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Vibration Control in Optimized Drilling and Key Issues to Be Applied in New Clean Geo-Energy Exploitation

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Abstract. With the global economy and industry development, environment-friendly and sustainable development has become the mainstream of energy exploration and utilization. New clean geo-energy exploitation has become one crucial transformation attempt of the traditional petroleum industry. However, different from the traditional petroleum development, key problems of low efficiency and high risk, caused by complex geological environment and bottom-hole-assembly (BHA) vibration, are the main barriers of unconventional resources exploitation. In the present paper, a novel method of optimized drilling technology with intelligent vibration control (ODVC) is proposed based on technique surveys and a review of traditional methods. As a discussion result of technical features and key issues, ODVC could be a good alternative to contribute to the new clean geo-energy resources exploitation.

Keywords. Green-geo-energy exploitation, optimized drilling, vibration regulation, intelligent control

1. Introduction

Economical, efficient, environmentally friendly energy exploitation and utilization is always a mainstream of public opinion and an inevitable trend of global energy structure transformation. However, according to the statistics, the energy demand of most countries experienced a sharp increase in the recent decade from 505.38 exajoules (2010) to 557.10 exajoules (2020) [1]. The huge gap in energy demand could hardly be covered by clean energy. On the other hand, as crucial chemical materials and strategic supplies, hydro-carbonaceous resources are vital to civilization development and national security. Therefore, even the transformation trend of international energy structure from traditional energy to clean and renewable energy is inevitable, traditional geo-energy is still the main component of energy consumption and will retain the key position for a long time to ensure social development and industrial progress [1, 2].

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In the meanwhile, the fossil energy industry is also looking for environmentally friendly and sustainable alternatives to traditional fossil fuels. The exploitation of new clean geo-energy, such as geothermal, shale resources, and combustible ice (natural gas hydrate, NGH), is one of the crucial transformation attempts. However, different from the traditional resource, low drillability and high friction resistance are two crucial issues to geothermal (hot dry rock), shale gas, and NGH resources development. The exploitation of these unconventional resources is facing challenges of efficiency, benefit, safety, and quality caused by the complex geological environment and BHA vibration. Increasing drilling efficiency and reducing vibration damage are the key requirements of new clean geo-energy resources exploitation.

Optimized drilling is an interdisciplinary systematic technology that integrates operation technology, oilfield chemistry, instruments and equipment, organization and planning, etc. Improving drilling efficiency, protecting resource reservoirs, and optimizing operation parameters are the main method of optimized drilling. In recent years, the applications of downhole impactors and absorbers had shown a good effect on increasing drilling efficiency and reducing vibration damage [3-9].

According to technical surveys, with the development of MEMS and auto-control technology, the current downhole instruments are tending to miniaturization design, implantable installation, and distributed measurement. And the downhole vibration control technology shows a trend to auto-control and adaptive adjustment of sensitive equipment. Considering the development and application scenarios of artificial intelligence technology, intelligent vibration control (based on miniaturized vibration sensor, axial & torsional impactor, and active absorber) will be the essential technology for the new clean geo-energy resource exploitation.

2. Drilling Vibration

2.1. Form and Characteristic

Torsional, axial, and lateral vibration are the three typical forms of drill string vibration (Figure 1), which are generally appeared as BHA bounce, slip/stick, whirl, and shock [10]. BHA bounce is caused by axial vibration, and is influenced by surface operation parameters and interaction force between bit and formation. It usually appears with a frequency of 1-20 Hz and amplitude of 0-100 g [11, 12]. Affected by friction between BHA and formation, the input energy of rotary table or top drive experiences a cycle from accumulation as strain to release as motion. It leads to the BHA slip/stick with a frequency of 0.1-5 Hz and an amplitude of 0-10 g [10]. Drilling string is easily bending and buckling in the well under the axial and lateral forces. So that the whirl and lateral shock are always associated appeared during the process of rotary drilling. The frequency and amplitude of whirl and lateral shock are usually in the range of 5-800 hz and 0-200 g respectively [13], which are extremely destructive to the downhole equipment.

