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The Review and Development of Devices with an Increasing Rate of Penetration (ROP) in Deep Formation Drilling Based on Drill String Vibration

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Abstract: The oil and gas resources stored in deep strata are an important replacement field of the petroleum industry. Accelerating the exploration and development of deep oil and gas is of great significance to the security of energy strategy. Drilling is the primary link and necessary means of deep oil and gas exploration and development. Slow drilling speed is one of the key problems restricting the exploration and development of deep oil and gas. The research and development of down-hole equipment with an increasing ROP provides a technical means for increasing the ROP. However, the energy of existing down-hole equipment with an increasing ROP comes from the drilling circulation medium, and the ROP increase effect of such equipment is relatively obvious in shallow and middle formations. However, with the increase in well depth, energy in the circulation medium increasingly struggles to reach deeper formations, and the ROP increase effect is not good at the later stage of drilling. In the drilling process, drill string vibration is a frequently encountered complex situation, but it also contains sufficient energy, and the energy of drill string vibration will increase with an increase in the well depth, which can meet the energy demand of increasing the ROP in deep oil and gas exploration. This paper analyzes the characteristics of drill string vibration, and introduces six kinds of devices that take drill string vibration as energy and realize drill string vibration reduction, bottom-hole pressurization, and high-pressure pulse jet, providing a new idea for the development of deep down-hole speed-increasing devices.

Keywords: ROP increase; energy of drill string vibration; drill string vibration reduction; bottom-hole pressurization; high-pressure pulsed jet

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1. Introduction

With the discovery of more deep and ultra-deep oil and gas fields, it becomes increasingly important to study the drilling technology of deep and ultra-deep wells [1–8]. The main problem faced by deep and ultra-deep wells is the slow drilling speed, and using down-hole drilling tools to improve the drilling speed is currently the most important way. Although the principle of down-hole drilling tools with an increasing ROP is different, they all need to provide stable energy to make them work. If the supply of energy cannot be guaranteed, it is difficult to achieve the expected goal of the drilling project after the use of the tool with an increasing ROP. The analysis shows that for the tools with an increasing ROP that use the circulating media, such as drilling fluid and gas to provide energy, in the case of deep and ultra-deep wells, the circulating media can only meet the role of carrying rock cuttings, but cannot meet the energy supply of other tools. Therefore, China University of Petroleum (East China) proposed the use of energy generated by drill string vibration, and successfully developed down-hole equipment with an increasing ROP using the energy of drill string vibration, which effectively solved the above problems. In the actual drilling process, this device has achieved remarkable results [9–16].

Based on the analysis of vibration characteristics of the drill string, this paper introduces the principle and characteristics of devices with an increasing ROP using energy of drill string vibration, and puts forward the prospect of future development of this technology.

2. Basic Characteristics and Law of Drill String Vibration

The bottom-hole drill string dynamic research test devices designed by China University of Petroleum (East China) according to the similarity principle was used to test the bottom-hole drill string motion state and force under different drilling assembly conditions [17–20]. The measured results of representative drill string combinations are shown in Figure 1.

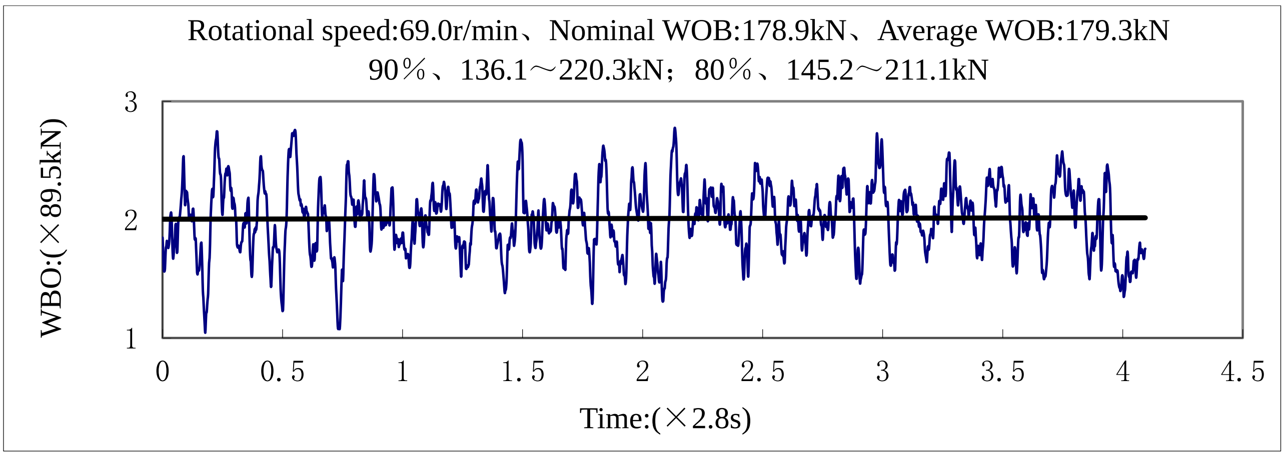
The prototype of the bottom-hole assembly (BHA) is 311 mm bit + 228.6 mmDC (drill collar) × 2 + 310 mmSST(spired stabilizer) + 228.6 mmDC × 4 + 203.2 mmDC × 6 + 127 mmDP (drill pipe).

