Development of an adjustable stabilizer for controlling the borehole trajectory

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Abstract

During the drilling process, many types of bottom-hole assembly are used to adjust the well inclination and azimuth. For the drilling of inclined wells or horizontal wells, it has to face problems of repeated round trips so as to control the borehole trajectory. Such problems lead to the increase in non-productive time and the drilling cost. In order to address this issue, the idea of generating different types of bottom-hole assembly without round trips of drill-string was formed. In this paper, an adjustable stabilizer has been developed to avoid repeated round trips of the drill-string. Firstly, the mechanism of adjustable stabilizer controlling the borehole trajectory is presented. Secondly, the structure and operating principle of the adjustable stabilizer are described. Thirdly, numerical verifications of the key components of the adjustable stabilizer are conducted. Finally, laboratory tests and field tests are carried out to examine the design. Results of the numerical simulations and the laboratory and field tests show that the adjustable stabilizer operates normally and three phases of the radial pistons can be reached through regulating the flow of the drilling fluid. In addition, the pressure differences for starting the phases are measured.

Keywords: Adjustable stabilizer, Bottom-hole assembly, Borehole trajectory, Drilling fluid, Extension

1. Introduction

During the exploration and exploitation of oil and gas, rotary drilling systems are used to drill wellbores for the purpose of reaching a target subterranean destination (Albdiry & Almensory, 2016). As the wellbores are drilled in three dimensional spaces, two parameters are used to describe the borehole trajectory, i.e., inclination and azimuth (Atashnezhad et al., 2014; Wang & Gao, 2016). During the drilling process, unintended deflections which may lead to deviation from the objective usually arise, putting forward the need of controlling the wellbore direction either to adjust a planned direction change or to compensate for the unwanted wellbore deflection. Particularly, when drilling a directional well, many sections are drilled with different types of bottom-hole assembly (BHA), packed BHA and pendulum BHA for example (Akgun, 2004; Bailey & Remmert, 2010; Panayirci et al., 2015). In order to develop different types of BHA so that the deflection angle of the wellbore can be controlled and a part of the vibration can be reduced, stabilizers which are usually undersized in comparison to the drill bit are used (Mahyari et al., 2010; Richard et al., 2016; Yigit & Christoforou, 2006). For different types of BHA, the location and number of stabilizers vary.

In conventional drilling applications, when the wellbore section has reached the required angle, the whole drill-string should be tripped out of the wellbore so as to remove or add a stabilizer from or to the drill-string (Gills et al., 2000). Since the stabilizer is used to support and centralize the drill bit, one BHA can be replaced with a second BHA in this way. Obviously, tripping the drill-string in and out of the wellbore is extremely costly and time consuming and will lead to additional drilling cost and nonproductive time (Radford et al., 2009; Evans et al., 2010; Lirette et al., 2013). With the development of drilling industry, deep wells (≥3000 m) and ultra-deep wells (≥6000 m) become increasingly common. Among these deep or ultra-deep wells, directional sections (for example build section) are included. This causes substantial increases in time and cost to trip the drill-string in or out of the wellbore.
In the drilling industry, the efficiency of the drilling application has become a primary factor for controlling the overall costs of oil and gas development (Abdalla et al., 2013). Since the round trip is time consuming and expensive, attempts should be made to address this problem. Based on this background, the concept of an adjustable stabilizer was proposed (Gills et al., 2000; Greener et al., 1998; Liu & Su, 2000; Lawrence et al., 2001). For an adjustable stabilizer, it can be retracted to an undergauge position when drilling the build section and be extended to a full gauge position when drilling the tangent section. The use of an adjustable stabilizer eliminates the need to trip the drill-string out and replaces the BHA when the build section or tangent section is completed. As a result, round trips can be saved with substantial savings in the drilling time and cost, as well as improvement on the well geometry (McCormick et al., 2011; Osmundsen et al., 2010).

For the present techniques, extension and retraction of the radial pistons are implemented by rotating the drill-string or regulating the axial weight on bit (WOB). In 2000, a new type of adjustable stabilizer powered by the drilling fluid was developed by the Halliburton Energy Services, Inc., however, there are only two phases (referred to as neutral phase and extension phase) for each adjustable stabilizer and the two phases corresponds to the pendulum BHA and packed BHA, respectively. In the recent drilling applications of Fuling Shale Gas Field in China, a “half-packed BHA” or “under-packed BHA” is anticipated to be generated so as to accurately control the borehole trajectory. However, the present techniques cannot meet this requirement (Gills et al., 2000; Wisenbaker et al. 1998; Radford et al., 2009).

