1. Mustafa HAMIDOV[1], 2. Elbrus AHMEDOV[2], 3. Hamida HAMIDOVA[3], 4. Sona RZAYEVA[4]

Azerbaijan State Oil and Industry University (1, 2, 3)
ORCID: 2.0000-0003-3348-7946; 4. 0000-0001-7086-9519

doi:10.15199/48.2024.02.30

Analysis and development of a mathematical model of the acoustic method for monitoring downhole parameters of the drilling process

***Abstract**. The article analyzes the control of downhole parameters of the drilling process and develops a mathematical model that describes this process. Analysis of the rotary drilling process showed that the main downhole parameters to be monitored and diagnosed are the degree of wear and breakage of the bit cutter. The method under study for monitoring and diagnosing downhole parameters is the most reliable and does not require special costs for transmitting information from the bottomhole to the wellhead. For the successful application of this method, a mathematical model has been developed that makes it possible to determine the energy of acoustic vibrations of the bit, taking into account bottom hole parameters. It is shown that the wear of the bit teeth leads to a decrease in the amplitude of the acoustic signal, and the breakage of the cone teeth causes a change in its frequency and amplitude.*

***Streszczenie.** W artykule dokonano analizy sterowania parametrami otworowymi procesu wiercenia oraz opracowano model matematyczny opisujący ten proces. Analiza procesu wiercenia obrotowego wykazała, że głównymi parametrami otworu wiertniczego, które należy monitorować i diagnozować, są stopień zużycia i złamania świdra. Badana metoda monitorowania i diagnozowania parametrów odwiertu jest najbardziej niezawodna i nie wymaga specjalnych nakładów na przesyłanie informacji z odwiertu do głowicy. Dla pomyślnego zastosowania tej metody opracowano model matematyczny, który umożliwia wyznaczenie energii drgań akustycznych świdra z uwzględnieniem parametrów dennego otworu. Wykazano, że zużycie zębów świdra prowadzi do zmniejszenia amplitudy sygnału akustycznego, a pęknięcie zębów stożka powoduje zmianę jego częstotliwości i amplitudy. (**Analiza i opracowanie modelu matematycznego metody akustycznej monitorowania parametrów odwiertu procesu wiertniczego**)*

Keywords: Drilling, downhole parameters, diagnostics, mathematical model, bits.
Słowa kluczowe: Wiercenie, parametry odwiertu, diagnostyka, model matematyczny, bity.

Introduction

Drilling is an integral part of the process of developing oil and gas fields. Important parameters of the drilling process are rotor speed, pressure at the bottom of the well, drilling fluid flow rate, bottomhole depth, and others [1-3]. Control of these parameters is necessary to ensure the safety of drilling workers, protect the environment and ensure the efficient use of equipment.

Increasing the depth of drilling wells requires, in turn, reducing the time spent and the use of express methods for monitoring bottom hole parameters. Therefore, instruments and equipment for downhole control of drilling processes are becoming increasingly important. In the process of drilling, the cutting structure of the bit, supports and the bit washing system are most intensively affected.

The bit flushing system plays an important role in the drilling process. It provides fluid (usually drilling fluid or water) through the bit to cool, lubricate and remove the resulting debris. During the flushing process, the system may be subjected to various stresses such as pressure and abrasive particles. This can cause wear or damage to flush system components, including pumps, piping, and filters. Regular maintenance and testing of the flushing system will keep it working and efficient.

There are many methods for controlling downhole parameters of the drilling process, each of which has its own advantages and limitations. One of the most common methods is the use of sensors on the drill string and in the drilling fluid to measure various parameters such as pressure, temperature, density and viscosity [4-6]. Another common method is the use of geophysical methods, such as seismic and electromagnetic tomography, to determine the geological structure of the well and control the density and permeability of the reservoir [7-9].

The method of acoustic tomography is based on the vibration of individual pipe elements under the influence of pressure pulsation in the pipeline and the emission of acoustic frequency signals that propagate through the transported medium. The assessment of the technical condition of the pipeline is carried out in accordance with the developed criteria that link the vibration emission properties of the defect with the likelihood of a leak.

Using this method, it is possible to carry out diagnostics of overhead and underground pipelines, channel and non-channel laying with a diameter of 80 mm or more, which are in operation at an internal pressure of more than 0.25 MPa and with the obligatory presence of a current of the transported medium through the pipeline.