According to Figure 1a, showing a rotational speed of 69.0 r/min, it can be concluded that when the rotational speed is set at 69.0 r/min, the WOB is applied at 178.9 kN, when the confidence interval is 90%, the fluctuation range of the WOB is 136.1~20.3 kN; when the confidence interval is 80%, the fluctuation range of the WOB is 145.2~211.1 kN, and the measured average WOB is 179.3 kN.

According to Figure 1b, showing a rotational speed of 92.0 r/min, it can be concluded that when the rotational speed is set at 92.0 r/min, the WOB is applied at 178.9 kN; when the confidence interval is 90%, the fluctuation range of the WOB is 105.0~210.4 kN; and when the confidence interval is 80%, the fluctuation range of the WOB is 123.1~210.2 kN, and the measured average WOB is 168.5 kN.

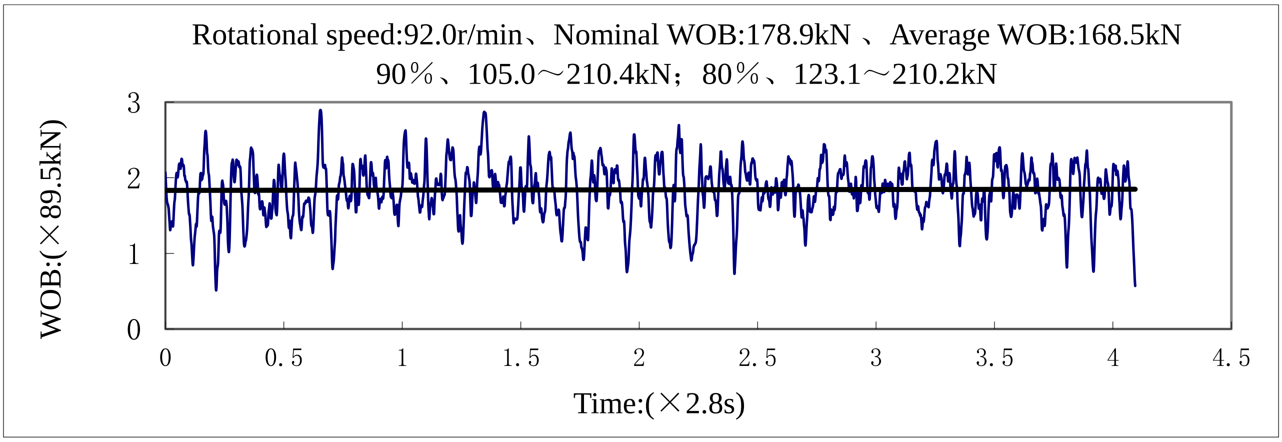
According to Figure 1c, showing a rotational speed of 115.0 r/min, it can be concluded that when the rotational speed is set at 115.0 r/min, the WOB is applied at 178.9 kN; when the confidence interval is 90%, the fluctuation range of the WOB is 80.1~236.8 kN; and when the confidence interval is 80%, the fluctuation range of the WOB is 101.2~218.5 kN, and the measured average WOB is 160.3 kN.

In conclusion, for the 311.1 mm hole, 228.6 mm drill collar, and pendulum drill, when the WOB is 178.9 kN and the rotational speed varies between 69 and 115 r/min, the actual WOB fluctuates between 80.1 and 236.8 kN. At the same time, the above graph analysis also shows that the fluctuation frequency is about 3~4 times the rotational speed. Similarly, laboratory experiments have found that for the 244.5 mm hole, 177.8 mm drill collar, and pendulum drill devices, when the WOB is 134.2 kN and the rotational speed varies between 70 and 120 r/min, the actual WOB fluctuates between 10 and 150 kN, and the fluctuation frequency is also 3~4 times the rotational speed.

