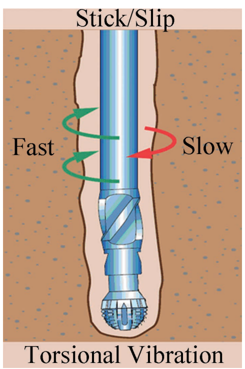

Figure 1
Stick/Slip Characteristics

The drilling system output energy leads to the cutters continuously cut into rock achieving rock breaking. Thus, the less energy consumed per unit volume of rock drilled, the more efficiency achieved[3]. In Figure 2, region I shows the depth of cut is inadequate resulting in the waste of input energy and lower ROP due to the lower WOB. As shown in the plot, the input energy and ROP initially do not keep the linear relationship. In region II, along with the increasing input energy, the depth of cutting into rock is adequate. Therefore, the bit performance becomes stable and keeping the linear relationship with the input energy. The output energy is exclusively utilized for rock breaking in this region. In region III, input energy is continuously applied but the ROP is not linearly increasing with the input energy, indicating more output energy lost. The onset of limiters (stick/slip) constrains the energy transfer, and the ROP stops responding linearly with increasing energy at this point. The torsional dysfunctions can not be completely removed, just can be damped out during drilling process. Based on the redesigning and optimizing parameters, the severity of torsional oscillation will be mitigated, thus the onset of founder point will be delayed.

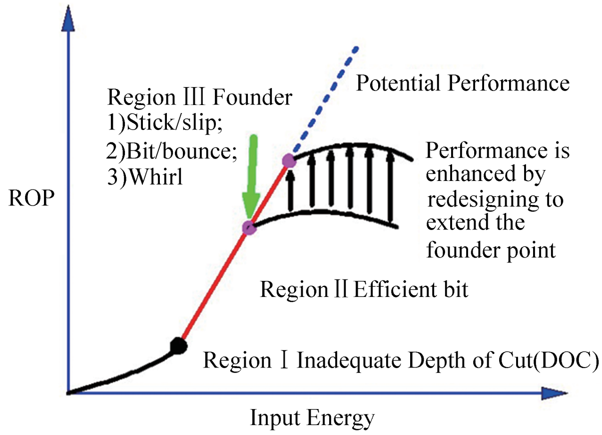

Figure 2
The Rock Breaking Mechanism Analysis Among the Drilling Parameters, ROP and Energy

2. DESICRIPTION OF STICK/SLIP SEVIRITY ESTIMATE MODEL

The linear response model is aimed to real-time estimate the drillstring tosional vibration severity in quantification. When the drillstring experiences a stick/slip event, which is subjected to various external forces, thus the motions of drillstring are extremely complex. The partial differential motions equation of the drillstring is based on Newton's equations of motion, which can be described likewise as[4]:

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = F_0 \sin\omega t\,. \tag{1}$$

Where, m is element mass matrix, c is element damping matrix, k is element stiffness matrix, $F_0\sin\omega t$ is element force, $x(t)$ is element displacement; $\dot{x}(t)$ is element velocity; $\ddot{x}(t)$ is element acceleration.

Based on Equation (1) and external excitations on the drillstring element, the basic torsional equation can be described as:

$$\tau' - \rho J\ddot{\alpha} = \theta_{\text{body}} \cdot t\,. \tag{2}$$

Where, τ' is the internal force for the drillstring, N; $\ddot{\alpha}$ is the angular acceleration of the element, arc/s^2; ρ is the density of drillstring material, kg/m^3; J is the torsional moment of inertia, m^4; θ_{body} is the total torques from external forces, N·m; t is the unit vector along the tangent direction.

$$\theta_{\text{body}} = \theta_{\text{mud}} + \theta_{bh} + \theta_g . \tag{3}$$

Where, θ_{mud} is the external torque from mud, N·m; θ_{bh} is the external torque from borehole, N·m; θ_g is the external torque from gravitation, N·m.