Based on the structure of the Halliburton Energy Services, Inc. (Gills et al., 2000), in this research, an adjustable stabilizer with three phases (referred to as neutral phase, half-extension phase, and full extension phase) so that pendulum BHA, “under-packed BHA”, and packed BHA can be generated is developed and verified by field tests. For each phase, it can be identified through reading the value of pressure gage on the surface. Though the structures of many components in this stabilizer are similar to the existing technique (such as the ramp actuator, radial piston, barrel cam, et al.), there are still many improvements when looked into more detailed. This paper first introduces the mechanism of the adjustable stabilizer controlling the borehole trajectory. The next section discusses the configuration and operating principle of the adjustable stabilizer. The following section presents the verification of the key components using the finite element method. The last section reports the laboratory and field tests of the adjustable stabilizer.

2. Mechanism of adjustable stabilizer controlling the borehole trajectory

There are many factors that influence the inclination and azimuth of a wellbore, such as the BHA type and the penetration rate of drilling (Li et al., 2009; Liu & Samuel, 2008). Among these, the lateral force on the drill bit is the most critical influence factor. The lateral force acted on the drill bit determines the bit rotation angle, and further controls the wellbore inclination. For a drill-string, the lateral force and rotation angle of the bit vary when the BHA type changes. Since the adjustable stabilizer is used to change the BHA type without round trips of drill-string, the wellbore trajectory can be controlled. In this part, the lateral force and rotation angle of the bit for two typical BHAs are discussed to show the mechanism of adjustable stabilizer, based on engineering mechanics. For the case shown in Fig. 1(a), the lateral force $F_t$ and the rotation angle $\theta_B$ of the drill bit follows,

$$F_t = \frac{F_te_i}{L_t} - \frac{M_t}{L_t} - \frac{q_tL_t}{2}$$  \hspace{1cm} (1)

$$\theta_B = \frac{q_tL_t}{24EI_t} X_t + \frac{M_tL_t}{6EI_t} Z_t + \frac{e_t}{L_t}$$  \hspace{1cm} (2)

where

$$q_t = w_t \sin \alpha$$ \hspace{1cm} (3)

$$I_t = \frac{\pi}{64} \left( D_t^4 - d_t^4 \right)$$ \hspace{1cm} (4)

$$X_t = \frac{3}{u_t} \left( \tan u_t - u_t \right)$$ \hspace{1cm} (5)

$$Z_t = \frac{3}{u_t} \left( \frac{1}{\sin 2u_t} - \frac{1}{2u_t} \right)$$ \hspace{1cm} (6)
where $F_s$ is the axial WOB, $e_i$ refers to the radial clearance of the first fulcrum above the drill bit (locates at the end of the first span), $L_i$ measures the length of the first span, $M_i$ denotes the bending moment of the first fulcrum, $q_i$ represents the lateral force on the drill-string, $\alpha$ defines the angle of inclination, $w_i$ is the weight of drill-string in the drilling fluid, $I_i$ is the moment of inertia of the drill-string, $D_i$ and $d_i$ are the outer and inner diameters of the drill-string, respectively, and $X_i$, $Z_i$ and $u_i$ are factors determined by system parameters. For the Eqs. (1) and (2), the approach for calculating the $L_i$ and $M_i$ can be found in the publication of Chen (2011).

As can be calculated by Eq. (1), the lateral force acting on the drill bit for the case shown in Fig. 1(b) is larger than that for the case shown in Fig. 1(a). For a certain drill-string, we may induce that the lateral force applied on the bit increases with the decreasing stabilizer diameter. For an adjustable stabilizer, the lateral force reduces when retracting the radial pistons from their full size and vice versa. As a result, either build section or tangent section can be reached in accordance with the drilling technology. Hence, the lateral force of the drill bit and the wellbore trajectory can be controlled sequentially.