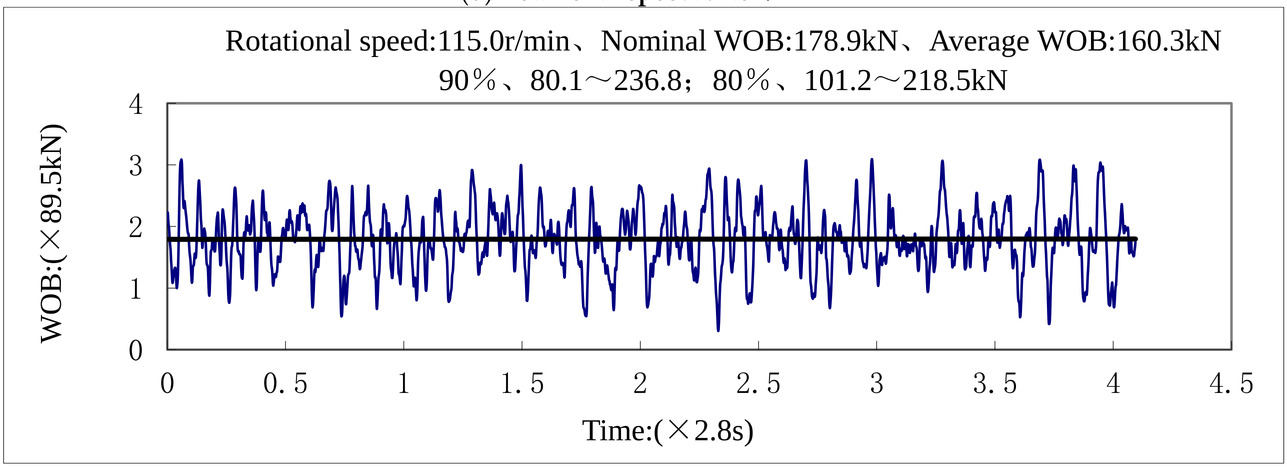


(**a**) **Rotational speed: 69.0 r/min.**

Figure 1. *Cont.*



(**b**) **Rotational speed: 92.0 r/min.**



(**c**) **Rotational speed: 115.0 r/min.**

Figure 1. The actual weight on bit (WOB) fluctuations with time.

Experimental research and previous field test results show that the bottom-hole WOB fluctuates with high frequency and large amplitude during the drilling process, and its fluctuation amplitude increases with an increase in the well depth, which provides reliable energy for the acceleration of hard formation in deep wells.

3. Principle and Current Situation of Down-Hole Devices with an Increasing ROP Based on Drill String Vibration

3.1. Principle of Pressurization and Acceleration of Down-Hole Drilling Fluid Based on Drill String Vibration

The high-frequency variation in the WOB will directly affect the bit, which makes the bit bear a great impact force when cutting the rock, possibly fracturing the cutter. The spring and damper are installed in the middle of the drill string and the upper part of the drill bit. When the WOB passes through the spring and damper, the WOB will be converted into the elastic potential energy and damping work, which can not only effectively attenuate the fluctuations in the WOB, but also prolong the time of the impact force. The principle of the high-pressure jet based on drill string vibration is that the spring and plunger pump work together to reduce the fluctuations in the WOB and transfer an effective WOB, finally realizing the overall pressure of the drilling fluid.

3.2. Drilling String Shock Absorption and Down-Hole Hydraulic Pressurizing Device

The drilling string shock absorption and down-hole hydraulic pressurizing device utilizes the above down-hole drilling fluid pressurization mechanism. The mechanical energy of the drill string vibration is converted into hydraulic energy with a 1.5~3 L/s drilling fluid, and the pressure of this part of drilling fluid can be increased to more than

120 MPa. The pressurized drilling fluid is ejected from the high-pressure nozzle to assist in breaking rocks. Drilling the string shock absorption and down-hole hydraulic pressurizing device is shown in Figure 2 [21–30]:

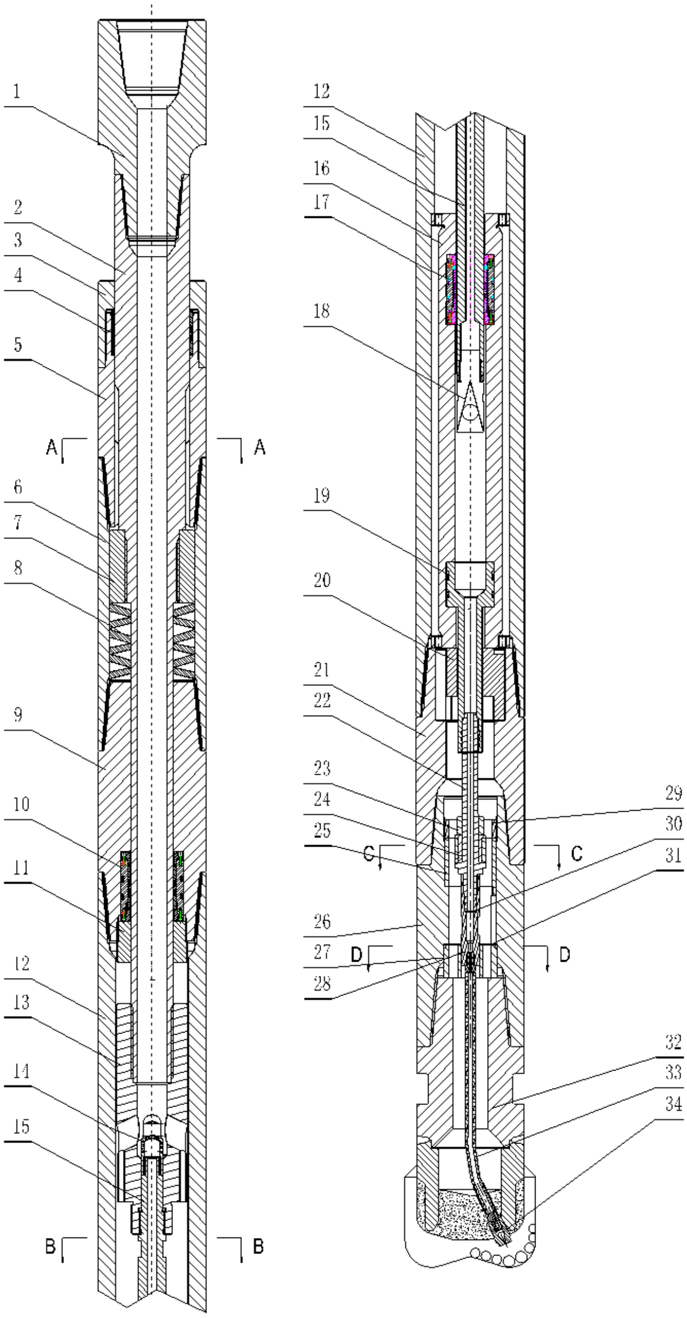


Figure 2. A schematic diagram of the drilling string shock absorption and down-hole hydraulic pressurizing device. 1: upper conversion joint, 2: spline mandrel, 3: sealing pressure cylinder, 4: spring chamber upper seal assembly, 5: spline outer cylinder, 6: spring protection cylinder, 7: spline limit nut, 8: spring, 9: spring lower seal joint, 10: spring chamber lower seal assembly, 11: lower sealing pressure cylinder, 12: supercharged assembly outer cylinder, 13: shunt pressure transfer joint, 14: drilling fluid filter, 15: plunger, 16: pressurizing cylinder, 17: ultra-high-pressure seal assembly, 18: inlet check valve, 19: high-pressure flow passage, 20: support flow block, 21: lower connector of booster device, 22: metal ultra-high-pressure drilling fluid passage, 23: limit nut, 24: six-party body, 25: anti-torsional overcurrent structure, 26: conversion connector, 27: hard pipe centralizer, 28: ultra-high-pressure drilling fluid passage extension pipe, 29: lock nut, 30: compression seal, 31: adjusting ring, 32: bit body, 33: ultra-high-pressure hose, and 34: ultra-high-pressure drilling fluid nozzle.

According to the function of the device, it can be divided into drill string force transmission assembly, torsional pressure transmission assembly, elastic reset element assembly, pressurized cylinder block, ultra-high-pressure drilling fluid transmission assembly, and drill bit. The drill string force transmission assembly is composed of the upper conversion joint, the spline mandrel, the shunt pressure transfer joint, the drilling fluid filter, the plunger, and the inlet check valve. The torsional pressure assembly is composed of the sealing pressure cylinder, the spring chamber upper seal assembly, the spline outer cylinder, the spring protection cylinder, the spring lower seal joint, the spring chamber lower seal assembly, the lower sealing pressure cylinder, the supercharged assembly outer cylinder, the lower connector of the booster device, and the conversion connector. The supercharging cylinder assembly is composed of the supercharging cylinder and the ultra-high-pressure seal assembly. The elastic reset element is a spring. The ultra-high-pressure drilling fluid transmission assembly is composed of the high-pressure flow passage, the metal ultra-high-pressure drilling fluid passage, the ultra-high-pressure drilling fluid passage extension pipe, the ultra-high-pressure hose, and the ultra-high-pressure drilling fluid nozzle. The drill bit is an ordinary drill bit.

The working process of the device is as follows. When the longitudinal vibration of the drill string occurs in the drilling process, fluctuations in the WOB lead to reciprocating movements in the drill string force transmission assembly, relative to the torsional pressure transmission assembly. When the WOB increases, the drill string force transmission assembly moves downward. The inlet check valve is closed, and the spring force and the drilling fluid pressure in the pressurizing cylinder jointly prevent this movement. As a result, the spring is compressed, and the drilling fluid pressure in the pressurizing cylinder increases. The pressurized drilling fluid is sent to the drill bit through the ultra-high-pressure drilling fluid transmission assembly, and is ejected from the ultra-high-pressure drilling fluid nozzle on the drill bit to assist in rock breaking. When the WOB decreases, the compressed spring becomes gradually restored. The drill string force transmission assembly moves upward, and the pressure in the pressurizing cylinder decreases. The inlet check valve is opened to suck in normal pressure drilling fluid and prepare for the next pressurization process.

