Real-time drilling rate prediction method of reaming while drilling based on mechanical specific energy

Guoxin Ma\(^1\), Xu Du\(^2\)*, Xuyue Chen\(^2\), Yuqun Hong\(^1\), An Wang\(^1\), Fengxi Zhang\(^1\)

1. College of Safety and Ocean Engineering, China University of Petroleum (Beijing), Beijing, 102249, China
2. Downhole Service Department Shanghai Petroleum Co., Ltd., Shanghai, 200041, China

Abstract: Reaming while drilling (RWD) is a drilling technique that uses a reamer and a pilot bit to expand the size of an open hole segment to be larger than the inner diameter of an upper casing string while fully drilling, especially in deep wells. This technique reduces the number of trips and is highly efficient and widely used in deep wells, ultra-deep wells, small clearance wells, and side-drilling and complex well conditions. However, in the actual operation process, the mismatching between the pilot bit and reamer often leads to slippage, string vibration, and low-quality borehole. In this paper, based on the mechanical specific energy model and the RWD weight distribution model, combined with the drilling weight, torque, and formation confined compressive strength at the interface of the pilot bit and reamer, a real-time rate of penetration (ROP) prediction model suitable for RWD is derived. Through the analysis of the downhole condition of the RWD operation, reasonable drilling parameters are determined and a set of real-time RWD performance prediction and optimization algorithm is proposed. Studies show that during the RWD operation, the size of the pilot bit and reamer and the shape of the cutter have an enormous influence on ROP. When drilling in different formations, the excellent cooperation among the pilot bit, reamer, and formation is the key to improve ROP and bottom hole assembly stability. How to optimize the bit and reamer to drill with the same ROP and predict the ROP is the focus of this paper. Field logging data test the ROP prediction model and real-time optimization method, and the results indicate that the ROP prediction model has high precision, small error, and high timeliness, which can fully meet the requirements of field engineering. This model can guide the selection of the bit, reamer, and drilling parameters in RWD, which is of considerable significance to RWD.

Keywords: Reaming while drilling, Mechanical specific energy model, Rate of penetration, Prediction algorithm

1. Introduction
Reaming while drilling (RWD) technology has become a way to cope with complex plastic creep formations, optimize wellbore structure, improve the quality of oil and gas well construction, improve drilling speed, and reduce the cost of drilling operations (Ho, 2013) because it reduces the drilling time, increases the drilling speed, and reduces the risk of stuck pipe. However, the technology can cause
engineering problems, such as stick-slip and drill string vibration in RWD, during the drilling process due to the incorrect matching of the collar bit, reamer, and formation. Mechanical specific energy (MSE) can monitor the working state of the downhole in real time, predict and avoid downhole accidents, optimize drilling parameters in time, improve drilling performance, and reduce drilling costs. In RWD, MSE theory can be used to predict the distribution of weight on the bit and reamer, optimize drilling parameters, and optimize the rate of penetration (ROP) in real time. Chen (2014) proposed a mechanical drilling speed prediction model on the basis of MSE and non-RWD and proved its correctness in the field test. Meyer-Heye, Ma Rutao, Jun Jing, and Jie Xu (2020) conducted considerable research on the weight distribution of RWD and achieved good results. This paper innovatively proposes a real-time optimization algorithm for drilling speed on the basis of the MSE model and the unfitness model between the drill bit and the reamer in RWD. The paper also suggests an operation method to increase the drilling speed during RWD. This algorithm provides a real-time optimization method for ROP, which considers factors such as current weight on bit, pilot bit and reamer combination, and drilling parameters. This consideration provides technical guidance for improving the drilling efficiency in actual RWD.

2. Model Development and Algorithm

2.1. Model Development

MSE is defined as the mechanical work of excavating a unit volume of rock. The MSE model is already rich based on previous studies. This article is based on the horizontal well MSE model proposed by Chen et al. (2014) who considered well deviation and friction loss. The model is verified to have good adaptability and applicability to horizontal and vertical wells (for vertical wells, the well declination parameter only needs to be set to 0°).