### 3. Structure and operating principle of the adjustable stabilizer

The adjustable stabilizer is provided for controlling the borehole trajectory and for saving round trips of drill-string. This downhole tool is developed specifically to save the drilling time and to improve the wellbore geometry. The position of the radial pistons is controlled by a barrel cam which controls the axial movement of five ramp actuators. By starting or stopping pumping, the retracted or extended position of the radial pistons can be realized. For the adjustable stabilizer, the state in which it is operating in can be measured by the signaling device and be determined by the value on the pressure gauge.

#### 3.1 Structure of the adjustable stabilizer

The adjustable stabilizer is schematically shown in Fig. 2 and Fig. 3. This tool comprises of a housing, an adapter substitute, a driving unit, a returning unit, an operating unit, a controlling unit, a balancing unit, and a signaling unit. The upper and lower threads are designed to connect with the upper and lower sections of the drill-string, respectively. As a result, the rotation of the drill-string also leads to the rotation of the adjustable stabilizer. This tool can be placed
directly above the drill bit or far away from the drill bit. For the previous case (connecting with the drill bit), the lower end of the adapter substitute should be a box thread.

The driving unit consists of a pushing cap, a square pin, an upper mandrel, and a lower mandrel. A part of the pushing cap is pressed into the upper end of the upper mandrel and there exists a slight interference between the lower end of the pushing cap and the upper end of the upper mandrel. In addition, the upper end of the pushing cap is hexagonal, and a square pin is mounted between the pushing cap and upper end of the upper mandrel (as shown in Fig. 3(a)) so that the mandrel can be rotated by rotating the pushing cap. In this way, the two mandrels can be assembled or be disassembled (the two mandrels are connected by thread) through rotating the pushing cap. For the upper mandrel, the outer diameter of its upper end is close to the inner diameter of the housing and sealing rings are mounted between the housing and the upper mandrel to prevent the drilling mud from flowing into the oil chamber.

Fig. 2 Cross-sectional view of the adjustable stabilizer.
The returning unit consists of a thrust bearing, a returning spring, a spring seat, and three retention pins. The returning spring is mounted between the shoulder of the upper mandrel and the spring seat. The thrust bearing is mounted between the shoulder of the upper mandrel and the upper end of the returning spring so that rotation of the upper mandrel in the assembling or disassembling processes of the tool is independent of the returning spring. Axial movement of the spring seat is limited by the retention pins so as to provide the returning spring with support. The retention pins are circumferentially mounted in the housing (as shown in Fig. 3(b)). When the pushing cap is pushed downward, the returning spring is compressed and the force is applied onto the retention pins.

The operating unit consists of 5 ramp actuators and 15 radial pistons. For each ramp actuator, a hole with its inner diameter is close to the outer diameter of the upper mandrel is designed so that the upper mandrel can pass through the ramp actuators. For the upper mandrel, a shoulder used to push the actuators is designed in the middle section. The upper mandrel and the lower mandrel are connected through a thread. The ramp actuators are axially limited by both the middle shoulder of the upper mandrel and the upper end of the lower mandrel, and thus the ramp actuators move synchronously with the two mandrels. Referring to Figs. 3(c) and 4, each ramp actuator has three inclined T-shape
grooves which are circumferentially distributed (as shown in Figs. 5(a) and 6(a)). In the middle section of the housing, several straight blades or spiral blades are developed and there are 15 piston seats which are arrayed in 5 lines in the blades. For each radial piston, there is a T-shape head developed to engage in the T-shape groove of the ramp actuator (Fig. 5(b)). It can be easily deduced that three radial pistons engage with each ramp actuator and that the inclined surface of the T-shape head will slide along the inclined surface of the T-shape groove (Fig. 6(b)). Once the ramp actuators are actuated to move along the housing axis, the radial pistons will be retracted or be extended (as shown in Fig. 3(c) and Fig. 4).

![Fig. 5 Key components of the adjustable stabilizer: (a) ramp actuator; (b) radial piston; and (c) barrel cam.](image)

With reference to Fig. 2, the balancing unit comprises of a balancing piston, a fixed piston, a filter plug, and three retention pins. The balancing piston includes sealing rings on its outer side and its inner side which engage the inner surface of the housing and outer surface of the lower mandrel respectively. The balancing piston is axially movable along the housing axis and can prevent the mixture of the oil above this piston and the drilling mud below it. Movement of the balancing piston depends on the pressure difference between the oil and the drilling mud. The fixed piston is fixed by three retention pins to generate a drilling fluid chamber so that the balancing piston plays it role. The filter plug is developed to filter the drilling mud so that debris beyond a critical size may be prevented and thus the flexibility of the balancing piston can be guaranteed.

