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Development and Application of a BHA Vibrations Analysis Model

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Abstract

BHA lateral vibration has been identified as one limiter that may hinder the rate of penetration (ROP). Based on Newton's equations of motion and Euler-Bernoulli beam bending equation, a steady-state forced-frequency response dynamic model was developed to analyze vibration performance for a single point mass in the BHA surrogate. Wherein, the connection between points relied on massless springs or dampers. The frequency-domain model more accurately represented actual mechanical states for a particular BHA configuration. On this basis, the state vector for a mass point was calculated by the semi-analytical transfer function matrix method at any given position in the BHA surrogate, which greatly reduced the number of discrete elements and the associated computing time. It caused rapid screening of a large number of design alternatives on a PC. The state vector included the lateral and angular deflections, as well as the beam bending moment and shear load, which were integrated as a dynamic vibration performance index called Lateral Vibration Strength Estimate (LSE) utilized to quantitatively evaluate the lateral vibration state. The field application demonstrates that the methods for modeling bottom hole assembly (BHA) vibration performance during drilling to enable improved design in pre-drill and operation for enhanced drilling rate of penetration, to reduce downhole equipment failure in drilling. Field validation for the surveillance tool was performed by comparing high-frequency downhole memory sensor data (100samples/second data rate).

Key words: Lateral vibration; Transfer matrix; LSE; State vector; Quantitatively evaluate

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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) in XiNan oil and gas field. The drilling operations typically include the use of a drilling rig coupled to a drillstring and BHA, which may include a drill bit or other auxiliary rock cutting devices (such as mud motor). The main function for BHA is to actually generate, not only the weight on bit and torque but also the fluid circulation. However, the irregular movement for bit in the bottom of hole and unsteady load on the bit may affect the vibration tendencies that may be identified along with the lithology and well track changing, BHA/hole wall interactions, configuration designs, improper drilling parameters and other operational variables during drilling operations. Worldwide estimated costs for vibration-related failures are about $300 million per year[1]. Meanwhile, lateral vibrations have been identified as the most destructive limiter to drill operations and equipments. BHA lateral vibrations involve beam bending dynamics in the stiff pipe near the bit and do not usually propagate directly to the surface as axial vibrations and torsional vibrations,

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which is impossible to be identified by surface parameters or drilling performance estimate index such as ROP, MSE etc. Therefore, the lateral vibrations severity estimate method and control process have been not developed yet.

On basis of Newton's equation of motion and Euler-Bernoulli beam bending equation, an advanced damped forced lateral vibration model in frequency-domain was developed, and the lateral displacement of each BHA element was utilized to guide the BHA design and estimate the lateral vibration severity in real-time. The model achieves higher accuracy diagnosis and computational efficiency due to more fit-for-purpose boundary condition effects combined with semi-analytical transfer matrices. Additionally, the model has been validated by downhole sensors providing stored data after several bit runs. The lateral vibration tendencies comparisons from model and measurements are fit well, providing useful insights into the judgments of reasonability of drilling parameters, bit dysfunctions for drillers in order to improve vibration performance during drilling process.

1. ANALYSES OF LATERAL VIBRATION AND MITIGATION GUIDELINES

While the pipe section is spinning at a certain rotary speed about its own axis, with the integration effects of compression, tension, centrifugal force and torque, the stabilizer and the joints of pipes erratically bang against a side of the hole creating high bending stress cycles resulting in self-excitation mode lateral vibration with multiple interaction nodal points. The flexural or dynamic lateral bending mode is referred as "Forward Whirl", and rotation and revolution are coexistence in clockwise. With the self-excitation frequency near the resonance, the pipe revolution about the centerline of the well at anticlockwise will be onset. The secondary sign is called "Backforward Whirl", as shown in figure1. "Backforward Whirl" is the most critical lateral vibration phenomenon, since it is the most destructive to each element of BHA. In addition, the high bending stress cycles may be dampened out along with pipes, thus it is not directly detectable at surface.