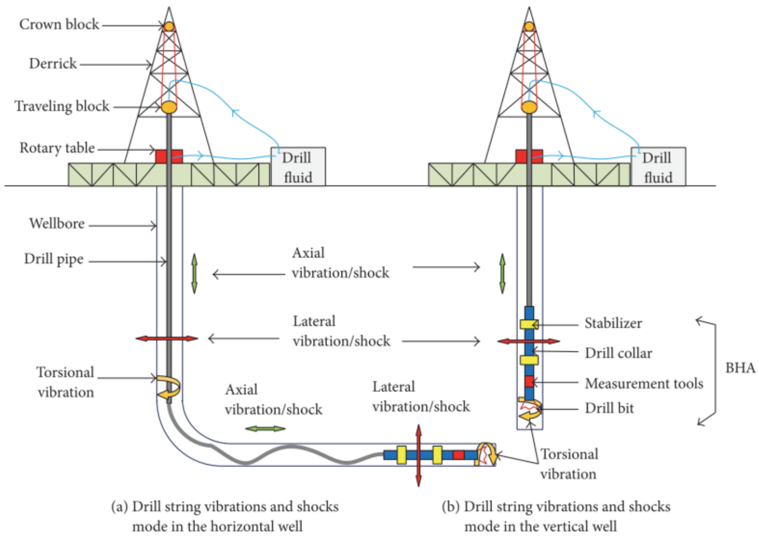

Figure 1. Typical V&S forms of BHA.

2.2. Vibration Evaluation

Studies of BHA vibration evaluation were carried out since the 1960s [14-16] to reveal the mechanism of string vibration and optimize the operation performance. A series of vibration models had been established [17-19]. Heterogeneity of formation properties and BHA strain/stress distribution leads to the coupling of vibration [20, 21]. The non-determinacy of contact position between BHA and well wall, the randomness of interaction between bit and formation, and the instability of operation parameters enhance the complexity of downhole vibration [22]. Therefore, the current models established on simplification and assumption can hardly reflect the downhole reality [23]. Downhole measurement is the most effective evaluation method of drilling vibration.

3. Traditional Vibration Control

Alternating loading, which is caused by drilling vibration, aggravates the fatigue damage of BHA and the wear of drilling bit. It is the primary cause of low-efficiency drilling in unconventional resources development [24]. Interestingly, as a result of recent vibration modeling and experimental studies, the positive impacts of vibration on efficient rock breaking, friction reduction of horizontal laterals, and stick/slip inhibition are also revealed [25]. It becomes a great challenge for researchers to coordinate the relationship between the positive and negative impacts on drilling efficiency.

3.1. Vibration Optimization

Generally, there is a strong correlation among the dynamic vibration response, operation parameters, formation characteristics, and BHA structure. And it always appeared as an enclosed optimal region [26] in the WOB and Rotate speed coordinate system as shown in Figure 2. Therefore, seeking optimal parameter boundary with specified BHA structure via vibration simulation and downhole data-analysis, are the early methods for drilling vibration optimization.

However, relevant studies indicated that resonance is a non-negligible component of drilling vibration, and the main frequency is variable due to the interaction effect of the bit-formation-drilling system [13]. Thus, different plates of different regions, formations, and BHA structures are required in the previous method. It is not maneuverable for wide applications. Therefore, BHA structure optimizing and vibration control equipment developing on the basis of model theories and mode decomposition, are more effective.

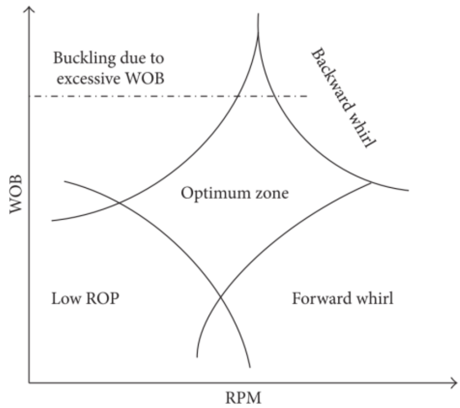

Figure 2. Enclosed optimal region.