The characteristics of the device are as follows. The device combines drilling string vibration reduction with drilling fluid pressurization. The vibration energy of the drill string, which can easily cause fatigue damage to the drill string, is converted into the pressure energy of the drilling fluid to achieve bottom-hole pressurization. The rock breaking efficiency is improved, and turns from harmful to beneficial. At the same time, the process does not affect normal circulation and drilling operations. The simple structure of the device can ensure that each component has a large enough size and strength under the space conditions at the bottom of the well, so as to ensure its working life to meet engineering requirements.

The device has been used in more than 100 wells in the Shengli oilfield, the Tarim oilfield, and the Jiangsu oilfield in China, with the ROP increasing by 30–325% and the tool life increasing by 237 h [21].

3.3. Drilling String Absorption and Hydraulic Pulsed Jet Generator Device

The drilling string absorption and hydraulic pulsed jet generator device converts the vibration mechanical energy of drill string into the hydraulic energy of the bottom-hole drilling fluid by using the above-mentioned pressurization mechanism of down-hole drilling fluid, which can increase the pressure of the bottom-hole drilling fluid by more than 2~10 MPa (average 4 MPa). Then, the pressurized drilling fluid spurts out from the nozzle of the drill bit to improve the rock cleaning effect.

Functional units, according to the device, can be divided into the drill string linkage assembly and the drill string split-type assembly. The linkage assembly with the drill string, including the upper tool joint, mandrel, and limit body, mounted on the outer part of the mandrel. The transfer assembly with the drill string, including the plunger cylinder outer barrel, drill bit, and spline outer cylinder, fitted above the mandrel, and the tool center joint connected with the spline outer cylinder. The drilling string absorption and hydraulic pulsed jet generator device is shown in Figure 3 [31–35].

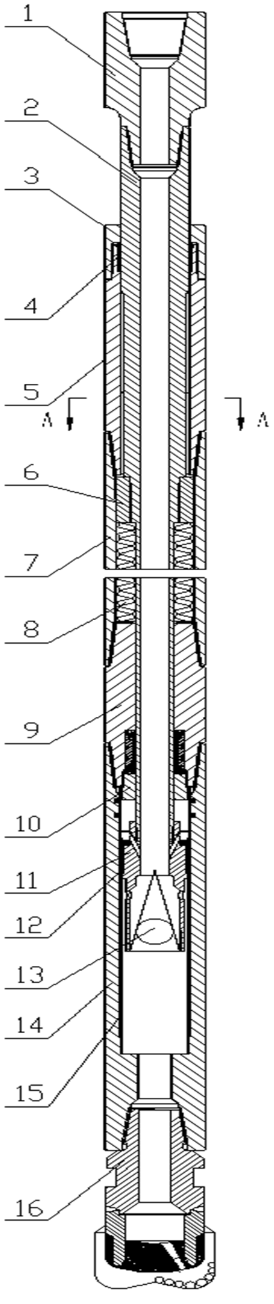


Figure 3. A schematic diagram of the drilling string absorption and hydraulic pulsed jet generator device. 1: tool upper joint, 2: mandrel, 3: upper seal assembly gland, 4: upper seal assembly, 5: spline outer cylinder, 6: limit body, 7: protective cylinder, 8: spring, 9: tool center joint, 10: lower seal assembly, 11: plunger head, 12: sliding seal assembly, 13: control check valve, 14: plunger outer cylinder, 15: plunger cylinder liner, and 16: drill bit.

The working process of the device is as follows. When the drill string vibrates downward, the drill string linkage assembly moves downward relative to the drill string split-type assembly. The volume in the plunger cylinder decreases. The elastic reset element compresses, and the movement speed of the plunger head increases first and then decreases. When the movement velocity is greater than the flow rate of the drilling fluid in the plunger cylinder, the control check valve is closed, the piston within the cylinder of the drilling fluid and the elastic reset device share increases the WOB, consequently increasing the drilling fluid pressure in the plunger cylinder. When the movement velocity is less than the flow rate of the drilling fluid in the plunger cylinder, the control check valve is opened, and drilling fluid is ejected through the nozzle. When the drill string vibrates upward, the plunger head moves upward relative to the plunger cylinder, the elastic reset element releases energy and causes the tool to reset, the control check valve is opened, and the drilling fluid enters the plunger cylinder, finally generating the pulse jet.

The characteristics of the device are as follows. It compresses and pressurizes all drilling fluid periodically at the bottom of the well to transfer the vibration energy of drill string and generate pulse jet. The average pressure of the pulse jet is higher than the average pressure without the device, and the rock breaking and carrying capacity is enhanced, which reduces the rock breaking difficulty. It can transfer the vibration energy of the drill string and make effective use of it, thus reducing the harm of the drill string vibration and effectively prolonging the service life of the drill tool. The energy generated by the drill string vibration increases with an increase in the well depth. The principle and structure of the device are easy to produce, maintain, and use. The pulsed jet generated by the device can be applied to any bit to alleviate bit balling.