The main advantage of using this method is that there is no need to change the pressure during diagnostics - the pipeline is operating normally.

It was revealed that the acoustic method of monitoring and diagnosing bottomhole parameters is the most reliable and does not require special costs for transmitting information from the bottomhole to the wellhead; for its application, a mathematical model has been developed that allows describing the processes of radiation and propagation of acoustic signals.

Known methods for controlling the drilling process are mainly based on monitoring changes in current in motors associated with changes in the load on the rotary table [10, 11, 17]. However, these methods do not have sufficient efficiency to obtain information about changes in drilling parameters. Therefore, they are most often supplemented by other methods of obtaining information, devoid of this drawback.

The use of various downhole telemetry systems is a common practice for monitoring and controlling the drilling process. Telemetry allows you to receive real-time data on the state of the well, such as pressure, temperature, depth, drilling speed and other parameters [12-14].

Of the variety of control methods, the acoustic control method is the most suitable for obtaining information about bottomhole parameters.

Problem setting

The lack of simple and reliable means and systems for monitoring downhole parameters in rotary drilling is due to the lack of reliable theoretical models that describe the physical processes of transmission of sound vibrations that occur during the operation of the bit and their propagation through existing communication channels.

The solution of the task will allow not only to develop effective algorithms for monitoring and diagnosing, but also to create the principles and methods of diagnosing to determine defects in bit elements and emergency conditions during drilling. At the same time, informative features are essential for describing the object of study.

The development of mathematical models for predicting downhole parameters of the drilling process is essential for optimizing and controlling this process. Models can be based on physical principles, empirical data, or a combination of both approaches. They may take into account various factors such as soil type, well depth, drilling tool properties, etc. The development of mathematical models makes it possible to predict the behavior of downhole parameters and predict possible problems or necessary adjustments during the drilling process [15, 16].

Considering the available power and energy in the drill string during the impact of the bit teeth on the bottomhole, we will take into account the sensitivity of rocks to the rate of application of dynamic loads. In this case, the power $N_{in}(t)$ and the energy $W_{on}(t)$ are described by periodic functions [18].

Expressions of power and energy:

$$(1)\quad N_{In}(t) = N_0\begin{bmatrix}\frac{\pi^2}{3}+\sum_{n=1}^{\infty}(-1)^n\cdot\frac{2cosnz\omega_1 t}{n^2}+\\ +(-1)^n\frac{\psi\pi}{n}\cdot sinnz\omega, t\end{bmatrix}$$

$$(2)\quad W_{on}(t) = W_0\begin{bmatrix}-\frac{1}{3}\pi^3(\psi+1)+\\ +2\,\psi\pi\sum_{n=1}^{\infty}(-1)^n\frac{2cosnz\omega_1 t}{n^2}+\\ +\sum_{n=1}^{\infty}(-1)^n(\frac{2\pi^2}{3n}-\frac{4}{n^3}sinn\omega_1 tz\end{bmatrix}$$

$$N_0=-2\frac{EF}{\nu}\cdot A_1^2\cdot\frac{\omega_1^2}{z^2};;\ W_0=\frac{EF}{\nu}\cdot A_1^2\cdot\frac{\omega_1}{z^3};\ \ A_1=rcos\alpha$$

where $z\omega_1$ - is the cyclic frequency of tooth impacts; N_0 - instantaneous power of KBT; E - is the modulus of elasticity of the KBT material; W_o -constant; F - is the cross-sectional area of the CBT; v - is the propagation velocity of elastic waves of longitudinal deformation; α - the angle of inclination of the cone axis to the face plane.

Making some transformations in (2) we get

(3)

$$W_{on}(t)/_{x=0}=\frac{EF}{\nu}\cdot A_1^2\frac{\omega_2}{Z^3}\left[\frac{1}{3}\cdot\pi^3+\sum_{n=1}^{\infty}Aqsin(n\cdot z\cdot\omega_1 t+\varphi_n)\right]=$$

$$=W_0^1+\sum_{n=1}^{\infty}W_{1n}sin(n\cdot z\cdot\omega_1 t+\varphi_n)$$

$$Aq=\sqrt{(\frac{2\pi\psi}{n^2})^2\ +(\frac{3\pi^2}{3n}-\frac{4}{\pi^3})^2};\psi=\frac{|Q_o|}{|P_g|}$$