3.2. Vibration Absorbing

Downhole absorber is an effective equipment to increase the efficiency of rock breaking and decrease the vibration damage of BHA by balancing the dynamic energy distribution. During the drilling operations, PDC cutters fed into formation and cut rocks under the axial and torsional force. Affected by the bit structure and anisotropy of formation properties, the working condition of bit is a cyclic process of torsion-static-torsion. Alternation of energy storage and release leads to the violent bounce and slip/stick of bit, and then causes the whirl of BHA. Therefore, absorbing the bit vibration directly is a feasible way to reduce the BHA vibration, increase rock breaking efficiency, and provide a higher allowance of WOB and rotate speed. Based on the structure of the traditional absorber joint, micro-absorber integrated into PDC bit is one of the new trends of absorber development.

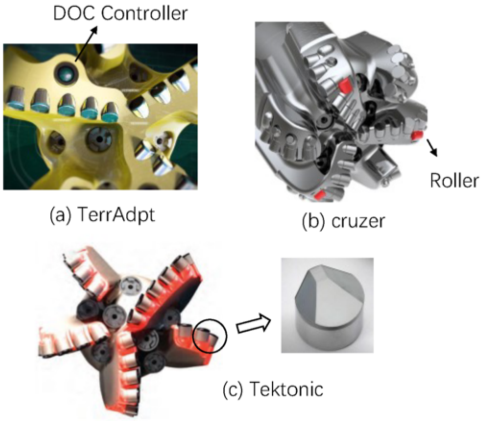

Figure 3. Adaptive damping bit.

TerrAdapt is a typical adaptive damping bit as shown in Figure 3a. With hydromechanical elastic elements, the level of bounce and slip/stick is reduced by absorbing the axial vibrations and controlling the depth of cut (DOC) adaptively. As a result of field applications, the rate of penetration (ROP) increased up to 63% [27]. Cruzer and Tektonic is another type of adaptive damping bit (Figures 3b and 3c). With special rollers or 3D structure cutters, it could decrease the vibration level by reducing the friction between cutters and formation. The availabilities of those bits are also indicated by field applications [28].

3.3. Vibration Enhancement

"Vibration is negative" used to be a law in drilling operations. However, with the development of vibration modeling and experimental studies, researchers gradually realize the positive impacts of vibration on efficient rock breaking, friction reduction of horizontal laterals, and stick/slip inhibition. Hydraulic hammer, hydraulic pulse and self-oscillation are the typical methods to generate axial and torsional shock.

Figure 4 shows a typical structure of downhole impactor [29] with hydraulic hammer. During the drilling operations, fluid is distributed into the front and rear chambers of the piston by valve plate to drive the reciprocating motion of hammer. According to recent researches, vibration with high frequency and low amplitude presents a more efficient performance on rock breaking. Therefore, controllable impactors with solenoid directional valves are proposed in recent years.

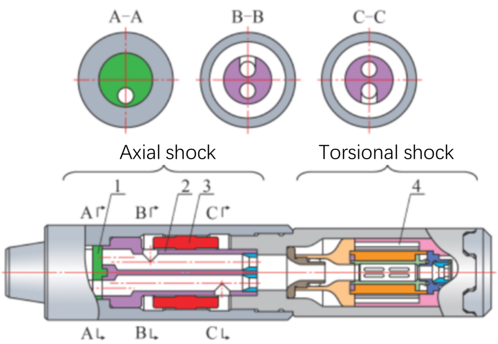

Figure 4. Axial-torsional coupling impactor.

4. Novel Vibration Control

4.1. Overview

Obviously, the previous methods and equipment belong to the kinds of passive and semi-active control. However, affected by the heterogeneity of formation properties, non-determinacy of contact position between BHA and well wall, the randomness of interaction between bit and formation, and the instability of operation parameters, the actual downhole vibration is nonlinear and presents the characteristics of multi-degree of freedom and multi-frequency. The current passive and semi-active methods cannot meet the variational requirements of different vibration characteristics in new clean geo-energy resources exploitation.