\[
\begin{align*}
MSE_b &= E_{mb} \cdot WOB^* \cdot e^{-\mu_b}, \\
\mu_b &= 36\frac{T_b}{D_b \cdot WOB}, \\
WOB^* &= WOB \cdot e^{-\mu_b},
\end{align*}
\]

\[
\begin{align*}
MSE_r &= E_{mr} \cdot WOR^* \cdot e^{-\mu_r}, \\
\mu_r &= 36\frac{T_r}{D_r \cdot WOR}, \\
WOR^* &= WOR \cdot e^{-\mu_r},
\end{align*}
\]

where \(MSE_b\) is the MSE on the bit; \(MSE_r\) is the MSE on the reamer; \(E_{mb}\) is the mechanical efficiency of the bit; \(E_{mr}\) is the mechanical efficiency of the reamer; \(WOB^*\) is the bottom hole actual (BHA) weight on the bit; \(WOR^*\) is the BHA weight on the reamer; \(WOB\) is the weight on the bit calculated by surface measurement; \(WOR\) is the weight on the reamer calculated by surface measurement; \(\mu_b\) is the friction coefficient of the bit; \(\mu_r\) is the friction coefficient of the reamer; \(\mu\) is the friction coefficient of the drill string; \(\gamma_b\) is the inclination of the well at the bit; \(\gamma_r\) is the inclination of the well at the reamer; \(A_b = \pi \cdot d_b^2/4\) is the bit area; \(A_r = \pi \left(d_r^2 - d_b^2\right)/4\) is the effective drilling area of the reamer; \(d_b\) is the bit diameter; \(d_r\) is the reamer diameter; \(D_b = d_b\) is the arm of torque on the bit; \(D_r = \left(d_r^2 - d_b^2\right)/\left(4 \cdot (d_r - d_b)\right)\) is the arm of torque on the reamer; \(RPM\) is the rotating speed; \(ROP\) is the rate of penetration.
The relationship between WOB and WOR is as follows, and its derivation process is shown by Xu et al. (2020):

\[ WOB = \frac{\lambda}{1 + \lambda} \cdot WOG, \quad WOR = \frac{1}{1 + \lambda} \cdot WOG, \]  

(3)

where \( WOG \) is the weight measured on the ground; \( \lambda \) is the ratio of weight on bit distribution, and its definition formula is as follows:

\[ \lambda = \frac{WOB}{WOR} = \frac{E_{mb} \cdot CCS_b}{E_{mb} \cdot WOB \cdot e^{-\mu_b \cdot \gamma} \cdot D_b \cdot \mu_r \cdot e^{-\mu_r \cdot \gamma} \cdot D_r}, \]  

(4)

Caicedo (2005) pointed out that during high-efficiency rock drilling, MSE should be equal to the confined compress strength (CCS) of the formation rock. Therefore, MSE can be used to detect the peak drilling efficiency by surveilling MSE to see if MSE (min) is roughly equal to the CCS of the rock drilled.

\[ MSE = CCS \]  

(5)

Furthermore, we can obtain:

\[ ROP_{pb} = \frac{13.33 \cdot \mu_b \cdot RPM}{D_b \left( \frac{CCS_b}{E_{mb} \cdot WOB \cdot e^{-\mu_b \cdot \gamma} \cdot A_b} - 1 \right)}, \]  

(6)

\[ ROP_{pr} = \frac{13.33 \cdot \mu_r \cdot RPM}{D_r \left( \frac{CCS_r}{E_{mr} \cdot WOR \cdot e^{-\mu_r \cdot \gamma} \cdot A_r} - 1 \right)}. \]  

(7)

In the formula, \( ROP_{pb} \) and \( ROP_{pr} \) are the predicted ROP at the pilot bit and the predicted ROP at the reamer, respectively.

In the actual prediction results, \( ROP_{pb} \) and \( ROP_{pr} \) are often different due to various factors, but different \( ROP_{pb} \) and \( ROP_{pr} \) cause the actual ROP to be low. To evaluate this inconsistency, the unfitness of the bit and reamer (\( \zeta \)) is introduced, and its derivation for the process is obtained from previous literature (Xu et al. 2020). The range is \([0, +\infty[\).

\[ \zeta = \left| \frac{ROP_{pr} - ROP_{pb}}{ROP_{pb}} \right|. \]  

(8)

The introduction of the concept of unfitness provides a quantitative indicator for evaluating the fit of the reamer, pilot bit, and drilling parameters.

2.2 ROP Prediction Algorithm

Based on the model of unfitness evaluation, this paper provides a schematic diagram of the ROP prediction algorithm, as illustrated in Figure 1. As described above, when the difference between \( ROP_{pb} \) and \( ROP_{pr} \) is large, we do not know which prediction ROP to use as the real prediction value.

