INTELLIGENT OPTIMIZATION DESIGN METHOD FOR HORIZONTAL WELL TRAJECTORY IN LONGDONG SHALE OIL

by

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In order to select a better design trajectory, it needs to spend a lot of energy on parameter adjustment and calculation. Therefore, this paper establishes the intelligent optimization design model of horizontal well trajectory in with the target length and drilling string drag under rotary drilling conditions as the targets, and takes the target entry accuracy as the complex constraints. Meanwhile, multi-objective optimization algorithm and distributed calculation are used to realize the automatic optimization of the well trajectory. Under the given arithmetic conditions, compared with the original design trajectory, a horizontal well was designed with this method, the trajectory length is shortened by 92.1 m, and the maximum build-up rate is changed from 5.50° per 30 m to 4.97° per 30 m, reducing by 9.6%. Under the same BHA and boundary conditions, the drag becomes 232.42 kN, which is 6.8% lower than that before optimization.

Key words*: shale oil, well trajectoryoptimization, horizontal well*

Introduction

In order to effectively utilize a single platform to control reserves and maximize the exposure of oil layer area, large well cluster horizontal wells are used for drilling and development. By optimizing the trajectory design of 3-D horizontal wells, not only can the difficulty of constructing large well clusters be reduced, but also the efficiency of reservoir development can be further improved [1, 2]. Numerous scholars at home and abroad have proposed various 3-D horizontal well trajectory optimization design models [3, 4]. Pang *et al.* [5] established a *straight increase stable edge twist horizontal section* horizontal well trajectory optimization design model with the goal of minimizing the length of the wellbore trajectory for the Bohai oilfield. Li, *et al.* [6] established a seven segment trajectory optimization design model based on the characteristics of 3-D horizontal wells in the shale gas field in the Fuling area, and determined the optimal trajectory for the shortest well depth through the combination of well inclination and azimuth angles. Gu *et al.* [7] established an optimization design model for shale gas cluster well trajectory based on the wellhead lay-out of shale gas drilling and production platforms, targeting the total length of wellbore trajectory, potential energy of wellbore trajectory, and lateral displacement.

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In response to the aforementioned issues, combined with the actual situation of the Longdong shale oil area, this paper proposes an intelligent optimization design method for the 3-D horizontal well trajectory of the Longdong shale oil. The method takes the minimum drill string friction and the shortest trajectory length as the dual objectives, and takes the target accuracy and tool inclination ability as constraints. The multi-objective optimization model is solved using the non-dominated sorting genetic algorithm II (NSGA-II). This method can reduce the drag of the drilling string, reduce the length of the trajectory, and achieve rapid automatic optimization after meeting the requirements of the target and engineering constraints. It can effectively improve the efficiency of 3-D horizontal well design for shale oil, and the optimized trajectory is more in line with engineering practice.

Optimization design model for wellbore trajectory

The Longdong Shale Oil Region adopts a large well cluster lay-out model. Due to the smoother wellbore trajectory, lower frictional torque, stronger extension ability, and clearer control elements compared to the five section and six section profiles, the seven-section profile design modelling process is used as an example to facilitate directional control by technical personnel [8]. Therefore, this article introduces the modelling process in detail as follows.

Design of wellbore trajectory parameters

Known conditions are given Wellhead O co-ordinate: (N_O, E_O, H_O). First target point T_0 co-ordinate: (N_{T0}, E_{T0}, H_{T0}). Co-ordinates of the final target point T_1: (N_{T1}, E_{T1}, H_{T1}). In this case, the design parameters to be optimized: H_A – vertical depth of inclination point, K_{AB} – the inclination rate of section AB of the inclined section, α_B – the inclination angle at the end of section AB of the inclined section, φ_B – azimuth angle at the end of section AB of the oblique section, L_{AB} – length of BC section of stable slope section, K_{CD} – the inclination rate of the CD section of the inclined section, α_D – the well inclination angle at the end of the CD section of the inclined section, φ_D – azimuth angle at the end of the CD segment of the oblique section, L_{DE} – length of stable slope section DE, and K_{T0} – the inclination rate of the E_{T0} section of the inclined section.