The effect of damping for the BHA, hole geometry and mud properties etc. are also taken into account for the model. Generally, the dynamic state on two ends of a section of drillstring can be related a transfer matrix. Thus, the function of the torque and twist on the bit is derived from the surface dynamic state based on the transfer matrix method. The linear partial differential Equation (2) has the following solution:

$$\begin{bmatrix} \alpha_{\Omega_{RPM}}(i) \\ \tau_{\Omega_{RPM}}(i) \end{bmatrix} = \begin{bmatrix} \cos(\frac{\Omega_{RPM}}{\sqrt{G/\rho}} \cdot l_i) & \frac{1}{\Omega_{RPM}\sqrt{G\rho}J_i} \cdot \sin(\frac{\Omega_{RPM}}{\sqrt{G/\rho}} \cdot l_i) \\ -\Omega_{RPM}\sqrt{G\rho}J_i \cdot \sin(\frac{\Omega_{RPM}}{\sqrt{G/\rho}} \cdot l_i) & \cos(\frac{\Omega_{RPM}}{\sqrt{G/\rho}} \cdot l_i) \end{bmatrix} \cdot \begin{bmatrix} \alpha_{\Omega_{RPM}}(i-1) \\ \tau_{\Omega_{RPM}}(i-1) \end{bmatrix} . \tag{4}$$

Where, G is Shear Moduli of the drillstring material, Pa; Ω_{RPM} is angular velocity, arc/s; l is arc length of the element, m.

The boundary condition of torque on the bit and surface twist are given by:

$$\tau_{\Omega_{RPM}}(0) = 0.0222 D_{\text{bit}} WOB , \tag{5}$$

$$\alpha_{\Omega_{RPM}}(MD) = 0 . \tag{6}$$

Where, D_{bit} is bit diameter, mm; WOB is weight on bit, N.

Substituting Equations (5-6) into Equation (4) yields the function of surface torque and bit twist:

$$X_\tau = \frac{60\alpha_{\Omega_{RPM}}(0)}{P \cdot \tau_{\Omega_{RPM}}(MD)} . \tag{7}$$

Where, $\alpha_{\Omega_{RPM}}(0)$ is the twist angular on the bit, arc; $\tau_{\Omega_{RPM}}(MD)$ is the surface torque of full stick/slip, N·m; P is the first-order resonance period, s.

Finally, the stick/slip severity estimate model is given by:

$$VSE_{\text{stick / slip}} = \frac{X_\tau \times d_{Tor}}{2 \times RPM} . \tag{8}$$

Where, d_{Tor} = $Tor_{\max}$ - $Tor_{\min}$, N·m/20s; RPM is the rotary speed at surface during 20s.

3. FIELD TEST CASES

3.1 Stick-Slip Optimization Guidelines

The following plot displays the stick/slip mitigation flow chart, and the basic principle of optimization is to decrease WOB along with increasing RPM or flow rate (mud motor). As long as the obtained VSE is below the original value after updating drilling parameters, it shows that the optimized drilling parameters could meet the needs of vibration-weakening, while if not, drilling parameters should be restarted updating or restored to the original values according to the current formation lithology, geometry etc. Principally, the change range of WOB, rotation speed and flow rate should not be more than 25%. Additionally, the goal of the hydraulic parameters optimization is to keep the hole cleaning, damping out the severity of stick/slip due to build up of cuttings on the bit. The detail as following:

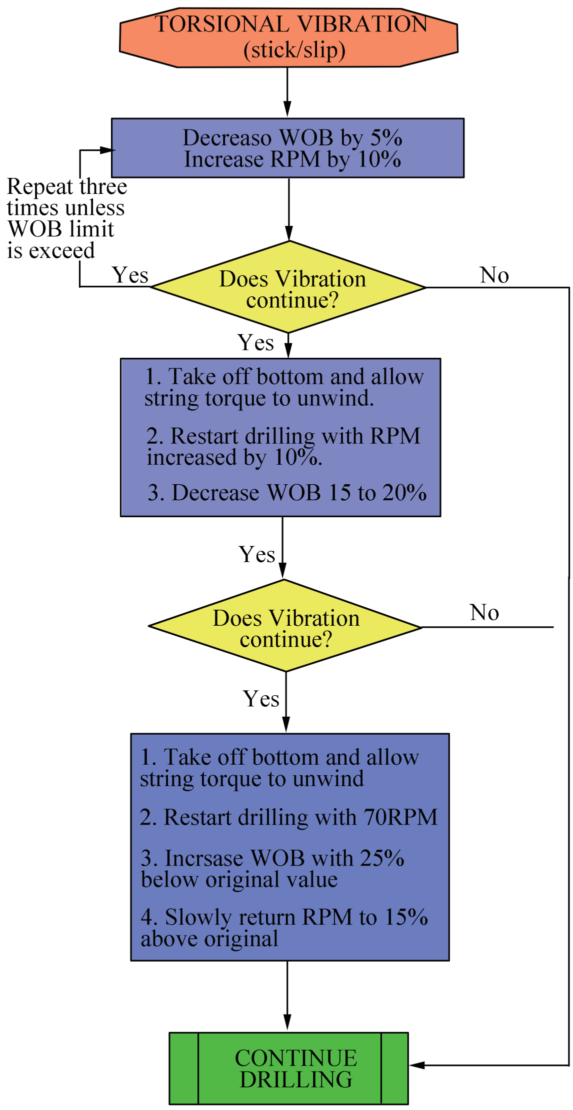

Figure 3
The Structured Method for Stick/Slip Mitigation

3.2 Cases Analysis

Based on the minimizing torsional vibration severity principle, keeping the optimum relationship between ROP and MSE, the real-time downhole vibration surveillance and mitigation system was developed to allow the real-time computation of recommendations of drilling parameters and delivery to the rig personnel. The system was configured for a recent in situ trial in the Yumen oilfiled, China, where drilling efficiency improvement, stick/slip resolving and hard stringer identification were taken.

The formation in the test interval is mainly grey mudstone and pelitic siltstone. The BHA data is as following:

Φ8-1/2”BESTT1955 PDC +Φ6-5/8”LZ+Φ8-2/5”STB+Φ8-2/5”STB+Φ6-5/8”NMDC+Φ6-1/2”DC×12+Φ6-1/2”LB+Φ5”HWOP×3 +Φ5”DP

In order to evaluate the performance of the system with that of conventional driller’s drilling habit, the drilling of hole section with conventional driller’s drilling habit was carried out at daytime from 8:00 am to 20:00 pm while the drilling of hole section with the system guidance with same bit, BHA, mud properties and formation was carried out at night time from 20:00 pm to 8:00 am.

Based on experiences of offset, the design parameters were 50-70RPM, 60-120KN WOB and flow rate is 28-30 l/s in order to achieve the best drilling efficiency and weakening the well bore vibration.

Figure 4 shows the applied section for the surveillance system. Above the first blue line, the driller followed conventional methods to set parameters, and the interval is from 3,725 m to 3,745 m. From 3,746 m to 3,760 m and 3,765 m to 3,780 m, the footage drilled with the system guidance. At the non-optimized interval, HMSE curve displays fluctuations severely, which is plotted in the right hand track. The optimized interval begins at 3,746 m, CCS value increased with the pelitic siltstone increasing, and the VSE-stick/slip value increased dramatically as shown in third trace from right. According to the system recommendations, RPM is increased from 60 to 65 RPM and WOB is decreased to 8 t. The VSE-stick/slip and HMSE value decreased dramatically and ROP increased obviously. The HMSE plot decreasing dedicated less energy was used for breaking rock after parameters updating. After 3,765 m, mudstone content increased sharply as shown in the first trace from left, CCS value reaches to 200 MPa (second trace from right, black), and VSE-stick/slip and HMSE curves both reaches a critical fluctuation level, restarts decreasing WOB to 6 t and increasing to 70 RPM. HMSE curve decreased dramatically again indicating the drilling performance improved.

Additional figures can display more light on the optimization effects. Figures 6 and 7 respectively display MSE-ROP-WOB and MSE-ROP-RPM values three-dimensional distributions for each interval. The blue data points derived from the interval with the surveillance system application, and the red color data points are from the non-optimized interval. The distribution of bulk of HMSE data is below and the ROP is higher in optimized interval compared with the non-optimized interval. The average HMSE value of 1,440 MPa in optimized interval is 14.6% lower than the average value of 1,652 MPa without the system surveillance, which means more efficiency for the optimized interval. Meanwhile, the average ROP value of 8.31 m/h in optimized interval is 25.7% higher than the average value of 6.61 m/h in non-optimized interval. The field application verified that the system can real-time monitor, analyze and mitigate various torsional dysfunctions, which achieves higher ROP and longer bit runs compare with conventional method.