Here, we propose the first allowable error value, which indicates that when \( \zeta \) is lower than this value, we can predict the true ROP of the well interval on the basis of the approximate \( ROP_{pb} \) and \( ROP_{pr} \). That is, the pilot bit, reamer, and drilling parameters are well coordinated in this well section, which can achieve efficient drilling operations. When the mismatch coefficient is higher than this value, the difference between \( ROP_{pb} \) and \( ROP_{pr} \) is too large. Adjusting WOG and the combination of pilot bit and reamer or even redesigning the operation plan of the well section is necessary to improve the operation of the well section effectiveness. On the basis of satisfying the first allowable error, a second
allowable error is further proposed. The significance of this value is to fine-tune the drilling parameters further to reach the optimal result. If the accuracy requirement is not that high in the actual operation, then it can be made equal to the first allowable error.

In the optimization process, the algorithm also insists on adjusting drilling parameters first, followed by adjusting the order of the pilot bit and finally the reamer. In field operations, drilling parameters are the easiest to adjust; the use of reamers is also often related to the field requirements for the borehole size after the reamer operation. Blindly modifying the reamer size may fail to meet the operation requirements.

![Figure 1. Schematic of the ROP prediction algorithm](image)

**3 Field Application**

To verify the guidance effect of the ROP prediction algorithm on the actual operation, this paper selects a well section of 7805–10515 ft. in Qatar as the calculation data. The data content includes key parameters, such as drilling tool size, WOG, ROP, and RPM. The data are sampled every 1 ft. interval. First, the MSE calculation of this section is performed, and the result is presented in Figure 2. In the figure, the deviation of MSE and CCS is not large in this section, and the ROP of the whole section is relatively high, especially ROP is hugely high approximately 9550 ft. At this time, the deviation of MSE and CCS is only 2.3% (average at the reamer and pilot drill). For the low ROP at 9900 ft., the deviation between MSE and CCS is as high as 47.8%. The reason for
this phenomenon is that when MSE is close to CCS, the energy of the drill bit is only used to break the formation rock. If MSE is much lower than CCS, then the energy at the drill bit is not enough to break
the rock. If MSE is much higher than CCS, then the energy applied on the ground is too high, which can cause problems such as bit stick-slip and drill string vibration. Therefore, if the difference between MSE and CCS is too large, then ROP decreases.

Second, the $\zeta$ of the well section is calculated, and the result is shown in Figure 3. In the figure, the trend of $\zeta$ and $ROP$ also basically maintains the same trend; in addition, $\zeta$ and $ROP$ decrease synchronously by approximately 8800 ft. We can basically judge the incompatibility of the reamer, pilot bit, and drilling parameters at this time. The increase in $ROP$ between 9050 ft. and 9110 ft. indicates that after adjusting the drilling parameters, the working conditions of the reamer and the pilot bit are adapted to the formation.

Based on the above two basic calculations, the basic model used in this article can be considered correct. Next, we verify the ROP prediction algorithm. Each drilling parameter of the well section is brought into the algorithm model, which can be the output, as displayed in Figure 4; the predicted ROP curve can be seen in the ROP sub-graph of the figure. By comparing the predicted ROP with the real ROP, the average deviation is 24.39%. Considering many uncertain factors in engineering operations, the prediction error within 25% should be acceptable.

4 Conclusion

Based on MSE theory, the weight distribution model, and the unfitness evaluation model, this paper proposes an $ROP$ prediction algorithm for RWD. Through the actual evaluation of a well area in Qatar by this algorithm, we can obtain the following conclusions:

• The optimized prediction result of this algorithm is close to the actual operation result on site. The calculation result of this algorithm can be basically considered correct and has a guiding effect on actual production.

• By using this set of algorithms, the suitability of downhole drilling tools and the rationality of the weight distribution can be monitored in real time; corrections can also be dynamically proposed. In the case of a few trips as possible, the ROP value is maximized, and the efficiency of RWD can be improved.

• The ROP value of the RWD operation is susceptible to the adaptation of the formation strength, pilot bit, reamer, and drilling parameters. The fluctuation of any parameter may cause the reduction of ROP. It should be adjusted in time during engineering operations.

• Compared with traditional methods, this algorithm is based on physical models and does not require geological models, finite element calculations, and a large amount of basic data of similar fields. The algorithm is highly adaptable and can optimize drilling parameters in real time.