The device has been used in more than 140 wells in the Karamay oilfield, the Xinjiang oilfield, and the Dagang oilfield in China, with the ROP increasing by 30~151% and the tool life increasing by 269 h [31].

3.4. A Down-Hole High-Pressure Jet Drilling Device Transforming Drilling String Vibration Energy

A down-hole high-pressure jet drilling device transforms the drilling string vibration energy in the upgraded drilling string absorption and hydraulic pulsed jet generator device, on the basis of innovation. The device uses drill string vibration to suck some of the drilling fluid in the inner annulus into the tool and mix it with the drilling fluid pumped from the surface, so as to increase the displacement at the bottom bit. Due to the increase in the drilling fluid flow in the tool, the amplitude of drilling fluid pressure lifting increases to more than 4~15 MPa (average 7 MPa), and the pressurized drilling fluid is ejected from the bit nozzle to improve the rock clearing effect. In addition, because the annulus drilling fluid contains small rock cuttings, the abrasive jet-assisted rock breaking effect can be produced at the bit.

The basic structure of the device is as follows. The mandrel body, limit ring, and piston assembly are connected through threads to form the drill string vibration linkage assembly. The impact proof seal end cap, spline cavity seal assembly, spline outer cylinder, oil injection hole plug, vent plug, spring protection cylinder, spring lower sealing joint, spring cavity seal assembly, annulus fluid inlet one-way valve, annulus fluid inlet flow pressure head, pressurized cylinder liner, pressurized cylinder liner seal, and pressurized assembly outer cylinder are connected to form the bottom-hole static vibration bearing assembly. A down-hole high-pressure jet drilling device transforming drilling string vibration energy is shown in Figure 4 [36–38].

The working process of the device is as follows. When the drill string vibrates downward, the drill string vibration linkage assembly moves downward. When the movement speed exceeds the flow velocity of the drilling fluid in the section of the pressurized cylinder liner, the annulus fluid outlet one-way valve and the drilling tool inner hole check valve are closed, the liquid pressure in the large-displacement fluid jet pulsation pressurization modulation chamber is increased, and the high-pressure positive pulse annulus fluid jet is formed on the ordinary nozzle. At the same time, the drilling fluid carrying small debris in the annulus filters through the screen of the inlet flow pressure head of the annulus fluid, and then flows through the annulus fluid inlet one-way valve and the annulus fluid inlet flow channel into the annulus drilling fluid storage chamber, which provides preparation for the annulus fluid to enter the large-displacement fluid jet pulsation pressurization modulation chamber. When the drill string vibrates upward, the drill string vibration linkage assembly moves upward, the annulus fluid outlet one-way valve and the drilling tool inner hole check valve are opened, and the drilling fluid in the drill hole normally flows to the bottom of the hole to play its role. At the same time, the annulus fluid inlet one-way valve closes, the annulus fluid outlet one-way valve opens, and the drilling fluid carrying small cuttings enters the large-displacement fluid jet pulsation pressurization modulation chamber through the annulus fluid outlet flow channel and the annulus fluid outlet one-way valve. While waiting for the drill string to vibrate downward, a large-displacement high-pressure positive pulse fluid jet is formed again, and so on.

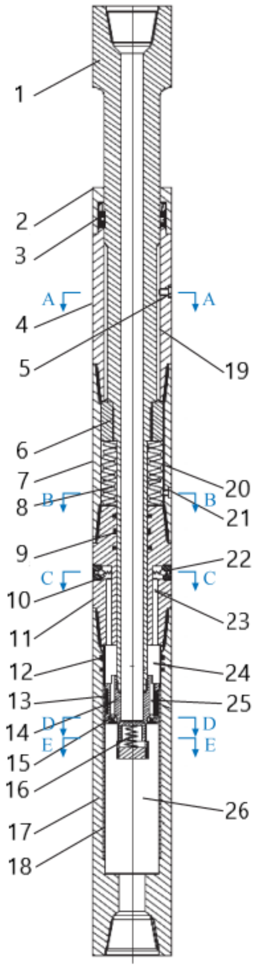


Figure 4. A structure diagram of a down-hole high-pressure jet drilling device transforming drilling string vibration energy. 1: mandrel body, 2: impact proof seal end cap, 3: spline cavity seal assembly, 4: spline outer cylinder, 5: oil injection hole, 6: limit ring, 7: spring protection cylinder, 8: spring assembly, 9: spring cavity seal assembly, 10: annulus fluid inlet one: way valve, 11: spring lower sealing joint, 12: pressurized cylinder liner seal, 13: piston body seal assembly, 14: piston assembly, 15: annulus fluid outlet one: way valve, 16: drilling tool inner hole check valve, 17: pressurized assembly outer cylinder, 18: pressurized cylinder liner, 19: spline lubricating fluid cavity, 20: spring lubricating fluid cavity, 21: vent hole, 22: annulus fluid inlet flow pressure head, 23: annulus fluid inlet flow channel, 24: annulus drilling fluid storage chamber, 25: annulus fluid outlet flow channel, and 26: large-displacement fluid jet pulsation pressurization modulation chamber.