The design of the seven segment wellbore trajectory is shown in fig. 1.

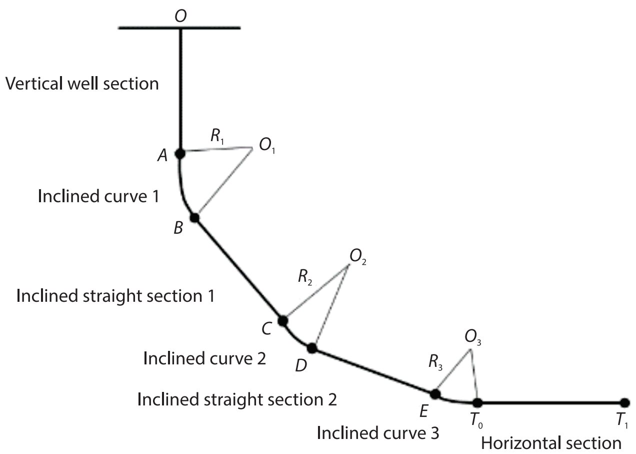

Figure 1. Schematic diagram of optimal design of seven stage wellbore trajectory

Firstly, calculate the wellbore direction of the horizontal section

The well inclination angle of the point T_0 and the azimuth angle at the end of the E_{T0} of the inclined section φ_{T0} are given:

$$\varphi_{T_0} = \begin{cases} \arctan\dfrac{E_{T_1}-E_{T_0}}{N_{T_1}-N_{T_0}} (N_{T_1}-N_{T_0}>0) \\ \arctan\dfrac{E_{T_1}-E_{T_0}}{N_{T_1}-N_{T_0}}+180^\circ (N_{T_1}-N_{T_0}<0) \\ 90^\circ (N_{T_1}-N_{T_0}=0, E_{T_1}-E_{T_0}>0) \\ 270^\circ (N_{T_1}-N_{T_0}=0, E_{T_1}-E_{T_0}<0) \end{cases} \tag{1}$$

$$\alpha_{T_0} = \frac{H_{T_1}-H_{T_0}}{\sqrt{(H_{T_1}-H_{T_0})^2+(N_{T_1}-N_{T_0})^2+(E_{T_1}-E_{T_0})^2}} \tag{2}$$

The incremental co-ordinate parameters of the inclined section read:

$$\gamma = \arccos[\cos\alpha_1 \cos\alpha_2 + \sin\alpha_1 \sin\alpha_2 \cos(\varphi_2-\varphi_1)] \tag{3}$$

$$\lambda_M = \frac{180}{\pi}\frac{L}{\gamma}\tan\frac{\gamma}{2} = \frac{180\times 30}{\pi\times\dfrac{\gamma}{L}\times 30}\tan\frac{\gamma}{2} = \frac{180\times 30}{\pi\times k} = R\tan\frac{\gamma}{2} \tag{4}$$

$$\Delta N = \lambda_M(\sin\alpha_1\cos\varphi_1 + \sin\alpha_2\cos\varphi_2) \tag{5}$$

$$\Delta E = \lambda_M(\sin\alpha_1\sin\varphi_1 + \sin\alpha_2\sin\varphi_2) \tag{6}$$

$$\Delta H = \lambda_M(\cos\alpha_1 + \cos\varphi_2) \tag{7}$$

The co-ordinate parameters of the stable slope section are presented:

$$\Delta N = L\sin\alpha_2\cos\varphi_2 \tag{8}$$

$$\Delta E = L\sin\alpha_2\sin\varphi_2 \tag{9}$$

$$\Delta H = L\cos\alpha_2 \tag{10}$$

where L is the length of the stable slope section, ΔN – the north-south displacement increment of the stable slope section, ΔE – the east-west displacement increment of the stable slope section BC, ΔH – the vertical depth increment of stable slope section, α_2 – the inclination angle at the end of the stable inclination section, and φ_2 – the azimuth angle at the end of the stabilizing section.

Borehole trajectory interpolation calculation

The calculation of measurement points for straight lines in the wellbore trajectory design model is relatively simple, and the interpolation calculation of measurement points for curves in space is carried out using the spatial arc method. As shown in fig. 2, assume a measurement segment 1-2 as an arc curve on spatial oblique plane, and solve for the position parameters at each point of the spatial arc.