where Q_o - is the static axial load; P_g-dynamic force

$$\varphi_n=arctg\frac{6\psi\pi n}{2\pi^3n^2-12};$$

$$W_{In}=W_0\cdot Aq\cdot W_0^I\ =-W_0\cdot\frac{1}{3}\pi^3(\psi+1)$$

Denoting $M=\frac{W_{on}(t)}{\frac{EF}{\nu}A_1^2\frac{W_1}{Z^3}}$ from (3) we get the rarity of the breed. Series characterizing the relative energy of the bit

$$(4)\ M=-\frac{1}{3}\pi^3(\psi+1)+\sum_{T=1}^{\infty}(-1)^2\begin{bmatrix}\frac{2\psi\pi}{n^2}cosnz\omega_1 t+\\ +(\frac{2\pi^2}{3n}-\frac{4}{\pi}\ sinnz\omega_1 t\end{bmatrix}=$$

$$=-\frac{1}{3}\pi^2(\psi+1)+\sum_{n=1}^{\infty}Aqsin(n\cdot z\cdot\omega_1 t+\varphi_n)$$

The amplitude level Aq and, accordingly, the energy according to expression (1) depend more on ψ. For clarity, N was calculated using formula (3) for the number of teeth Z=65 with a change in the value of ψ from 0 to 500.

As the results of calculations for the series show, the sum of the first four harmonics for all values of ψ is an order of magnitude greater than the sum of the remaining terms of the series.

If the cyclic frequency of impacts of the teeth is denoted by m=ω_1z, then expression (4), taking into account A1 = rcos α, can be represented as follows:

$$(5)\quad W_{on}(t)=\frac{EF}{\nu}r^2cos^2\alpha\frac{m}{z^4}\begin{bmatrix}-\frac{\pi^3}{3}(\psi+1)+\\ +\sum_{n=1}^{\infty}Aqsin(nz\omega_1 t+\varphi_n)\end{bmatrix}$$

where $r=r_o+h_o$, ho is the initial height of the cutter teeth

As can be seen from formula (5), the cyclic frequency does not change due to the wear of the teeth of the cutter bit, the radius r changes and, accordingly, the area of the tooth rim.

The latter, in turn, affects the change in the dynamic impact of the tooth crown on the surface.

The change in the area of the end of the tooth crown can be determined according to Fig. 1 as follows.

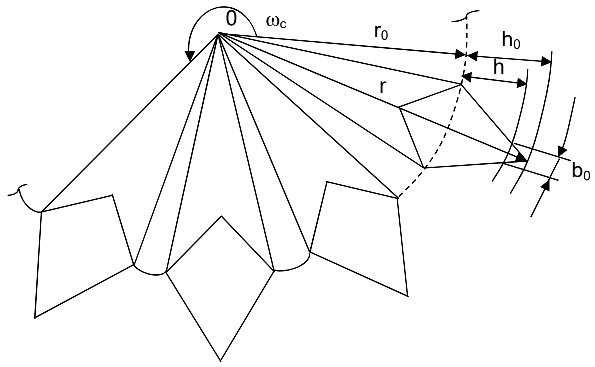

Fig. 1. The degree of wear of the teeth of the cutter bit

We accept the width of the teeth as they wear bo, and the radius of the crown after wear is r_o+h, where h is the current height of the teeth. Then, the area of the end of the cutter teeth will increase. With an increase in the area of the end of the cone teeth, the pressure force of the tooth rim increases when it meets the rock and, accordingly, the energy level of the acoustic signal changes due to a change in r.

Taking into account the above formulas and using approximate formulas, we obtain:

$$(6)\qquad W_{on}^Z(t)=K_1(t)\frac{m_o}{Z_o^4}(1+3\frac{\Delta Z}{Z_o})$$

Where : $m_o=\omega_1\cdot Z_o$, Z_o- number of cutter teeth at the start of bit operation

$$K(t)=\frac{EF}{\nu}\cdot\frac{m}{Z^4}\left[-\frac{\pi^3}{3}(\psi+1)+\sum_{N=1}^{\infty}Aqsin(n\cdot z\cdot\omega_1 t+\varphi_{n)}\right]$$

The resulting formula (6) makes it possible to determine the dependence of the bit vibration energy on the change in the number of teeth. As can be seen from expression (6), the amplitude of acoustic oscillations and the cyclic frequency of the cone change almost little relative to the nominal values, since it is assumed to be $\omega_1$constant. When the cone teeth wear, the dynamic force P_g can also change, which in the general case mainly depends on the length and weight of the CBT. With a constant magnitude of the weight Q_o, the dynamic force P_g decreases and ψ grows.