The characteristics of the device are as follows. The device can produce a high amplitude and a high-pressure pulse jet to achieve the purpose of high-pressure drilling. The drilling string vibration energy can be effectively converted to the bottom-hole drilling fluid, and the overflow rate of the nozzle drilling fluid is increased. The device has low cost, high safety, and a wide application range.

The above device has been applied for four wells in the Shengli oilfield in China, with the ROP increasing by 51~220% and the tool life increasing up to 210 h [36].

4. New Ideas of Down-Hole Devices with an Increasing ROP Based on Drill String Vibration

Drilling string vibration machinery can provide a new energy source for down-hole tools. Using different mechanical structures to transform this energy can help to realize different speed enhancement techniques. Based on this idea, the author's research team developed three kinds of devices to convert drill string vibration energy into drilling fluid hydraulic energy, and also designed a "mechanical downhole vibration absorption impact drilling tool" (patent no. ZL201010617044.0) to convert drill string vibration energy into bit axial impact and "downhole torsional impact excitation device based on drill string vibration" (patent no. ZL201410514618.X), which converts drill string vibration energy into the torsional impact of drill bit. The design of these devices provides new ideas for the field of speed raising in deep wells, but this is only the beginning. With the development of the idea of drilling string vibration energy utilization, more and better down-hole speed enhancement tools will be developed to serve the drilling site.

4.1. Mechanical Down-Hole Vibration Absorption Impact Drilling Tool

The mechanical down-hole vibration absorbing impact drilling tool is based on the longitudinal vibration of the drill string. Along the axis of the drill string, the plunger is driven to reciprocate relative to the impact chamber. The drilling fluid flowing through the impact chamber accumulates energy under the longitudinal vibration of the drill string to control the impact of the impact cylinder. At the same time, the vibration reduction return spring is used to absorb the energy of the longitudinal vibration of the drill string and to reset the tool. The impact assembly transforms part of the vibration energy into the impact force, which is not only used to stabilize the drill pipe and the drill bit, but also to realize rotary impact drilling. The mechanical down-hole vibration absorption impact drilling tool is shown in Figure 5 [39].

The basic structure of the device is as follows. The upper fitting joint is integrated with the spline mandrel. The spline cylinder, vibration reduction return spring outer cylinder, and impact assembly outer cylinder are integrated and coordinated with the hexagon shaft of the bearing structure, which is used to transfer torque and allow the spline mandrel to reciprocate up and down. The spline mandrel is connected with the plunger through the shunt structure, spline cylinder, vibration reduction return spring outer cylinder, impact assembly outer cylinder as a whole, and vibration reduction return spring outer cylinder. The upper part of the impact assembly outer cylinder is then provided with a spring. The impact cylinder moves up and down along the axis, and the water hole for the normal circulation of the drilling fluid is arranged in the middle and lower part of the bearing structure.

The working process of the device is as follows. In rotary percussive drilling, based on the longitudinal vibration of the drill string, the upper fitting joint moves up and down with the plunger under the action of the drill pipe. The vibration reduction return spring in the vibration reduction return spring outer cylinder acts through compression and extension. It can be used in vibration reduction at the same time to ensure that the vibration reduction return spring impacts the impact assembly outer cylinder. While the impact assembly does not move up and down with the drill string, when the upward movement of the drill string, upper fitting joint, spline mandrel, and shunt structure move upward together with the plunger, the negative pressure is generated in the impact chamber, and the bearing structure bears the impact of the impact cylinder and inhales the drilling fluid. When the drill string moves down, the upper fitting joint, spline mandrel, shunt structure, and plunger move down together. The drilling fluid is compressed in the impact chamber, so that the impact cylinder moves up relative to the plunger. The spring is compressed to achieve the purpose of energy storage. Finally, the function and impact of vibration absorption are realized, and the efficiency of rock breaking is improved.

The characteristics of the device are as follows. The structure of the tool is not complicated, the principle is feasible after experimental verification, and the size and strength of each component are enough to ensure that the working time can meet the needs of the project. By combining the drill string vibration reduction with the low impact and high frequency of the drill bit, the energy generated by the longitudinal vibration of the drill string can be converted into the elastic potential energy of the vibration reduction return spring, which is conducive to improving the impact work and realizing the rotary impact drilling. Even if part of the tool mechanism fails, the spring can still be used to reduce the longitudinal vibration of the drill string, and normal drilling operations will not be affected.