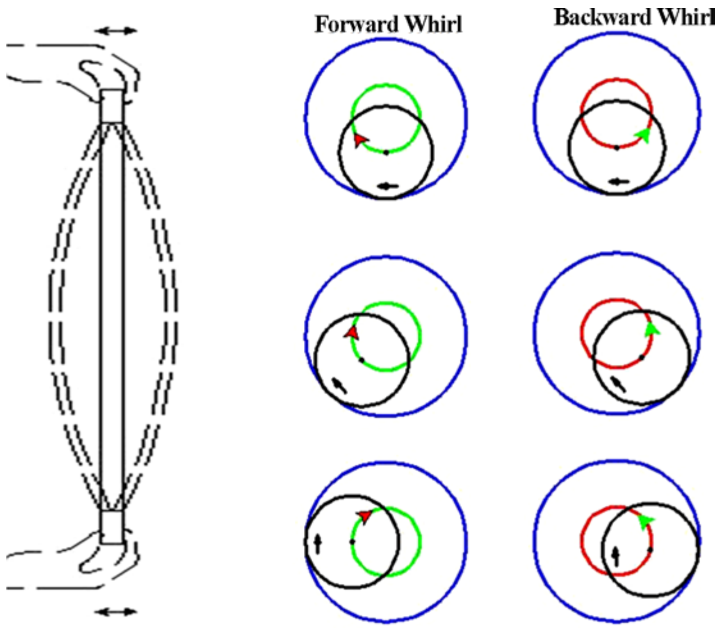

Figure 1
Motion Characteristics of Lateral Vibrations for BHA Joint and Body

The main failures or dysfunctions resulting from whirl are shown in following[2]:

(a) Increased mean surface torque, low ROP and loss of toolface.

(b) One-sided wear on stabilizer, BHA and joint of drillsting.

(c) Looseness of thread and BHA failure due to high frequency bending stress cycles.

(d) Cutters/Inserts damaged and broken PDC blades.

The following plot displays the whirl mitigation flow chart, and the basic principle of adjustment is to increase WOB along with decreasing RPM or flow rate (mud motor). As long as the obtained vibration tendency is below the original value after updating drilling parameters, it shows that the optimal drilling parameters could meet the needs of vibration-weakening, while if not, drilling parameters should be restarted updating or pick up drillstring off bottom as to release torque and 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 equal to 10%. Additionally, the goal of the hydraulic parameters optimization is to keep the hole cleaning, damping out the severity of whirl avoiding cuttings building. The detail process is shown in Figure 2:

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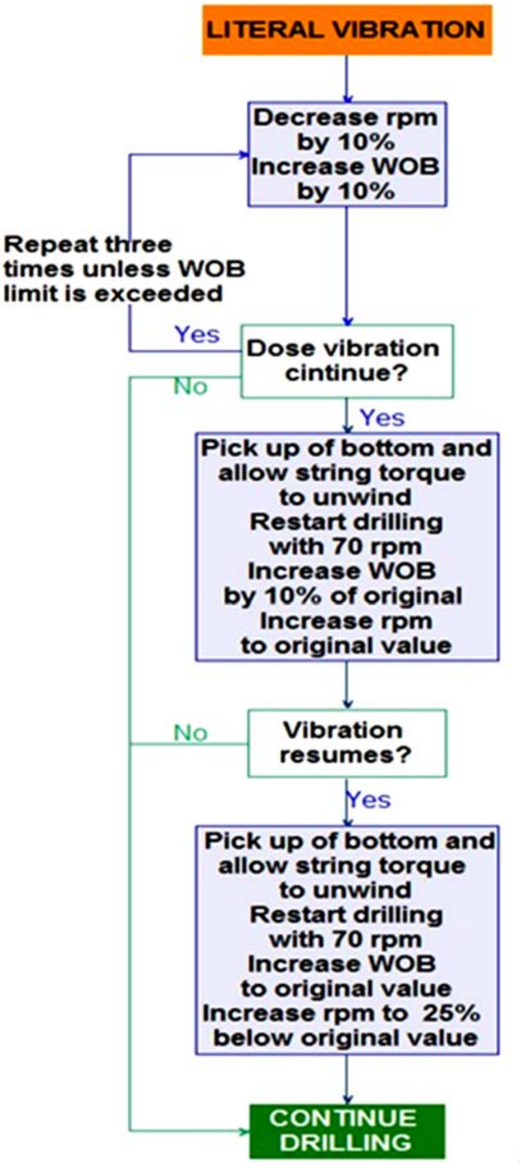

Figure 2
The Structured Method for Whirl Mitigation

2. LATERAL VIBRATION SEVIRITY ESTIMATE MODELING

2.1 Kinematics Analysis

The figure3 illustrates a top-view looking downhole at a cross section of one BHA surrogate. The x-axis is oriented uphole, the z-axis is in the vertical plane orthogonal to x, and y-axis forms the third orthogonal directions in a right-handed system. A short of section of this BHA rotates about the centerline of wellbore with frequency Ω, at a distance *r*, from the axis. To consider periodic motion, the distance *r* will be defined as a function of the rotation angle about the centerline. Meanwhile, the segment of BHA rotates in clockwise at angular velocity $-\omega_0$, which means negative directions[3].