Wherein

$$\psi = \frac{|Q_o|}{|P_g|}\left(1 \pm \frac{\Delta P}{P_g}\right)$$

Therefore, the dependence of the energy on ΔP will be expressed as:

$$W_{on}^{p}(t) = K_2\left[-\frac{\pi^3}{3}\cdot\frac{|Q_o|}{|P_g|}\left(1 \pm \frac{\Delta P}{P_g}\right) + \sum_{n=1}^{\infty} Aq\sin(nz\cdot\omega_1 t + \varphi_n^I)\right]$$

$$K_2 = \frac{EF}{\nu}\cdot\frac{m}{Z^4}\cdot A_{1o}^2;\varphi_n^I = arctg\frac{6\pi n}{2\pi^3 n^2 - 12}\cdot\frac{|Q_o|}{|P_g|}\cdot\left(1 \pm \frac{\Delta P}{P_g}\right)$$

Result

Thus, the analysis of the rotary drilling process showed that the main downhole parameters to be monitored and diagnosed are the degree of wear and breakage of the bit cones.

It was revealed that the acoustic method for monitoring and diagnosing downhole parameters is the most reliable and does not require special costs for transmitting information from the bottomhole to the wellhead; for its application, a mathematical model has been developed that allows describing the processes of radiation and propagation of acoustic signals. The developed model describes the conditions for the occurrence of acoustic vibrations and the propagation of these signals during drilling. At the same time, their energy was chosen as the main quantity characterizing acoustic vibrations.

The process of propagation of acoustic signals along the drill string has been analyzed, the possibility of using the analogy between the parameters of acoustic and electrical oscillations to describe this process has been established.

Thus, the main functional dependencies were obtained for the acoustic energy of the bit, taking into account all downhole parameters. As can be seen from the formula, a change in r and **ψ** causes a change in the amplitude of acoustic oscillations, and Z in amplitude and frequency. In order to determine the state of the bit during drilling at the wellhead using an acoustic information signal, the amplitude and frequency of the acoustic signal should be measured.

Conclusions

Theoretical and practical results make it possible to significantly increase the efficiency of the drilling process due to the increase in the efficiency and reliability of monitoring and diagnosing wear and breakage of the bit cone teeth based on mathematical models of the radiation and propagation of acoustic vibrations emitted by the bit.

Based on the analogy between the processes of propagation of acoustic and electromagnetic oscillations, a theoretical chain model of the CBT signal transmission path was constructed, which makes it possible to determine the acoustic energy emitted by the rotary table depending on the state of the bit during drilling.

On the basis of a system of differential equations in partial derivatives for electrical circuits, a mathematical model has been developed for the transmission of acoustic vibrations of the bit through the CBT to the wellhead, at the same time, the energy of these vibrations depends on the state of the bit during drilling.

REFERENCES

[1]. Olawale, S.B., Longe, P.O. & Ofesi, S.F. Evaluating the effect of drill string rotation and change in drilling fluid viscosity on hole cleaning. J Petrol Explor Prod Technol 11, 2981–2989 (2021). https://doi.org/10.1007/s13202-021-01209-y

[2]. Kelessidis V.C., Maglione R., Tsamantaki C., Aspirtakis Y. Optimal determination of rheological parameters for Herschel–Bulkley drilling fluids and impact on pressure drop, velocity profiles and penetration rates during drilling. Journal of Petroleum Science and Engineering.Volume 53, Issues 3–4, September 2006, Pages 203-224. https://doi.org/10.1016/j.petrol.2006.06.004.

[3]. Liu N, Zhang D, Gao H, Hu Y, Duan L. Real-Time Measurement of Drilling Fluid Rheological Properties: A Review. Sensors (Basel). 2021 May 21;21(11):3592. doi: 10.3390/s21113592. PMID: 34064161; PMCID: PMC8196762.

[4]. Nayeem Ayesha, Venkatesan R., Faisal Khan. Monitoring of Down-hole Parameters for Early Kick Detection December 2015, Journal of Loss Prevention in the Process Industries 40. DOI:10.1016/j.jlp.2015.11.025.