• Given that this model is based on a purely physical model, the prediction results have high requirements on the accuracy of the input data; the input errors are also accumulated in the iterative calculation, resulting in a high deviation rate.
Figure 4. Comparison between predicted ROP and real ROP

Acknowledgments
This work was financially supported by the National Natural Science Foundation of China (Grant numbers: 51804322; 51821092; 51774301; U1762214), National Key Research and Development Project (Grant numbers: 2017ZX05009-003; 2017ZX05005-005-007), and other projects (Grant number: 2462017YJRC050).
References

[1] Centala, P., V. Challa, B. Durairajan., R. Meehan, L. Paez, U. Partin, S. Segal, S. Wu, L. Garrett, B. Teggart. 2011. Bit design—top to bottom. *Oilfield Review*. 23(2): 4-17.

[2] Chen, X., H. Fan, B. Guo, D. Gao, H. Wei, and Z. Ye. 2014. Real-time prediction and optimization of drilling performance based on a new mechanical specific energy model. *Arabian Journal for Science and Engineering*. 39(11): 8221-8231.

[3] Chen, X., D. Gao, B. Guo, and Y. Feng. 2016. Real-time optimization of drilling parameters based on mechanical specific energy for rotating drilling with positive displacement motor in the hard formation. *Journal of Natural Gas Science and Engineering*. 35: 686-694.

[4] Gopalsing, P. M. 2006. Advanced Drilling Using a Dual Bit System. Paper presented at the SPE Western Regional/AAPG Pacific Section/GSA Cordilleran Section Joint Meeting.

[5] Ho, T., C. Alferez, M. Cortez, I. Nott, and X. McNary. 2013. Optimal Bit, Reamer Selection and Operating Procedures Improve Hole Enlargement Performance in Deepwater Gulf of Mexico. Paper presented at the SPE/IADC Drilling Conference, Amsterdam, The Netherlands.

[6] Jing, J., Y. Lu, X. Zhu, L. Dai, and W. Liu. 2018. Weight Distribution Characteristics During the Process of Hole Enlargement When Drilling. *Arabian Journal for Science and Engineering*. 43(11): 6445-6459.

[7] Kueck, A., M. Ichouiti, C. Herbig, A. Hohl, G.P. Ostermeyer, and H. Reckmann, 2017. Optimal Matching of Bit and Reamer for Increased Reliability of Hole-Opening BHAs. Paper presented at the Abu Dhabi International Petroleum Exhibition & Conference, Abu Dhabi, UAE.

[8] Ma, R., Y. Ji, H. Wang, and F. Han. 2012. Dual-factor method for calculating weight distribution in reaming while drilling. Paper presented at the IADC/SPE Asia Pacific Drilling Technology Conference and Exhibition.

[9] Meyer-Heye, B., H. Reckmann, and G.P. Ostermeyer. 2010. Weight distribution in reaming while drilling BHAs. Paper presented at the IADC/SPE Drilling Conference and Exhibition.

[10] Mirani, A.A., and R. Samuel. 2018. Discrete Vibration Stability Analysis With Hydromechanical Specific Energy. *Journal of Energy Resources Technology*. 140(3).

[11] Xu, J., X. Chen., X. Du, L. Sun., Y Hong., Y Zou, W Wang, 2020, A method for selecting the correct reamer and bit combination in reaming while drilling. Paper will presented at the ARMA 2020 Symposium, Colorado, USA.

[12] Mohan, K., F. Adil, and R. Samuel. 2015. Comprehensive hydromechanical specific energy calculation for drilling efficiency. *Journal of Energy Resources Technology*. 137(1).

[13] Pessier, R.C., and M.J. Fear. 1992. Quantifying Common Drilling Problems With Mechanical Specific Energy and a Bit-Specific Coefficient of Sliding Friction. Paper presented at the SPE Annual Technical Conference and Exhibition, Washington, D.C.

[14] Teale, R. 1965. The concept of specific energy in rock drilling. Paper presented at the International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts.

[15] Thomson, I. J., S.R. Radford, J.R. Powers, L.T. Shale, and M. Jenkins. 2008. A systematic approach to a better understanding of the concentric hole-opening process utilizing drilling mechanics and drilling dynamics measurements recorded above and below the reamer. Paper presented at the IADC/SPE Drilling Conference. Balkema.