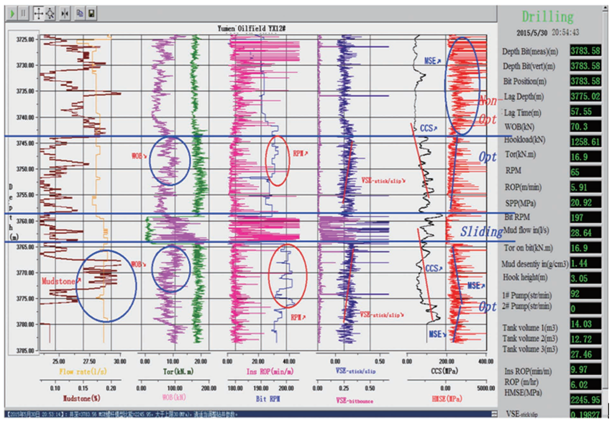

Figure 4
The Comparison of Drilling Performances Between the Intervals

Figure 5
The Content of Mudstone Increases From 3,767 m

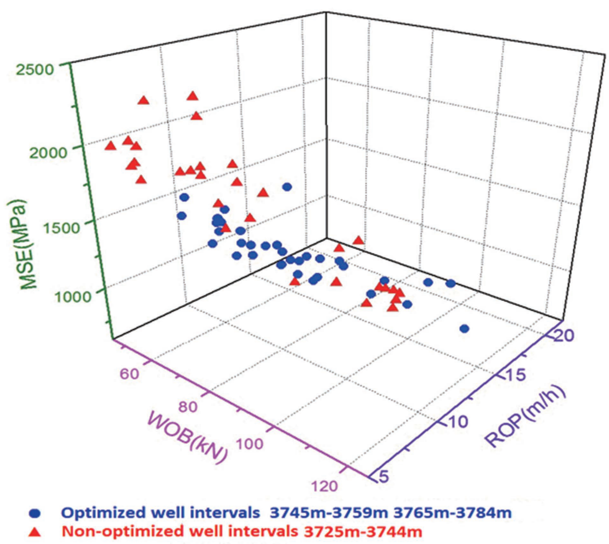

Figure 6
WOB-ROP-MSE 3-D Distribution

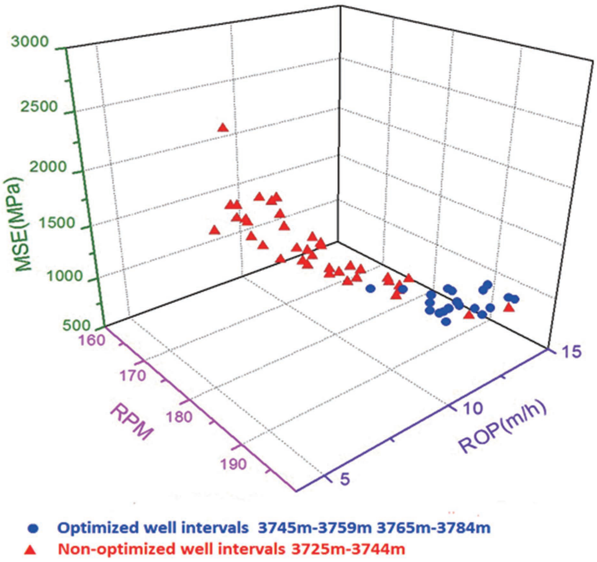

Figure 7
RPM-ROP-MSE 3-D Distribution

CONCLUSION

(a) Based on Newton's equations of motion, established frequency domain, single degree of freedom, damped and forced drill string torsional vibration prediction model, with more accuracy for downhole drill string mechanical state description.

(b) Investigate forced dynamic response with periodic excitations, adopts semi-analytical transfer matrices solution to establish the response function of the surface parameters and BHA torsional oscillations. The solution reduces the number of discrete elements and the associated computing time, enabling rapid screening of a large number of design alternatives on a PC.

(c) The forced dynamic response parameters of torsional vibration are integrated into one index named as vibration strength index (VSE), which can real-time estimate BHA stick/slip severity in quantification.

(d) The real-time downhole vibration surveillance and mitigating system was developed, which has the ability to continually monitor, analyze torsional dysfunctions and provide measurements to mitigate the severity of vibrations.

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