[5]. Guo, P.; Zhang, Z.; Wang, X.; Yue, Z.; Zhang, M. A Novel Borehole Cataloguing Method Based on a Drilling Process Monitoring (DPM) System. Energies 2022, 15, 5832. https://doi.org/10.3390/en15165832

[6]. Saadeldin R, Gamal H, Elkatatny S. Detecting downhole vibrations through drilling horizontal sections: machine learning study. Sci Rep. 2023 Apr 17;13(1):6204. doi: 10.1038/s41598-023-33411-9. PMID: 37069188; PMCID: PMC10110595.

[7]. Wiederhold, H., Kallesøe, A.J., Kirsch, R. et al. Geophysical methods help to assess potential groundwater extraction sites. Grundwasser - Zeitschrift der Fachsektion Hydrogeologie 26, 367–378 (2021). https://doi.org/10.1007/s00767-021-00495-x

[8]. Tsai, C.-C.; Lin, C.-H. Review and Future Perspective of Geophysical Methods Applied in Nearshore Site Characterization. J. Mar. Sci. Eng. 2022, 10, 344. https://doi.org/10.3390/jmse10030344

[9]. LI Chuan-hui, LIU Xue-wei. The application of geophysical techniques in reducing the drilling risks induced by gas hydrates[J]. Progress in Geophysics, 2014, 29(1): 300-305. doi: 10.6038/pg20140142

[10]. Xiaoli Li a, S.K. Tso. Drill wear monitoring based on current signals. Wear, Volume 231, Issue 2, July 1999, Pages 172-178. https://doi.org/10.1016/S0043-1648(99)00130-1.

[11]. Mannan M.A., Broms S., Lindström Bo. Monitoring and Adaptive Control of Cutting Process by Means of Motor Power and Current Measurements. CIRP Annals. https://doi.org/10.1016/S0007-8506(07)62720-6 Volume 38, Issue 1, 1989, Pages 347-350

[12]. De Moura Fonsêca D. A., Salazar A. O., Villarreal E. R. L., Echaiz Espinoza G. A., and. Leite A. C. Q. B., "Downhole Telemetry Systems to Monitor Electric Submersible Pumps Parameters in Oil Well," in IEEE Access, vol. 9, pp. 12824-12839, 2021, doi: 10.1109/ACCESS.2020.3049116.

[13]. Krivoshchekov, S. N., Melekhin, A. A., Turbakov, M. S., Shcherbakov, A. A., and N. I. Krysin. "Development of a telemetric system for monitoring downhole parameters in the course of wells construction (Russian)." OIJ 2017 (2017): 86–88. doi: https://doi.org/10.24887/0028-2448-2017-9-86-88.

[14]. Hongtao Li, Jie Liang, Chengxiao Li, Gao Li, Yingfeng Meng, Peng Yang, Jinlong Liu, Liqun Xu. A novel method to improve mud pulse telemetry performance during gaseated underbalanced drilling. Journal of Petroleum Science and Engineering.Volume 213, June 2022, 110400., https://doi.org/10.1016/j.petrol.2022.110400.

[15]. Dairbayeva Gullazata1, Kabylzhan Ainur. Controlling the Parameters of Process of Drilling Wells Using Mathematical Modeling. Advances in Engineering Research (AER), volume 102.407. Second International Conference on Mechanics, Materials and Structural Engineering (ICMMSE 2017). DOI 10.2991/icmmse-17.2017.68.

[16]. A. Ahmad, M. Sulaiman, P. Kumam, M. A. Bakar and Miftahuddin, "Analysis of a Mathematical Model for Drilling System With Reverse Air Circulation by Using the ANN-BHCS Technique," in *IEEE Access*, vol. 9, pp. 119188-119218, 2021, doi: 10.1109/ACCESS.2021.3107405.

[17]. Аскеров Дж.С., Гамидов М.Г. «Исследование процесса передачи энергии акустических сигналов на устье скважин», Международный научный журнал «Синергия наук», №17(ноябрь), 2017, с.462-469.

[18]. A.A.Abouzed and G.A.Cooper «Experimental veritcation of a drilling cimulator ,paper presented at the 8th international Conference of Mining ,Petroleum and Metallurgial Engineering,Suez Canal University ,Egypt 17-19 March 2003