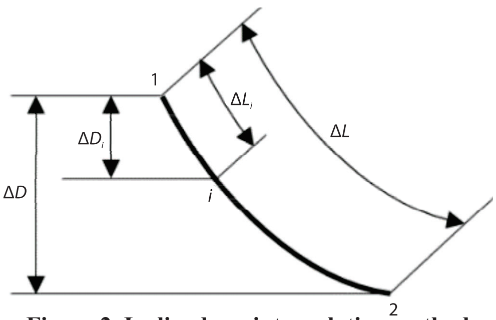

Figure 2. Inclined arc interpolation method

Drill string frictionrque rigid rod model

This article uses rigid rod model [9] to achieve numerical calculation of drill string frictionrque through Python programming. Discrete the entire drill string into micro element segments, and take any micro element segment with an arc length of ds on the wellbore trajectory curve. Differential equations for overall force on the drill string are given:

$$\frac{\mathrm{d}(-F)}{\mathrm{d}s}=-Elk_b\frac{\mathrm{d}k_b}{\mathrm{d}s}-q\cos\alpha\mp\mu_1 n_t \tag{11}$$

$$\frac{\mathrm{d}M}{\mathrm{d}s}=\mu_2 n_t\frac{D_0}{2} \tag{12}$$

where ∓ is the lifting and downward entry, F – the axial tensile force on the drill string, M_T – the torque of the pipe column, s – the depth of the well, q – the weight of the drill string per unit length, α – the inclination angle of the well, El – the bending stiffness of the drill string, n_t – the contact force between the drill stringa and the wellbore, μ_1 – the axial friction coefficient of the drill string, and k_b – the curvature of the wellbore axis.

The calculation formula for wellbore curvature, k_b, reads:

$$k_b=\sqrt{\left(\frac{\mathrm{d}\alpha}{\mathrm{d}s}\right)+\sin^2\alpha\left(\frac{\mathrm{d}\varphi}{\mathrm{d}s}\right)^2} \tag{13}$$

The calculation formula for the contact force on the drill string based on different buckling states of the string (the judgment on the buckling state will not be repeated here):

$$n_t=\begin{cases}\sqrt{\dfrac{A^2+B^2}{1+\mu_2{}^2}}+K_s\left|F\right| \\ \sqrt{\dfrac{A^2+B^2}{1+\mu_2{}^2}\left[1+\dfrac{4}{11}\left(\dfrac{F}{F_{\sin}}-1\right)\right]}+K_s\left|F\right| \\ \dfrac{r_bF^2}{4EI}++K_s\left|F\right|\end{cases} \tag{14}$$

$$A=EI\frac{\mathrm{d}^2k_b}{\mathrm{d}s^2}+k_bF-k_n\left(-k_bM_T+EIk_bk_n\right)+\frac{q}{k_b}\frac{\mathrm{d}\alpha}{\mathrm{d}s}\sin\alpha \tag{15}$$

$$B=\frac{\mathrm{d}}{\mathrm{d}s}\left(-k_bM_T+EIk_bk_n\right)+EIk_n\frac{\mathrm{d}k_b}{\mathrm{d}s}-\frac{q}{k_b}\frac{\mathrm{d}\varphi}{\mathrm{d}s}\sin^2\alpha \tag{16}$$

$$k_n=\frac{\sin\alpha}{k_b{}^2}\pi\left(\frac{\mathrm{d}\alpha}{\mathrm{d}s}\frac{\mathrm{d}^2\varphi}{\mathrm{d}s}-\frac{\mathrm{d}\varphi}{\mathrm{d}s}\frac{\mathrm{d}^2\alpha}{\mathrm{d}s}\right)+\cos\alpha\left[\frac{1}{k_b{}^2}\left(\frac{\mathrm{d}\alpha}{\mathrm{d}s}\right)^2+1\right]\frac{\mathrm{d}\varphi}{\mathrm{d}s} \tag{17}$$

where K_s is the curvature of the helix, k_n – the deflection of the wellbore axis, F – the load, and $F\mathrm{s}_{\mathrm{in}}$ – the critical load under sinusoidal buckling.

