Study on optimization of weight on bit for automatic bit feeding based on improved ant colony algorithm

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Abstract. In the process of automatic bit feeding, to make the drilling process reach the optimal technical and economic indicators, the effect of the parameters on the drilling process should be analyzed. A drilling control parameter optimization model taking unit footage cost as the objective function is established to seek the optimal weight on bit (WOB) - rotary speed combination under certain constraint conditions. The objective function is optimized by the improved ant colony algorithm, and is finally applied to the specific example for simulation. A contrastive analysis is carried out with several kinds of typical optimization algorithm. It is indicated from the result that the improved ant colony algorithm can effectively reduce the unit footage cost, prolong the service life of drill bit, and shorten the trip time.

1. Introduction

In the process of well drilling, as required by the well drilling cost, well deflection, down-hole troublesome conditions and etc., it is expected that the weight on bit (WOB) can be changed in real time according to the drilling parameters to achieve the purpose of optimized well drilling. So far, seeing from the practice of optimal drilling technology application, in the drilling process, the optimal process is related to bit teeth wear and bearing wear (i.e. the bit life), and the corresponding optimal parameters are also changed with the increase of wear and tear. Therefore, the drilling parameters should be adjusted continuously throughout the whole drilling process to ensure that the drilling process is carried out in an optimal state all the time.

The bit wear and the rate of penetration are in a reciprocal relationship. It is particularly important to take these two indicators into consideration with a condition of the lowest cost, obtain the optimal WOB and rotary speed in well drilling, and thus meet the drilling requirements. Both the study on WOB optimization based on Genetic Algorithm and the study on WOB optimization based on BP neural network have achieved corresponding optimization results. However, the former requires a relatively long time to optimize and its process is complex, while the latter requires a great deal of adjacent well data to train, which cannot truly reflect the present well status. To overcome the shortcomings of the above studies and keep the WOB and rotary speed optimal all the time, in this paper the objective function of unit footage cost is established; the objective function is optimized by the improved ant colony algorithm; the optimal WOB - rotary speed is obtained; lastly, the advantages of optimized bit feeding in the aspect of cost are verified through the application of instance.

2. Introduction of Ant Colony Algorithm

2.1. Ant Colony Algorithm
In 1991, the Italian scholar M. Dorigo proposed the concept of an ant colony algorithm, pointing out that the process of searching for food sources by the ant colonies in living nature was regarded as a heuristic random search algorithm. Such ant colony algorithm has been widely applied in various fields because of its extremely strong global search performance, simple principle and easy operation [1][2].

The basic principle of ant colony algorithm is: the communication between ants and ants as well as ants and the outside world depends on pheromones, a volatile chemical substance secreted by ants themselves [3][4]. Ants can leave pheromones on their way from the nest to the food source and back to the nest, creating a pheromone trail. On relatively short path, more ants pass through this path in unit time, so the concentration of pheromone is relatively high, causing that more ants choosing this path which forms a positive feedback mechanism. Pheromones in other routes gradually volatilize, thus ants can move on the shortest path [5].

2.2. Improved Ant Colony Algorithm

The basic ant colony algorithm is easy to fall into a local optimal solution and needs a relatively long time to converge to a global optimum. Therefore, in this paper, a kind of improved ant colony algorithm is adopted to carry out the study [6]. The improving principle is to enhance the concentration of pheromone on each node on the path corresponding to the optimal solution of the objective function in the feasible paths found in each cycle, reduce the concentration of pheromone on each node on the path corresponding to the worst solution of the objective function in the feasible paths found in each cycle. Through this kind of improvement, the optimizing strategy of the basic ant colony algorithm is further enhanced [7]. It is mainly improved from following three aspects:

1. State Transition Rule

An ant \( k \) located at the node \((r, u)\) selects the location \( s \) to which it will move though state transition rule formula (1):

\[
\begin{align*}
\tau_s &= \arg \max_{u \in \text{allowed}_k} \left[ \tau(r, u)^\alpha \cdot \eta(r, u)^\beta \right] q \leq q_0 \\
S_s &= \begin{cases} 
\text{argmax} & \text{allowed}_k \end{cases}
\end{align*}
\]

Where, \( \text{allowed}_k = \{0, 1, \ldots, n-1\} \) denotes that the location to be chosen by ant \( k \) next is allowed; \( \tau \) is the pheromone factor; \( \eta \) is the visibility factor; \( \alpha \) is the information heuristic factor; \( \beta \) is the expectation heuristic factor; \( q \) is random number uniformly distributed in interval \([0, 1]\), \( q_0 \) is a parameter in interval \([0, 1]\). \( S \) is a random variable [8].

