Design and mechanical analysis of a new automatic vertical drilling tool used in a slim borehole

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Abstract. A new kind of electronic-controlled automatic vertical drilling tool is developed to satisfy the requirements of slim-hole, which has a unique push-actuator to push-the-bit. This paper introduced the mechanical structure and working process of the automatic tool, and analyzed in detail one of the most critical component - the push-actuator. The analysis reveals that, with the pitch-row of studdles increasing form 20mm to 24mm, the ratio of push-out force to forward force gradually decreases from 2.04 to 0.78, and the completion time of push-out process reduces from 75.8s to 42.8. This result indicates that, using studdles with shorter pitch-rows, larger straightening force could be obtained. On the contrary, studdles with longer pitch-rows could realize more quickly sensitive response of deviation control. These unique characters make the vertical drilling being able to be adapted to different geological conditions and technological requirements, the applicability and feasibility of the drilling tool remarkably improved. Thus this vertical drilling tool owns a great promotional value for oil & gas exploration.

1. Introduction
Facing to the reality that the exploitation of traditional oil & gas is going to the end and the development of unconventional oil & gas is forwarding to more complex geological conditions, the challenge of drilling engineering is becoming more and more arduous, advanced technology and equipment is pressing needed by the requirements of modern drilling engineering. Under such a background, owning to majority of new oil & gas wells are drilled in the blocks with high-dip formations, conventional packed hole assembly and pendulum drill assembly could not meet the technological requirements of modern vertical drilling engineering, the primary problem nowadays is how to increasing penetration rate while preventing deviation. Deviation control has always been one of the hardest technical difficulties in oil & gas drilling, until the end of 21 century, the barrier of passive borehole deviation mechanism and control method had broken through by automatic vertical drilling technic [1, 2], which is originated from Germany’s superdeep drilling program (KTB) [3, 4] and can obtain the maximum WOB (weight on bit) & ROP (rate of penetration) [5, 6]. Nowadays, automatic vertical drilling technic has been widely used in drilling deep & super-deep wells and complex-structure wells, making a great contribute to solve the problem of preventing deviation in high dipping blocks [7, 8].
For the past few decades, owning to low cost and high efficiency, slim-hole drilling has been rapidly developed and shown great economic benefit [9], especially for oil prices depressed today. Though more than 10 kinds of automatic vertical drilling tools, such as Power V by Schlumberger [10], Verti Trak by Baker Hughes [11] and SL-AVDS by Sinopec [12], have been developed and obtained successful commercial application at present, these vertical drilling tools always owning a relative larger diameter, which could not be satisfied for slim hole drilling. Therefore, a new automatic vertical drilling tool specifically used in slim borehole needs to be urgently designed.

For this purpose, a new kind of automatic vertical drilling tool with electronic closed loop control system is designed by China University of Geosciences. Considering the drilling requirements of maximizing weight on bit (WOB) and rate of penetrate (ROP), push-the-bit model is selected for the vertical drilling tool because it is unconstrained by rotating speed. To service in a slim borehole, a unique push-actuator machinery using linkage mechanism is designed to minimize the radial dimension. In this paper, the mechanical structure and the deviation control progress of the new vertical drilling tool are introduced, furthermore, as the most critical component directly influences the deviation correction performance, the mechanical characteristic of the unique push-actuator are analyzed in detail.

2. Overall design

2.1. Mechanical structure

Figure 1 is the structural schematic of automatic vertical drilling tool. The device has two joints, respectively connect to drill bit and drill pipe, and there is an inner drill pipe mounting between the joints to deliver pressure and torque. These three parts are rotating together with upper drill pipes, to ensure the work part of the drill tool can maintain relative static. There are two bearing units connect push-pad base and bearing connector with inner drill pipe. On push-pad base, there are three push-actuators circumferential distribute uniformly with 120°, mainly include wearing plate, push pad, two studdles, tackle and connecting rod, which constitute link mechanism by pin rolls, and each of push-actuator connects with its independent electronic control section. In one push-actuator, prevented by restrict screws, the tackle can only move along the groove of push-pad base with its eight wheels from beginning to end, and the spring is compacted by the tackle along spring axle. Between push-pad base and bearing connector, an annular space is separated by inner sleeve and outer sleeve, which is a sealing workspace of the drill tool and fulfilled with insulating oil. In consideration of oil leakage, a compensating mechanism is introduced in with a piston to keep oil pressure, the piston can be pressed

![Figure 1. Structural schematic of automatic vertical drilling tool and its push-actuator.](image-url)
By drilling fluid from the through-hole to annulus in bearing connector. In the annular space, there are transmission shaft, flange, displacement sensor, electromotor, chip section and battery. In chip section, there are gyroscopic sensors, gravity accelerometers and single chip microcomputers (SCM), these parts constitute the electric control section of the drilling tool. The transmission shaft is connected with the electromotor and flange respectively by lead screw and flat key, holding the transmission shaft can only move along axial but not rotation. To avoid the damage by unexpected sudden reactive force from borehole wall, a gas spring is mounted between each connecting rod and transmission shaft as a buffer part. Through these optimal structural design, traditional push-pistons are deprecated, thus the outside diameter is minimized to 145mm to satisfy the requirements of oil & gas slim-hole vertical drilling.