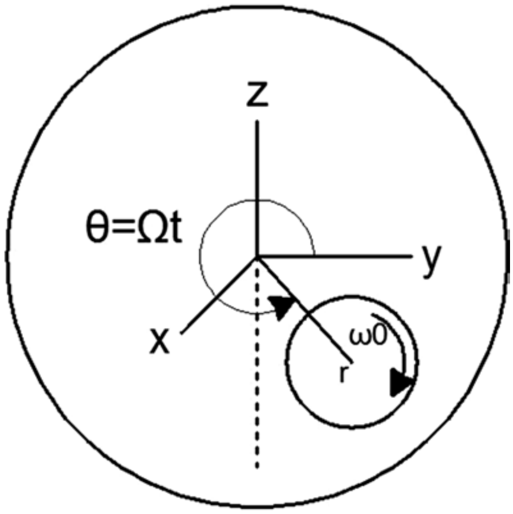

Figure3
The Motion of a Short Section of BHA

The BHA section is subjected to an applied axial loading *P*, shear load *V* at one end and *V*+*dV*at other end, and bending moment *M* and *M*+*dM*, respectively, as shown in figure4. The load applied to this element at the ends of the section arises from the connection to similar BHA elements above and below this BHA section.

The centre of mass of the element is located at position of $\vec{R}(t)$, which can be calculated by equation (1), using $\theta=\Omega t$:

$$\vec{R}(t) = r(t)\cos(\Omega t)\vec{j} + r(t)\sin(\Omega t)\vec{k} \tag{1}$$

The total angular velocity vector (*x*", *y*", *z*") of the BHA element relative to the inertial reference frame (*x*', *y*', *z*') may be written as equation (2), where the angles ϕ and ψ represent the rotation angles about the (*y*' and *z*') axes respectively:

$$\begin{cases} \vec{\omega}_I = -\omega_0 \cdot \vec{i}\,'' + \Omega \cdot \vec{i} \\ \vec{\omega}_I = -\omega_0 \cdot (\vec{i} + \psi \cdot \vec{j} - \phi \cdot \vec{k}) + \Omega \cdot \vec{i} \end{cases} \tag{2}$$

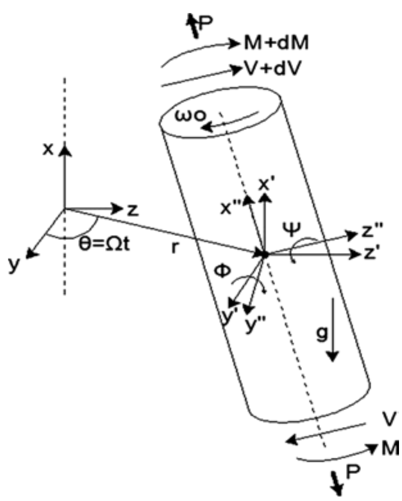

Figure 4
The Analysis of Forces for a Short Section of BHA

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2.2 Description of Lateral Vibrations Severity Estimate Model

While the lateral motion is occurring, the state vector μ is defined as to estimate the vibration performances for BHA surrogates. The vector includes the lateral and angular deflections, as well as the beam bending moment and shear load, which are also named as Lateral Vibration Strength Estimate index. The state vector μ may be written as following equation (3):

$$\mu = \begin{bmatrix} y \\ \theta \\ M \\ V \\ 1 \end{bmatrix} \tag{3}$$

Where y is the lateral deflection of beam from the centerline of the well, m, θ is the angular deflection, °, M is the bending moment, N-m and V is the shear load of the beam, N.

With the linear superposition principle, the vector μ may be regarded as a static component μ^s and a dynamic component μ^d. The system is assumed to oscillate at the frequency ω of the forced input. The state of vector for any BHA element is written as following equation (4), where x and t means time and space respectively.

$$\mu(x,t)=\mu^s(x)+\mu^d(x)\sin(\omega t) \tag{4}$$

BHA consists of many mass elements, each mass may be assumed to have an associated spring or damper connecting to them. With the transfer function matrices, state vector μ_i for each element is written as following:

$$\begin{cases} T_i = M_i B_i \\ \mu_i = T_i T_{i-1} \ldots T_1 \mu_0 \end{cases} \tag{5}$$

Where the notation M_i is a mass transfer matrix (for element index i ranging from 1 to N); B_i is a beam bending element transfer matrix; μ_0 is used to designate the sate at the bit.