2. Pheromone Global Updating Rule

After each round of iteration is ended, only the ants constructing the shortest path from the beginning of the algorithm to current iteration are allowed to release pheromones [9]. Make a global update by Formula (2):

\[
\tau(r, s) = (1-\rho)\tau(r, s) + \rho \Delta \tau(r, s)
\]

\[
\Delta \tau(r, s) = \begin{cases} 
\tau_L^{-1}(r, s) & \text{if } L_s \in L_gb \\
0 & \text{otherwise}
\end{cases}
\]

Where \( L_gb \) is the globally optimal path that have found so far, \( L_gb = nL_au \), \( n \) is the number of nodes, \( L_au \) is the length of path built by greedy algorithm; \( \rho \) is the global pheromone volatile parameter, where \( 0<\rho<1 \); \( \Delta \tau(r, s) \) is the amount of initial pheromone [10].

3. Pheromone Local Updating Rule

The local updating rule can make the pheromone track amount on corresponding path reduce gradually, which can effectively avoid converging to one same path [11][12]. When passing through a side \((r, s)\) every time, ants will immediately make local update on such side as per Formula (3):
Where $\xi$ is the local pheromone volatile parameter, $0 < \xi < 1$.

The algorithm flow chart is shown as Fig.1.

Fig.1 Flow chart of Improved Ant Colony Algorithm

3. Building of WOB Optimization Model based on Objective Function

Based on the effect of different parameters on the drilling cost, taking unit footage cost as the standard for measuring the technical and economic effect, drilling control parameters optimization model with unit footage cost as the simple target is built to seek the optimal WOB - rotary speed combination and make the drilling process achieve the optimal technical and economic effect.

(1) Relationship between bit footage $H$ and various parameters including WOB, rotary speed, tooth wear extent and etc.

According to the Improved Yangge Mode, the penetration rate model on micro time slot is described as:

$$v_{pc} = \frac{dH}{dt} = C_H C_p K_d (W - M) N^2 \frac{1}{1 + C_z h}$$

The bit teeth wear model on micro time slot is:

$$\frac{dh}{dt} = \frac{A_f (a_1 N + a_2 N^3)}{(D_2 - D_1 W)(1 + C_z h)}$$

The bit footage model is:

$$dH = \frac{C_H C_p K_d (W - M) N^2 (D_2 - D_1 W)}{A_f (a_1 N + a_2 N^3)} \left[ 1 + C_z h \right] dh$$

Integrate Formula (6), where $h_f$ denotes the final wear extent of the teeth, so:
In the formula, \( H_f \) is the bit’s wear extent, \( h_f \) is the footage of the corresponding bit; \( \nu_{pc} \) is the rate of penetration in m/h; \( W \) is the WOB in KN; \( N \) is the rotary speed in r/min; \( K_d \) is the stratum drillability coefficient; \( M \) is the threshold WOB in KN; \( C_H \) is the hydraulic decontamination factor; \( C_p \) is the differential pressure influence coefficient; \( D_1 \) and \( D_2 \) are the WOB influence coefficients; \( a_1 \) and \( a_2 \) are the rotary speed influence coefficients; \( A_f \) is the stratum abrasiveness coefficient; \( C_1 \) is the tooth wear influence coefficient; \( C_2 \) is the tooth wear coefficient; \( h \) is the bit tooth wear extent.

(2) Relationship between bit life \( t_f \) and various parameters including WOB, rotary speed, wear extent and etc.

Integrate the two sides of Formula (5), and conclude:

\[
t_f = \frac{D_2-D_1W}{A_f(a_1N+a_2N^3)}(h_f + \frac{C_1}{2}h_p^2)
\]

(8)

(3) Unit footage cost

The objective function of unit footage cost \( C_{cos} \), can be defined as:

\[
C_{cos}(W,N) = \frac{C_r}{C_H C_p K_d (W-M)N^2} \left[ \frac{C_1}{C_2}h_f + \frac{C_2-C_1}{C_2^2}ln(1+C_2 h_f) \right]
\]

(9)

In the formula, \( C_{cos} \) is the unit footage cost in Yuan / m; \( t_E \) is the converted time of bit and trip cost in h; \( C_r \) is the drilling machine’s operation expense in Yuan / h.

(4) Constraint conditions

The objective function of unit footage cost can be expressed as:

\[
\text{obj } \_\text{func } = \min(C_{cos}) \rightarrow \min(C_b + C_r(t+t_r)/H)
\]

(10)

Where \( C_b \) is the bit cost in Yuan / piece; \( t_r \) is the trip and joint making time in h; \( t \) is the bit working time in h; \( H \) is the bit footage.