By using the finite difference numerical solution method, the overall stress model of the drill string can be written:

$$F_i=F_{i+1}+\frac{1}{2}EI_i(k_{bi}^2-k_{bi+1}^2)+(-q_i\cos\alpha_i\mp\mu_1 n_{ti})\Delta s_i \tag{18}$$

$$M_{Ti} = \frac{1}{2}\mu_2 n_{t1} D_{bi} \Delta s_i + M_{Ti+1} \tag{19}$$

where F_i and F_{i+1} are the axial forces of the i^{th} drill string near the ground and one end near the drill bit, M_{Ti} and M_{Ti+1} – the torques at both ends of the i^{th} drill string, k_{bi}^2 and k_{bi+1}^2 – the wellbore curvatures at both ends of section i, q_i – the line weight, EI_i – the bending stiffness, n_{ti} – the contact force, Δs_i – the length, and D_{bi} [m] – the outer diameter of the i^{th} drill string.

By modifying the overall force model based on actual drilling conditions, and giving the boundary and friction coefficient values of the differential equation, the axial force and torque transmission law of the pipe string in any 3-D wellbore can be obtained.

Establishment and solution of a multi-objective wellbore trajectory optimization design model

This article considers the engineering constraints of two objective functions, one complex constraint, and ten decision variables for the seven segment horizontal well trajectory design model.

Two objective functions

By calculating the incremental co-ordinate parameters of each key node, the objective function 1 of wellbore trajectory length and the objective function 2 of drill string friction (can be obtained, respectively:

$$\min F_1 = \sum_{i=1}^{7} \Delta L_i = L_{OA} + L_{AB} + L_{BC} + L_{CD} + L_{DE} + L_{ET_0} + L_{T_0T_1} \tag{20}$$

$$\min F_2 = stiff(L_i, \alpha_i, \varphi_i) \tag{21}$$

The 13 decision variable constraints

Target accuracy is taken as a complex constraint condition, and the definition of target accuracy is the sum of the squares of the difference between the given geological target co-ordinates and the designed orbit target co-ordinates, *i.e.*:

$$\left(\sum_{i=1}^{6} \Delta N_i - N_{T_0}\right)^2 + \left(\sum_{i=1}^{6} \Delta E_i - E_{T_0}\right)^2 + \left(\sum_{i=1}^{6} \Delta H_i - H_{T_0}\right)^2 \le e \tag{22}$$

Based on engineering conditions and experience, the remaining 12 decision variables were constrained, and seven segment trajectory optimization mathematical models were ultimately established.

Solution of multi-objective trajectory optimization design model based on NSGA-II

The fast non-dominated sorting genetic algorithm NSGA - II with elite strategy is usually used in the field of multi-objective optimization, which has the characteristics of fast convergence speed and good robustness [10]. In order to accelerate the problem of long trajectory solving time, the map function in Python's scalable parallel operation library SCOOP is used for distributed computation of two objective functions, greatly improving computational performance and efficiency.

Example analysis

This article conducts an example analysis of the Longdong Shale Oil HuaHA-1 well and compares the optimized wellbore trajectory with the original wellbore trajectory.

Basic overview of the original wellbore trajectory design for HuaHA-1 well

The original wellbore trajectory design profile data is shown in tab. 1.

Table 1. Well profile design of HuaHA-1 before optimization

Sounding [m]	Wellbore deviation [°]	Orientation [°]	Vertical depth [m]	North co-ordinate [m]	Eastern co-ordinates [m]	Closed azimuth [°]	Closure distance [m]	Dogleg degree [° per 30 m]
0	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
350	0.0	0.00	350.0	0.00	0.00	0.00	0.00	0.00
594	44.7	255.27	569.9	–23.00	–87.49	90.5	255.27	5.50
1828	44.7	255.27	1446.53	–243.7	–927.1	958.6	255.27	0.00
2420	64.7	345.0	1876.5	–4.0	–1173.0	1173.0	269.80	4.00
2605	90.1	345.0	1916.66	169.4	–1219.5	1231.2	277.91	4.10
4541	89.3	345.0	1927.13	2038.8	–1720.4	2667.6	319.84	0.01

Optimization design of wellbore trajectory for HuaHA-1 well

This article utilizes the established seven segment 3-D horizontal well trajectory optimization design model to optimize the wellbore trajectory of HuaHA-1 well.