For the adjustable stabilizer, it is important to know its status, for example being retracted or extended. Based on this, a signaling unit is designed. The signaling unit includes an orifice plate, a signaling seat, a signaling device, an adjusting sleeve, and a series of dishing springs. The orifice plate is threaded onto the lower end of the lower mandrel.
and thus its movement is controlled by the lower mandrel. The signaling device has a cone head which is used to match with the orifice. The signaling device is inserted into the signaling seat and flow channels are designed (as shown in Fig. 3(d)). The adjusting sleeve and the dishing springs are developed to adjust the position of the signaling seat. The adjusting sleeve and the dishing springs are compressed between a shoulder on the lower end of the housing and the upper end of the adapter substitute.

3.2 Operating principle of the tool

Returning to Fig. 2, the adjustable stabilizer has a lower connection to lower drill-string and an upper end connected to the upper drill-string. Drilling fluid from the upper drill-string flows into the adjustable stabilizer and into the bore of the mandrels. The upper mandrel communicates with the fluid passage and determines the positions of the radial pistons. Once the pump is started, the drilling fluid urges the pushing cap to move, resulting in the movement of both the upper mandrel and the lower mandrel toward the lower end of the housing. Axial displacement of the mandrels is determined by the urging force applied on the pushing cap, as well as the stiffness of the returning spring. During the process of drilling fluid flowing through the drilling assembly below the adjustable stabilizer, a pressure loss occurs. The urging force acting on the pushing cap is determined by the pressure loss. For a certain returning spring, the axial displacement of the mandrels increases with an increase in the pressure loss of the drilling fluid. In addition, axial movement of the mandrels are restrained by the inner pin in the limit positions of the barrel cam.

The balancing piston separates an oil chamber from a wellbore fluid chamber. The oil chamber locates in an annulus formed by the housing and the two mandrels, containing the returning spring, the spring seat, the ramp actuators, the barrel cam, the thrust bearings, and the retention seat. The oil chamber is filled with oil and is used to lubricate the components mounted in the oil chamber. The balancing piston can move along the lower mandrel, so the pressure of the wellbore fluid chamber is the same as that of the oil chamber. A wellbore fluid port in which a filter plug is installed communicates with the balancing piston so that the wellbore pressure can be transmitted to the balancing piston and thus the oil chamber (as shown in Fig. 7). In Fig. 7, there is \( P_2 < P_1 \) because pressure loss exists when the drilling fluid circulates through the tools below the adjustable stabilizer (for example the drill bit). The balancing piston is moveable along the mandrel and the volume of the oil chamber can maintain constant for different axial positions of the lower mandrel.

As the ramp actuators are restricted axially by the two mandrels, the ramp actuators move axially together with the mandrels. During this process, each ramp actuator actuates three radial pistons (as can be seen from Figs. 3(c), 4, and 6(c)). For the structure presented in Fig. 2, there are 5 ramp actuators and 15 radial pistons. For each radial piston, it can move in a radial direction of the housing and cannot move axially along the housing axis. Because each ramp actuator includes three ramped faces for engagement with the inner radial surface of the radial pistons, radial movement of the radial piston can be effected with movement of the mandrels. For example, the ramped outer surface of a ramped actuator increases in radial dimension in a direction toward the upper end of the housing, so the radial pistons will be extended when the mandrels are urged to move downward the housing.