Constraint conditions: Tooth wear extent: \( 0 \leq h_f \leq 1 \); Rotary speed: \( N \geq 0 \); WOB: \( M > 0, M < W < D_2 / D_1; M < 0, 0 < W < D_2 / D_1 \); The WOB and rotary speed product constraint condition is: \( WN < PD \) (\( PD \) is the maximum output power of the drilling machine).

4. Instance Analysis

The drilling parameters for the 2800m well section of an oil field is optimized. Type 21 bit in Φ251mm suitable for medium - hard formation is adopted for the drilling of such well section. Set: \( C_H = 1, C_p = 1, h_f = 0.75 \).

(1) Determination of related coefficients of the drilling parameters optimization model

The bit parameters of 251mm type bit are \( D_1=0.0146, D_2=6.44, a_1=1.5, a_2=6.53 \times 10^{-5}, C_1=5 \). It is concluded from the regression analysis on Formula (4) ~ (9) that \( K_d=0.00229, M=10.1kN, \lambda=0.682, C_2=3.679, A_f=0.00228 \), the bit cost \( C_b=900 \) Yuan/piece, its trip time \( t_r=5.75h \), and the drilling machine operating expense \( C_r=250 \) Yuan/h. Where the converted time of bit and trip cost is:

\[
t_E = C_b/C_r + t_r = 9.35h
\]
Determination of the parameters of improved ant colony algorithm

To make the ant colony algorithm improved in this paper comparable with other optimization algorithms, the parameters are selected as similar as the parameter values of other optimization algorithms. According to the experiences, set the parameters to be determined as below [13][14]: initialized ant colony A(t)=120, pheromone weight $\alpha=1$, heuristic information weight $\beta=2$, parameter $q_0=0.9$, global pheromone volatile parameter $\rho=0.1$, local pheromone volatile parameter $\xi=0.1$, initial pheromone amount $\Delta \tau(r,s) = (nL_{a0})^{-1}$ and maximum cycle index GEN=300.

Simulation

Make simulation in MATLAB R2017a. The simulated optimized result is shown as Fig.2, which indicates that the unit footage cost is changed with the change in number of iterations. Where GEN $\geq$ 150, the unit footage cost almost has no change.

A comparative analysis is made on the optimization result of the ant colony algorithm improved in this paper and the classical Genetic Algorithm (NSGA-II), Particle Swarm Optimization (PSO) and the Classical Extremum Method (CEM). The specific data is shown as Tab.1:

| Algorithm          | WOB KN | Rotate speed r/min | Algorithm run time s/times | Unit footage cost yuan/m |
|--------------------|--------|--------------------|----------------------------|-------------------------|
| NSGA-II            | 323.26 | 60.49              | 0.1834                     | 84.5126                 |
| PSO                | 333.23 | 78.58              | 0.2041                     | 76.8347                 |
| CEM                | 340.56 | 62.54              | 0.2176                     | 80.2614                 |
| Improved Ant Colony Algorithm | 314.45 | 65.67              | 0.1583                     | 66.5583                 |

It is concluded from Tab.1 that:

1) In comparison with NSGA-II, PSO and CEM, the improved ant colony algorithm can obtain the optimal WOB - rotary speed combination in a shorter time, which has the advantage of high convergence rate and high efficiency.

2) Under identical condition of drilling process and hydraulic parameter, in comparison with NSGA-II, PSO and CEM, the improved ant colony algorithm can obtain a lower unit footage cost.

3) When the number of iterations exceeds 150, by keep other drilling conditions unchanged and changing the WOB - rotary speed combination, the unit footage cost has almost no change; in other words, the WOB and rotary speed reach certain ideal values respectively, as shown in Fig.2.

From the above, the improved ant colony algorithm has high convergence rate, good distributivity and high precision. In comparison with the optimization results of NSGA-II, PSO and CEM, the improved ant colony algorithm can obtain the optimal WOB - rotary speed combination faster, so as to lay the theoretic foundation for achieving the real-time optimization of drilling parameters.
5. Conclusion
In this paper, the unit footage cost is used as the target for the optimization of drilling control parameters in automatic bit feeding, and the ant colony algorithm having global optimization ability is adopted to realize the optimization of WOB and rotary speed parameter for the automatic bit feeding in well drilling process, so as to achieve the optimal technical and economic effect. The algorithm not only effectively solves the problem of optimizing the single target drilling control parameters and obtains the optimal unit footage cost under the optimal WOB - rotary speed combination, but also has high convergence rate and high efficiency, which meet the real-time needs on optimization of drilling control parameters. The optimization result is relatively ideal, but such algorithm is less applied in the optimization of WOB in automatic bit feeding. Therefore, researchers and scholars are expected to increase the studies of ant colony algorithm in this field, to further perfect the optimization performance of the algorithm in this field.

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