2.2.1 Mass Matrices

Based on Newton's equations of motion, the general force balance equations for BHA elements in the static and dynamic modes may be written as equations (6).

$$\begin{cases} m\ddot{y} = V_i - V_{i-1} - mg\sin\phi - ky - b\dot{y} = 0 \\ m\ddot{y} = V_i - V_{i-1} - ky - b\dot{y} \\ m\ddot{y} = V_i - V_{i-1} + \varepsilon m\omega^2 - ky - b\dot{y} \end{cases} \tag{6}$$

Where y is the lateral deflection of beam, m; $k$is wellbore contact stiffness coefficient; b is damping coefficient; ε represents the dimensionless ratio of off-axis distance to the radius of the well resulted from a centrifugal force (Value range 0-1).

Simplification of the equation (6):

$$\begin{cases} V_i = V_{i-1} + mg\sin\phi + ky \\ V_i = V_{i-1} + (k + ib\omega - m\omega^2)\cdot y^d \\ V_i = V_{i-1} - \varepsilon m\omega^2 + ky \end{cases} \tag{7}$$

BHA motion is assumed as a complex harmonic forced response, where $y^d = e^{i\omega t}$ and $i = \sqrt{-1}$.

On basis of the equation (7), the static mass matrix and dynamic mass matrix may be written as the following equations. The equation (8) is under static loading, the equation (9) is under dynamic loading and the centrifugal force is considered in equation (10).

$$M_S = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ \kappa & 0 & 0 & 1 & (mg\sin\phi) \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{8}$$

$$M_S = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ (\kappa + ib\omega - m\omega^2) & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{9}$$

$$M_S = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ \kappa & 0 & 0 & 1 & (-\varepsilon m\omega^2) \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{10}$$

2.2.2 Stiffness Matrices

According to BHA's physical characteristics, it belongs to uniform beams. Therefore, deflection from shear force can be omitted compared with bending deformation. On basis of Euler-Bernoulli beam bending equation for a uniform beam, as shown in equation (11).

$$EI\frac{\partial^4 y}{\partial^4 x} - p\frac{\partial^2 y}{\partial^2 x} = 0 \tag{11}$$

Where the denotation E is constant Young's modulus, pa; I is bending moment of inertia, m^4; P is axial loading, N; y is lateral deflection for BHA element, m.

The characteristic equation (11) for the general solution is represented by equation (12).

$$y = e^{\beta x} \tag{12}$$

The equation (12) is combined with equation (11), the solutions are as following:

$$\begin{cases} \beta^2(\beta^2 - \dfrac{p}{EI}) = 0 \\ \beta = 0, \pm\sqrt{\dfrac{\mathrm{p}}{EI}} \end{cases} \tag{13}$$

Where the denotation β is real, illustrating the beam in tension. The denotation β is imaginary, illustrating the beam in compression. The denotation β is equal to 0, illustrating no axial loading. The deflection of an axial loaded beam may be represented by general solution of equation (11).

$$y = a + bx + ce^{\beta x} + de^{-\beta x} \tag{14}$$

On basis of equation (11), other state vectors are determined by following equations:

$$\begin{cases} \theta = \dfrac{\partial y}{\partial x} \\ M = EI\dfrac{\partial^2 y}{\partial^2 x} \\ V = -EI\dfrac{\partial^3 y}{\partial^3 x} \end{cases} \tag{15}$$

The equation (14) is combined with equation (15), the solutions are as following:

$$\begin{cases} y = a + bx + ce^{\beta x} + de^{-\beta x} \\ \theta = b + c\beta e^{\beta x} - d\beta^{-\beta x} \\ M = EI(c\beta^2 e^{\beta x} + d\beta^2 e^{-\beta x}) \\ V = -EI(c\beta^3 e^{\beta x} - d\beta^3 e^{-\beta x}) \end{cases} \tag{16}$$

The equation (17) is combined with equation (5), the resulting beam bending stiffness transfer function matrix B for BHA element（$x=l$）may be represented as the following equation (17).