2.2. Working process

The deviation control of this vertical drilling tool is shown in figure 2. When well deviation occurs, the gyroscopic sensors and gravity accelerometers in electronic control section can measure the inclination and give the signal to SCM, by analysis inclination signals, the SCM actuates electromotor run clockwise, driving the transmission shaft move forward to push the gas spring and connecting rod, while displacement sensor is concomitantly moving. The connecting rod push the tackle sliding on the groove platform of push-pad base and compress the spring, while the studdles move upward and pushing the push-pad out, until the wearing pad touches the upper side of borehole wall. Under the reactive force form the borehole wall, the rock cutting of drill bit on the low side of hole-bottom is intensified, the well path gradually return to vertical. After the inclination restoring in expectation range, the electric control section command the electromotor rotates reversely, together with the back force from compressed spring, the push-pad goes back into the base groove to initial non-operating state, then execution of push-the-pit is completed once and the vertical drilling tool turn to prepare for next deviation decreasing time. During this process, the displacement sensor can continuously supervise the motion of transmission shaft, delivering the signal to SCM to control the electromotor run or stop. The spring axle not only can relieve the spring radial run-out, but also work as a mechanical position limitation part to avoid the tackle sliding out of its stroke.

![Figure 2. Deviation control flow chart of automatic vertical drilling tool.](image)

3. Mechanical analysis of push-actuator

3.1. Simplified two-dimensional calculation model

As the most critical part under stress, the reliability and performance of the push-actuator directly determine the deviation control behavior of the vertical drilling tool. In order to analyze the approximate
characteristics, the push-actuator are simplified as a two-dimensional calculation model, which is shown in figure 3 and 4 respectively represents the initial non-operating state and the maximum pushing state during its working process. On the initial state, the push-pad is closed in the groove of the push-pad base. When the deviation occurs, the electric motor rotates under the instruction of SCM and give a forward force $F_0$ to connecting rod and tackle, pushing the tackle sliding forward on the groove plat of push-pad base. In the meantime, because of the structure of link mechanism, the studdle moves forward while rotating $\theta$ degree and pushing the push-pad rising $\alpha$ degree. At this point, the push-pad gives a push-out force $F_p$ to the high side of borehole wall and the drilling tool has moved to the low side of the borehole, the maximum stroke of the push-pad is $\Delta d$ (the difference between the diameter of the borehole and drilling tool outside diameter).

According to lever principle and moment equilibrium, the geometrical and mechanical relationship of the push-actuator are as follow:

\[
\sin \alpha = \frac{\Delta d}{l_3 + l_4} \quad (1)
\]

\[
\sin \theta = \frac{l_2 \Delta d + (l_3 + l_4)l_1}{(l_3 + l_4)l_2} \quad (2)
\]

\[
K = \frac{F_p}{F_0} = \frac{l_2 \sin(\theta - \alpha)}{(l_3 + l_4)\cos \alpha \cos \theta} \quad (3)
\]

Where $l_1$ is the distance between the connecting rod and push-pad on initial state, $l_2$ is the pitch-row of studdle, $l_3$ and $l_4$ respectively represent the distance from the pin hole to the front-end and rear-end. The angles $\alpha$ and $\theta$ are shown in figure 4, and $K$ is the ratio of push-out force to forward force. For this drilling tool, the parameters of $l_1$, $l_2$ and $l_4$ are respectively 15mm, 150mm and 100mm, the external diameter is 145mm to match a 152mm PDC drill bit, thus the maximum $\Delta d$ is 7mm. By using different studdles with various pitch-row, different pushing force $F_p$ can be attained, the value of ratio $K$ can be calculated according to formula (1)-(3).