Boundary condition settings

The optimization design model for the trajectory of a seven segment horizontal well has a total of 13 constraint conditions. Under the premise of meeting engineering requirements, appropriate target accuracy can be given. In this article, the target accuracy is set to 0.5 m^2. The upper and lower bounds of the remaining 12 optimization parameters are set based on the actual drilling experience and tool usage ability of Longdong shale oil 3-D horizontal wells.

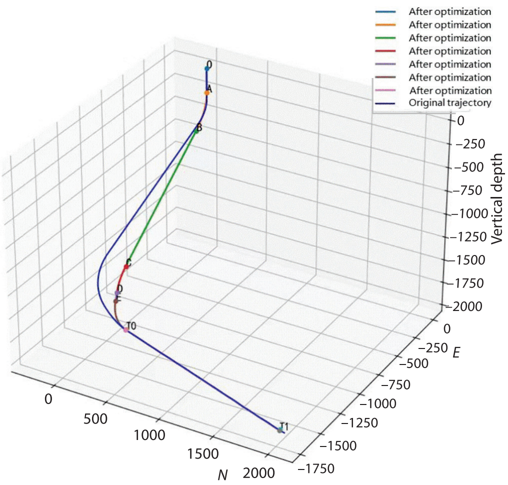

Figure 3. Comparison of the original designed wellbore trajectory and the optimized wellbore trajectory

Analysis of the variation law of drill string friction

Multiple trajectory optimization design schemes were optimized, and the results are shown in tab. 2. The optimized trajectory diagram is shown in fig. 3.

The results show that the depth of the inclination point after multi-objective optimization has changed from 350-259 m. Shorten the trajectory length by 92.1 m. The maxi-

Table 2. Trajectory design key optimization parameter statistics table

Optimize parameters	Value	Optimize parameters	Value
H_A [m]	289	α_D [°]	56.7
K_{AB} [° per 30 m]	2.91	φ_D [°]	299.3
α_B [°]	36.0	L_{DE} [m]	80.6
φ_B [°]	260	K_{ET} [° per 30 m]	4.97
L_{BC} [m]	1245	α_{T0} [°]	89.97
K_{BC} [° per 30 m]	4.67	φ_{T0} [°]	345.03

mum slope rate has changed from 5.50° per 30 m of the original design trajectory to 4.97° per 30 m, which is 9.6% lower than the original slope rate, which reduces the construction difficulty in engineering. In addition, when the inclination rate changes, the larger the inclination rate is and the greater the frictional resistance of the drill string is. This is because an increase in the inclination rate will reduce the radius of wellbore curvature and increase the geometric constraints on the drill string, resulting in an increase in frictional resistance. Compared with the original-design-trajectory, the depth of the optimized inclination point has been reduced from 350-259 m in the original design trajectory. The depth of the deviation point greatly affects the magnitude of the frictional resistance of the drill string.

During optimization design process, through analysis, it was found that the variation of drill drag is closely related to offset distance, target front distance, inclination rate, and inclination depth. Under the same drilling tool combination and boundary conditions, the frictional resistance of the drill string increased from 249.417-232.42 kN, a decrease of 6.8% compared to before optimization. This indicates that the wellbore trajectory designed using multi-objective optimization can meet engineering requirements and has certain advantages in reducing costs and reducing the risk of column buckling.

Conclusions

After analyzing the actual example, the conclusions are as follows.

- The intelligent optimization design method proposed in this article can achieve automatic optimization under given constraints, effectively improving the efficiency of trajectory design.
- The NSGA-II used in this article can improve computational efficiency by integrating distributed computing, solving the problem of long computational time in trajectory design and solution.

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Nomenclature

D_{bi} – outer diameter, [m]
El – bending stiffness, [Nm^2]
F – axial tensile force, [N]
H_A – vertical depth, [m]
M_T – torque, [ms^{-1}]

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