$$B = \begin{bmatrix} 1 & L & \left(\dfrac{-2+e^{\beta l}+e^{-\beta l}}{2p}\right) & \left(\dfrac{2\beta l - e^{\beta l}+e^{-\beta l}}{2p\beta}\right) & 0 \\ 0 & 1 & \left(\dfrac{e^{\beta l}-e^{-\beta l}}{2\beta EI}\right) & \left(\dfrac{2-e^{\beta l}-e^{-\beta l}}{2p}\right) & 0 \\ 0 & 0 & \left(\dfrac{e^{\beta l}+e^{-\beta l}}{2}\right) & \left(\dfrac{-e^{\beta l}+e^{-\beta l}}{2\beta}\right) & 0 \\ 0 & 0 & \left(\dfrac{-\beta e^{\beta l}+\beta e^{-\beta l}}{2}\right) & \left(\dfrac{e^{\beta l}+e^{-\beta l}}{2}\right) & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{17}$$

3. FIELD TEST CASES

3.1 BHA Surrogates Optimization

In 2016, pilot program has been executed in XingTan1#, South West of oil field in China. The first purpose is to optimize the configurations of BHA surrogates with lateral vibration performance estimate. Figure5 shows diagram for each of the three BHA configurations. Note that there are two stabilizers configured in BHA-2. The stabilizer is located at the far left to the bit in BHA-3 compare with BHA-2. There is one stabilizer used in BHA-1 near the bit. The detail descriptions are as following:

BHA-1:

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

BHA-2:

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

BHA-3:

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

Figure 5
Diagrams of BHA-1, BHA-2 and BHA-3

Figure6 provides state vectors display comparison for three of BHA surrogates operation at 100RPM and 80000N of bit weight. The lateral vibration potential simulation for BHA-1 is significantly lower than BHA-2 and BHA-3. Especially for the lateral displacement, the effect is most remarkably, which means that the contacts for BHA-1 with wellbore may be less than other BHA surrogates during drilling process. However, the

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yellow color curve shows the larger amplitudes of the states for BHA-2 than others, which represents the most severe vibration potential. On basis of analysis about the vibration performance for three BHA surrogates, BHA-1 has been determined to be utilized in spud four drrilling.