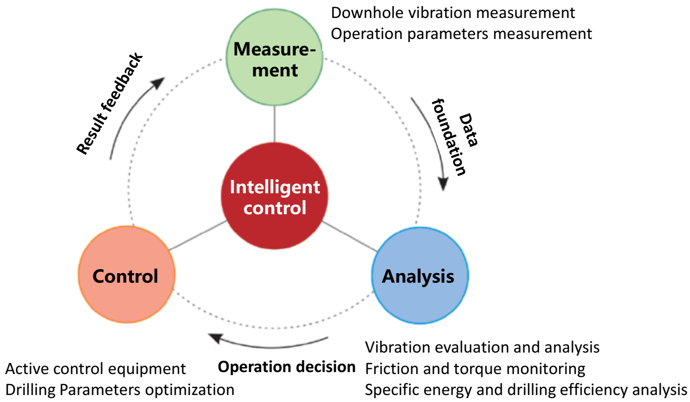

Figure 5. Schematic diagram of ODVC.

According to the status and developing trend of downhole vibration control, MEMS, auto-control and AI technologies, a novel method of ODVC is proposed based on the actual exploration requirement (Figure 5): Measuring high-frequency data along the drilling string; digging potential relationship among the vibration response, formation features, operation parameters, specific energy and ROP; Analyzing and providing decisions for downhole vibration control and surface parameter optimization; controlling with evaluation and feedback via downhole measurement.

4.2. Key Issues

4.2.1. Distributed Measuring Equipment

Reliable data acquisition is the foundation of subsequent analysis, controlling, and optimization [13]. Affected by the structural and mechanical properties, the dynamic vibration response shows different features along the drilling string (Figure 6) [30]. However, due to the directional drilling requirements, traditional measuring tools could only be installed at the upstream of screw motor, which means the measured data cannot represent the real working condition of BHA, especially the condition of drilling bit. The development of distributed downhole measuring tools is the first key issue of ODVC.

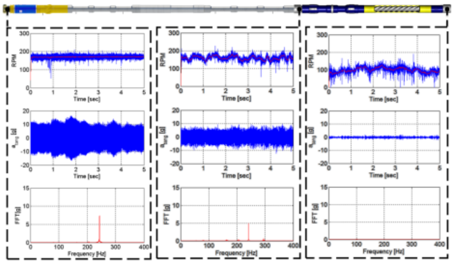

Figure 6. Different features along the drilling string.

Figure 7. Measuring modules installed in bits.

Therefore, a series of miniaturized measuring devices were designed as shown in Figure 7. Different from the normal downhole measuring equipment, the miniaturized modules could be installed in the joint of drilling string (including the bit) without any changes to the current drilling system and operation process. So that, it is a feasible solution for the distributed measurement. As the standard parameters specification of international commercial products and the prototype of our previous work, the modules were generally designed with a sampling rate of 0-1k Hz, measuring ranges of ±40 g for vibration and ±200 g for shock.

4.2.2. Smart Materials and Structure System

Active control is the key of ODVC. Based on the phenomena of magneto-rheology (MR) or electrorheology (ER), smart materials [31] (Figure 8) could perceive external stimuli and respond according to their physical properties. With the unique advantages (low power consumption, lightweight system, high reliability, and fast response), MR dampers have been widely adopted in different fields of vibration control, especially the senior vehicle's suspension system and vibration isolation of building structures. MR damping mechanism is a feasible solution for the intelligent control of downhole vibration (Physical bandpass filter of positive/negative vibration).

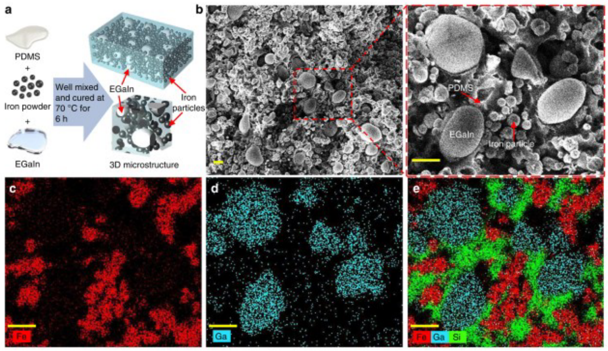

Figure 8. Composition of MR material.