By referring to Fig. 8, there are three types of position associated with the barrel cam: a first maximum downward position (H or H4) represent the radial pistons are in maximum extension, a second maximum downward position (H2) represent the radial pistons are in middle extension, and a maximum upward position (H1 or H3) represents the radial pistons are in neutral phase. The inner pin slides along the closed groove of the barrel cam and the barrel cam cycles between three different positions in a repeated pattern. When the mud pump is off, the radial pistons will be in a neutral position the same with the outer surface of the blades of the housing, and the inner pin locates at H1. When the pump is started, the barrel cam moves with the mandrel and the inner pin slides from H1 to H2, creating a middle extension of the radial pistons. Stop the pump once again and then the inner pin slides in the groove from H2 to H3, leading to a neutral position once again. Start the mud pump for the second time, then the inner pin slides from H3 to H4, creating a largest diameter of the radial pistons (maximum extension). Stop the pump for the second time, then the inner pin slides from H4 to a position similar to H1. During the operations, the inner pin can be regarded to be fixed on the housing, and thus the engagement between the inner pin and the barrel cam is realized through rotation of the barrel cam.
As the adjustable stabilizer is several kilometers away from the ground, then knowing the status of the tool is of great importance. Based on this, a signaling unit is developed and mechanism of this unit can be presented by referring to Fig. 9. The orifice plate is fixed on the lower end of the lower mandrel, and thus it will move along the housing axis. The orifice plate has a cone bore for engagement with the cone head of the signaling device. For different phases of the radial pistons, displacements of the mandrels are also different. For the engagement of the orifice plate and the signaling device, the cross sectional area used for flowing of the drilling fluid varies, which means the drilling fluid can be throttled when the radial pistons are extended. Each status of the radial pistons corresponds to a type of cross sectional area. During the process of operation, pressure loss of the drilling fluid changes and thus the status of the radial pistons can be measured.

Fig. 7 Schematic diagram of the pressure in and out the tool

Fig. 8 Illustration of the controlling unit of the adjustable stabilizer
4. Numerical verifications of the key components

One of the keys to the successful development of the adjustable stabilizer is the strength verifications of the key components. For the adjustable stabilizer, the housing bears the WOB imposed by the BHA and the torque transmitted by the rotary table. In addition, both of the mandrels as well as the retention pins used to support the spring seat bear axial forces. In this section, static analysis for the key components pointed is conducted by using the continuum code ABAQUS (Simulia, 2013). For the components analyzed, 42CrMo is used and the mechanical property of this material is shown in Table 1.

Table 1 Mechanical property of the material of the key components

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Density (Kg/m$^3$)</th>
<th>Elasticity modulus (GPa)</th>
<th>Poisson’s ratio</th>
<th>Yield strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>7850</td>
<td>209</td>
<td>0.3</td>
<td>930</td>
</tr>
</tbody>
</table>

For the housing, fixed constraint is applied onto its lower end and an axial compressing force (represents the WOB) of 250 kN and a torque equal to 20 kN⋅m are exerted onto its upper end. As can be seen from the stress contours of the housing shown in Fig. 10, the maximum stress is 94.7 MPa. In addition, the maximum stresses locate at the edges and corners of the radial bores of the housing where stress concentrations are easily formed, so we may conclude that the housing is safe. In Fig. 10, the upper part is the stress contour of the whole housing and the below one is the middle section of the housing.
Static analyses are conducted for both mandrels. For each mandrel, fixed constraint is applied to one end and an axial compressing force with its value equal to 20 kN is applied on the other end. As can be seen from Figs. 11 and 12, the maximum stresses of the upper mandrel and the lower mandrel are 42 MPa and 46.3 MPa, respectively. In fact, the mandrels bear a small axial force, so they can be regarded to be safe. What should be addressed is that unit of the geometric model presented in Fig. 10 is different from that presented in Figs. 11, 12, and 13, so the order of the magnitudes are different.

Fig. 11 Stress contour of the upper mandrel with the axial compressing force equals to 20 kN: (a) stress distribution of the whole upper mandrel; and (b) cross-section view of the stress distribution of the upper mandrel.

Fig. 12 Stress contour of the lower mandrel with the axial compressing force equals to 20 kN: (a) stress distribution of the whole lower mandrel; and (b) cross-section view of the stress distribution of the lower mandrel.

The drilling fluid urges the pushing cap to move downward, leading to compression of the returning spring. The force that is applied onto the returning spring is transmitted to the spring seat and then acts on the retention pins. There are three pins used to support the spring seat. As can be seen from Fig. 13, stress concentration occurs and the maximum stress of the retention pin is 164.4 MPa. Since the force exerted by the drilling fluid is less than 20 kN, then we may deduce that this structure is safety.

Fig. 13 Stress contour of the spring seat with the axial force equals to 20 kN.
5. Test results and discussion

In order to verify the feasibility of the adjustable stabilizer, both laboratory and field tests are conducted. After manufacturing the components (some of the components are shown in Fig. 6), the adjustable stabilizer is assembled. Fig. 14 presents a general view of the laboratory tests of adjustable stabilizer. During the laboratory tests, the adjustable stabilizer is placed horizontally. An adapter with a throttling device is mounted onto the lower end of the tool and water is used as the circulating fluid. By controlling flow rate of the circulating water, different pressure losses can be reached. Tests results show that the three phases of the radial pistons described above can be reached, the diameters of the radial pistons for the phases are 200mm, 207mm, and 215mm, respectively.