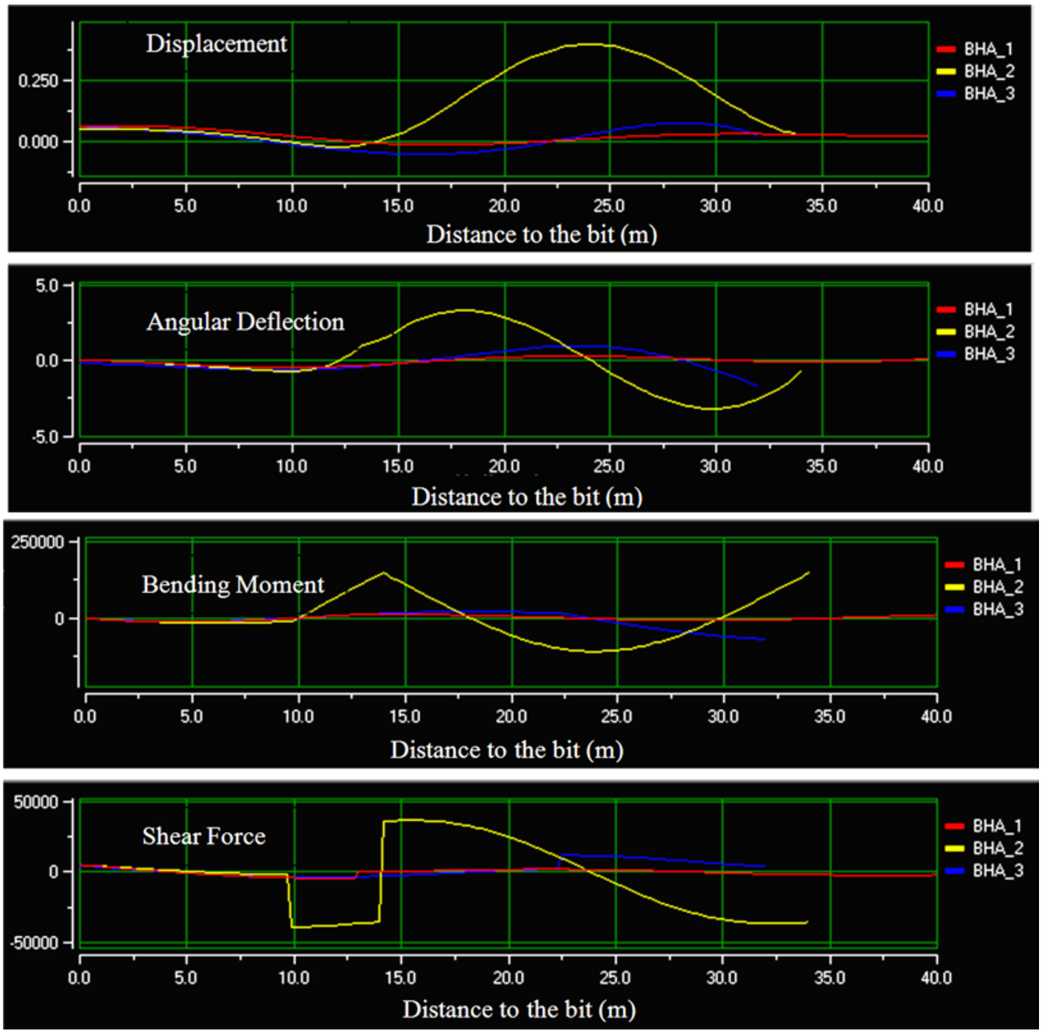

Figure 6
The State Vectors Comparison for Three BHA Surrogates

3.2 Lateral Vibrations Strength Estimate Validation

The pilot interval depth is form 1808m to 2020m, and the lithology is grayish-green siltstone and brown mudstone.

Figure 7
The Lithology Graph for the Pilot Interval

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During drilling process, BHA lateral vibration state vectors are calculated in real-time with surface data acquiring. Meanwhile, the downhole vibration recorder (100HZ) is utilized to obtain field-data dynamic measurements of lateral acceleration. According to correspondence between surface calculation results and downhole measurements, the validation of lateral vibration estimate will be determined.

The figure8 provides the comparison result, the solid line colored red represents the downhole lateral acceleration changing with time, and blue line is lateral displacement change by vibration models. The higher fluctuations for curves mean more and more destructive vibration is onset. There are three severe vibration zones with higher peaks of accelerations curve, and the amplitude of displacement curve is also increasing. The character of the fit between two methods is remarkably good.

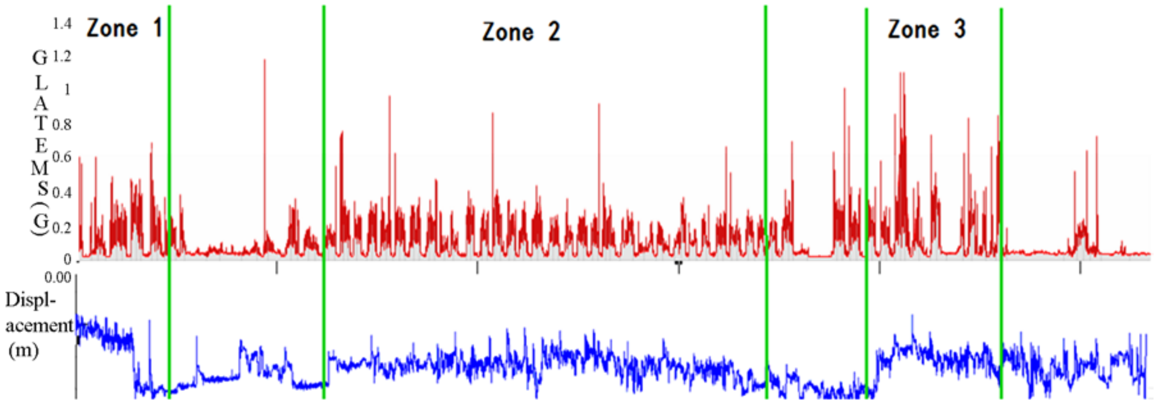

Figure 8
Comparison of BHA Displacement Estimate and Measured Data

CONCLUSION

(a)Based on Newton's equations of motion and Euler-Bernoulli beam bending equation, established frequency domain, single degree of freedom, damped and forced BHA lateral vibration potential estimate model, with more accuracy for each BHA element mechanical states description.

(b)On basis of BHA lateral vibration estimate models, semi-analytical method with transfer function matrices is utilized to analysis the BHA element and obtain the state vectors along with distance to the bit. 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 displacement for each BHA element is regarded as the lateral vibration strength estimate index utilized to estimate lateral vibration severity in quantification in real-time. The filed pilot displays that the estimates results and measurements fit well, which is meaningful for mitigating downhole lateral vibrations and improving drilling performance.

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