4.2.3. Closed-Loop Decision Making

For the various scenarios and requirements of applications, different control strategies are necessary for the MR damper. Fuzzy logic control is an intelligent control method based on fuzzy set theory, fuzzy language variables, and fuzzy logic reasoning. It is proposed by Zadeh in 1965, applied in the automobile industry in 1985, and is now widely used in the field of vibration control [32].

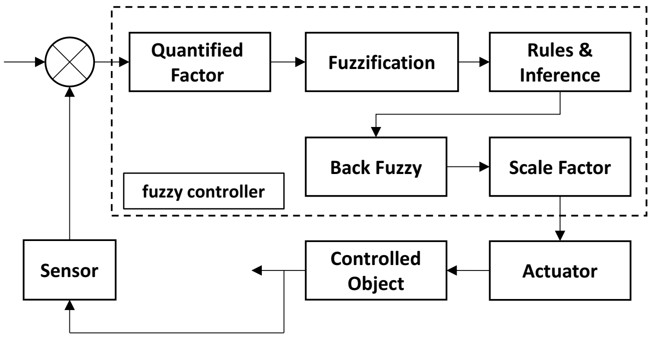

Figure 9. Schematic diagram of fuzzy logic control.

Figure 9 shows a typical schematic diagram of fuzzy logic control: target value and sensor error are fuzzified as fuzzy language by using quantified factor; controlled quantity is proposed by fuzzy rules and inference, and then be back fuzzified to quantified value; parameters of the actuator and controlled object are measured by senor and feedback to the controller.

4.2.4. Parameters Optimization of Drilling Operation

Drilling operation is a complex project which affected by multi-factors and cooperated with multi-systems. Normally, the target and decision strategies of each sub-system are coupled with a complex relationship of conflict, competition, and concession.

In our recent research, a scoring function (Equation 1) was proposed based on quantitative analysis of specific energy, bottom hole cleaning condition, drilling vibration. The intermediate parameters (torque, ROP, pressure loss, etc.) are calculated by general models and neural networks.

$$S = S_v \cdot S_E = h\left(H, N, Q, R, \rho, T, \ldots\right) \tag{1}$$

Therefore, treating design schemes as points in Cartesian coordinates system with three axes of WOB, flow rate and rotate speed. And then the problem of parameters optimization could be transformed into seeking extreme value in the space curve face. Particle swarm optimization algorithm (equation (2)) could be a feasible solution to obtain the optimized parameters.

$$\begin{cases} v_{id}^{k} = w \cdot v_{id}^{k-1} + \delta_1 \cdot r_1 \cdot \left(p_{id} - x_{id}^{k-1}\right) + \delta_2 \cdot r_2 \cdot \left(p_{gd} - x_{id}^{k-1}\right) \\ x^{k} = x_{id}^{k-1} + v_{id}^{k-1} \end{cases} \tag{2}$$

5. Conclusion

Transformation trend of international energy structure from traditional energy to clean and renewable energy is inevitable. The exploitation of new clean geo-energy is one active attempt on seeking environmentally friendly and sustainable alternatives to traditional fossil fuels. Different from the traditional resource, low drillability and high friction resistance of geothermal (hot dry rock), shale gas/oil, and NGH resources, lead to a series of challenges on efficiency, benefit, safety, and quality. Increasing drilling efficiency and reducing vibration damage are the key requirements of those new clean geo-energy resources exploitation.

However, as the result of worldwide studies, the downhole vibrations are playing positive and negative roles simultaneously during the drilling operation. The current methods of downhole vibration control cannot coordinate the relationship between the two types of impacts on drilling efficiency. New active vibration control methods and equipment are urgently needed.

Therefore, a novel solution of optimized drilling with intelligent active vibration control was discussed in the present paper. Based on a technology survey and our previous studies, miniaturized measuring devices, MR fluid, fuzzy logic control, and PSO algorithm were proposed for the four main issues of distributed measurement, active controlling technology, close-loop decision making, and surface parameters optimization. It could be a feasible alternative for the efficient exploitation of new clean geo-energy resources.

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