Fig. 14 General view of the laboratory experimental apparatus.

Fig. 15 shows the field tests of the adjustable stabilizer which are carried out in a well of Zhongyuan Oil Field located in Puyang city of China. In the tests, drilling mud is circulated to operate the adjustable stabilize and a three roller bit is mounted onto the lower end of the adjustable stabilizer. During the normal drilling process, pressure loss occurs because the drilling mud flows through the BHA and the drill bit. For this field test apparatus, 3 nozzles with their inner diameter 12 mm are mounted into the drill bit to throttle the drilling mud. Results show that the adjustable stabilizer operates regularly and three phases are realized by regulating the pressure loss of the drilling mud. Based on the test results, it is indicated that the structure and design of the adjustable stabilizer presented in this paper is feasible and that this technique is of great significance in controlling the borehole trajectory. Fig. 15(a) denotes that the radial pistons are in neutral phase with a diameter of 200 mm, corresponding to Fig. 4(a). Fig. 15(b) denotes that the radial pistons are in middle extension phase with a diameter of 207 mm, corresponding to Fig. 4(b). Fig. 15(c) denotes that the radial pistons are in maximum extension phase with a diameter of 215 mm, corresponding to Fig. 4(c). Since the displacement of the radial pistons is very small (for the two phase variations, the displacement of the radial piston are 3.5 mm and 4mm, respectively). However, when looked into more detail, the difference of the three pictures can be clearly found. The pressure loss for the middle extension and maximum extension of the radial pistons are 1.4 MPa and 2.6 MPa, respectively.
Fig. 15 General view of the field tests of the adjustable stabilizer: a) the radial pistons are in neutral phase with a diameter of 200 mm; b) the radial pistons are in middle extension with a diameter of 207 mm; c) the radial pistons are in maximum extension with a diameter of 215 mm.

5. Conclusions

Downhole tool failures present one of the major problems during the drilling process, especially for the wells with heavyweight muds. Because it is difficult to trip out the drill-string, and rotating in and out of the wellbore becomes necessary. By using an adjustable stabilizer, tool failures and slide lubricants can be reached. For the present techniques, extension and retraction of the radial pistons are realized through rotation of the drill-string or regulation of the axial WOB. Based on this background, a new designed adjustable stabilizer is presented to reduce the round trips of the drill-string.

By introducing the equations of lateral force on the bit and rotation angle of the bit, mechanism of adjustable stabilizer controlling the borehole trajectory is presented. For different phases of the radial piston, different types of BHA can be generated. Once the BHA changes, the lateral force on the drill bit and rotation angle of the drill bit change. In this way, controlling of the inclination and azimuth can be realized.

Structure and operating principle of the adjustable stabilizer are presented. The adjustable stabilizer includes a housing, an adapter substitute, a driving unit, a returning unit, an operating unit, a controlling unit, a balancing unit, and a signaling unit. The WOB and torque are transmitted by the housing and the adapter substitute. The key component of the returning unit is the returning spring which leads to retraction of the radial pistons when the pump is off. For the operating unit, the radial pistons engage with the ramp actuators which are fixed on the upper mandrel so that they can move accompany with the mandrels. The controlling unit is designed to limit the movement of the mandrels. The balancing unit is developed to provide an identical pressure for the two chambers separated by the balancing piston. The signaling unit is used to mark the pressure difference for different phases of the radial pistons so that the phases of the adjustable stabilizer can be known by measuring the pressure of the drilling mud. When regulating the drilling fluid, pressure difference of the drilling fluid in and out of the adjustable stabilizer varies, urging the mandrels to actuate the retraction or extension of the radial piston.

In order to verify the safety of the drilling tool, simulation analyses of several key components are carried out. Results show that the safety factors of those components are big enough. Then, a real adjustable stabilizer is manufactured and assembled. Laboratory tests are conducted to examine the motion of the radial pistons, with water is used as the circulating fluid. Results show that three phases of the adjustable stabilizer are realized. Finally, field tests of the adjustable stabilizer are carried out, and the test results also show that the adjustable stabilizer operates normally.
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