3.2. Mechanical analysis of push-out process

Due to the linkage design of this unique push-actuator, the push force can be adjusted by selecting different studdles with various pitch-row for different geological conditions and technological requirements, which remarkably improves the applicability of this automatic vertical drilling tool. In order to fabricate conveniently and avoid self-locking phenomenon, the pitch-row of studdle $l_2$ are selected from 20mm to 24mm on integer numbers. Figure 5 shows the relation curves between the values of ratio $K$ and push-out distances using different studdles. As can be seen from the relation curve, the value of $K$ increases effectively with the increasing of push-out distance. And the larger the push-out displacement, the faster the growth rate of $K$ increases. As the increasing of the studdle pitch-row $l_2$, the value of $K$ reduces obviously. At the maximum push-out state ($\Delta d$=7mm), with the pitch-row
increases from 24mm to 20mm, the value of $K$ drops from 2.04 to 0.78, which decreases 61.8%. When the push-actuator using studdles with 22mm pitch-row, the $K$ value is 1.06 and the push-out force $F_p$ is nearly equal with the forward force $F_0$. So with the studdle pitch-row longer than 22mm, the push force can be reduced by the linkage mechanism, on the contrary, the push force can be enlarged if the pitch-row shorter than 22mm. Thus the feasibility of vertical drilling tool was effectively improved by this unique character of the push-actuator, the studdle can be easily exchange by actual working conditions. If the drilling formation is soft, studdles with relative longer pitch-row could be selected to reduce sticking, on the contrary, if the formation is hard, a shorter pitch-row could be chosen to gain larger straightening force.

![Figure 5. Relation curves between the values of ratio $K$ and push-out distances.](image)

The phenomenon mentioned above is due to the linkage mechanism design of push-actuator, during the push-out process, the angle $\theta$ of studdle gradually growth and the push-out force changed. Table 1 shows the angle variations during push-out process using different studdle pitch-row, with the studdle pitch-row increasing from 20mm to 24mm, the start angle $\theta_S$ ($\Delta d=0$mm) and end angle $\theta_E$ ($\Delta d=7$mm) both decreasing fast, respectively from 48.59° and 73.74° drop to 38.68° and 53.13°, and the angle stroke of studdle decreasing from 25.15° to 14.45°, reducing more than 42.5%. According to trigonometric function system of the linkage mechanical analysis, the larger the end angle, the larger the $K$ value, thus a larger push-out force can be obtained. When the end angle $\theta_E$ increases to 60°, the push-out force $F_p$ is equal with the forward force $F_0$, therefore studdles with a pitch-row shorter than 22mm are selected, the push-out force $F_p$ could be enlarged.

**Table 1.** Angle variations of push-out process using different studdle pitch-row.

| Pitch-row of studdle $l_2$ (mm) | Start angle $\theta_S$ ($^\circ$) | End angle $\theta_E$ ($^\circ$) | Angle stroke $\theta_S-\theta_E$ ($^\circ$) |
|---------------------------------|----------------------------------|----------------------------------|---------------------------------|
| 20                              | 48.59                            | 73.74                            | 25.15                           |
| 21                              | 45.58                            | 66.10                            | 20.52                           |
| 22                              | 42.99                            | 60.78                            | 17.79                           |
| 23                              | 40.71                            | 56.59                            | 15.88                           |
| 24                              | 38.68                            | 53.13                            | 14.45                           |
In order to analysis the process of push-out behavior, as the time goes on, the changing of push-out distance and push-out force are shown in figure 6. Under a constant rotate speed of electromotor, the connecting rod and the tackle can move along the axial direction with an invariable velocity, which is set as 0.1mm/s. With the studdle pitch-row increasing from 20mm to 24mm, the push-out velocity decreasing obviously, and the completion times using different studdles are respectively 75.8s, 61.4s, 53s, 47.2s and 42.8s, the completion time reducing 43.5% between the pitch-row of 20mm and 24mm. Because of the exist of angle $\theta$, the push-out velocity gradually drops along with the push-out process carry through, thus the longer the studdle pitch-row, the faster the push-out velocity. This means if a quick response of deviation control is needed, a relative longer studdle pitch-row should be chosen.

Figure 6. Relation curves between velocity coefficients and push-out distances.

4. Conclusion
As a new kind of electronic-controlled automatic vertical drilling tool, the outside diameter is shrunken effectively by optimal structural design for slim borehole drilling. In order to obtaining better performance and reliability, each push-actuator are controlled by its independent electronic control system, and hard links of the drive system are ameliorate by buffer spring. Besides, the applicability and feasibility of this drilling tool are remarkably improved by its optimal designed push-actuator with link mechanism, which can be able to adjust to different geological conditions and technological requirements. Based on the mechanical analysis using different studdles with five pitch-rows from 20mm to 24mm, due to the exist of $\theta$, with the pitch-row increases, the ratio of push-out force to forward force gradually decreases from 2.04 to 0.78 and the completion time of push-out process reduces from 75.8s to 42.8s. These unique characters makes the vertical drilling can be feasibly adapted to actual working conditions, studdles with relatively shorter pitch-rows can be chosen to gain larger straightening force, by which a larger WOB and ROP can be exerted in hard formations, on the contrary, studdles with relatively longer pitch-rows are suitable for soft formations and obtained more quickly sensitive response of deviation control. As a results, this electronic-controlled automatic vertical drilling tool owning a great promotional value for oil & gas exploitation.

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