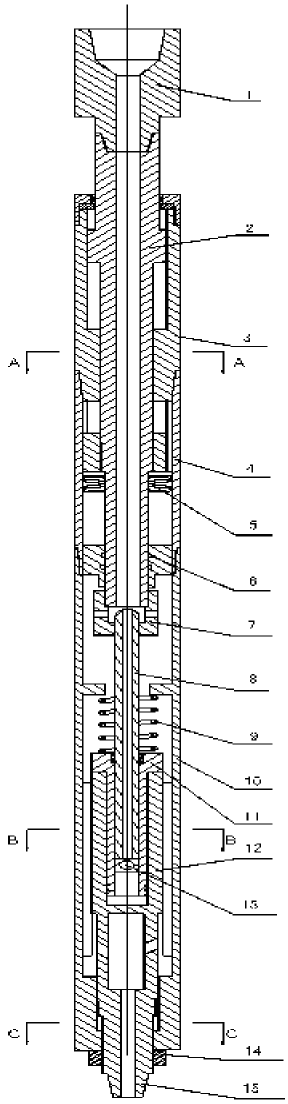


Figure 5. A structure diagram of the mechanical down-hole vibration absorption impact drilling tool. 1: upper fitting joint, 2: spline mandrel, 3: spline cylinder, 4: vibration reduction return spring outer cylinder, 5: vibration reduction return spring, 6: spring limit joint, 7: shunt structure, 8: plunger, 9: spring, 10: impact assembly outer cylinder, 11: impact cylinder, 12: bearing structure, 13: check valve, 14: limit structure, and 15: lower fitting joint.

4.2. Down-Hole Torsional Impact Excitation Device Based on Drill String Vibration

The down-hole torsional impact excitation device based on drill string vibration makes use of harmful drill string vibration in the process of drilling, and generates a high-frequency torsional impact vibration of the drill bit through the vibration transformation structure. The down-hole torsional impact excitation device based on the drill string vibration is shown in Figure 6 [40].

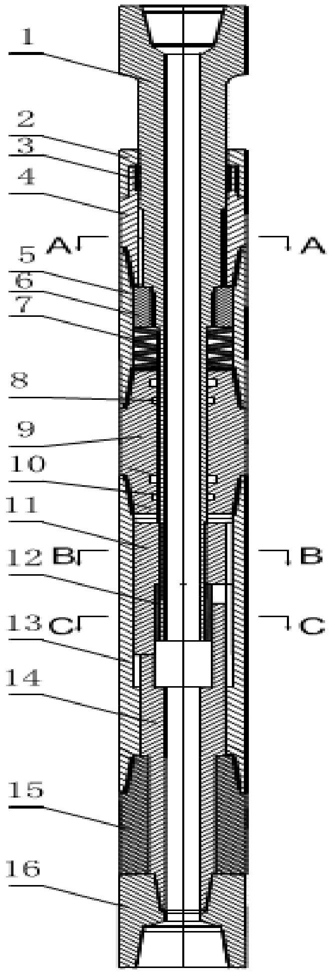


Figure 6. A structure diagram of down-hole torsional impact excitation device based on drill string vibration. 1: vibration transmission shaft, 2: sealing gland, 3: spline chamber sealing assembly, 4: spline outer cylinder, 5: spring protection cylinder, 6: limit ring, 7: spring, 8: spring chamber sealing assembly, 9: spring lower sealing joint, 10: separation seal, 11: active torsional impact body, 12: active torsional impact body compression block, 13: transmission torsional protection cylinder, 14: driven torsional impact body, 15: limit joint, and 16: conversion joint.

The basic structure of the device is as follows. The vibration transmission shaft is connected with the active torsional impact body compression block thread, the active torsional impact body clearance is installed on the installation surface of the active torsional impact body of the vibration transmission shaft, the limit ring is connected with the limit thread of the vibration transmission shaft, and the spring is arranged in the spring protection cylinder. The sealing gland is connected with the end cap of the spline outer cylinder through threads. The upper thread of the spring protection cylinder is connected with the external thread of the spline outer cylinder, and the lower thread is used to connect the spring lower sealing joint. The spring is a combination of the disc spring and the liquid spring, or a combination of the spiral spring and the liquid spring. The driven torsional impact body and conversion joint are connected with a high-frequency vibration transmission assembly through threads.

The working process of the device is as follows. When the drill string vibrates downward, the active torsional impact body relative to the transmission torsional protection cylinder moves downward. Due to the limiting effect of the limit joint on the driven torsional impact body, the driven torsional impact body can move in the circumferential direction with respect to the torsional transmission intermediary assembly. The active torsional teeth in the active torsional impact body moves relative to the driven torsional teeth. This motion causes the driven torsional impact body not only to bear torque, but also to produce circumferential torsional impact vibration relative to the torsional transmission intermediary assembly. When the drill string vibrates upward, the active torsional impact body moves upward relative to the transmission torsional protection cylinder. Due to the limiting effect of the limit joint on the driven torsional impact body, the driven torsional impact body can only move in a circumferential direction relative to the torsional transmission intermediary assembly. The active and driven torsional teeth move relative to each other. This motion causes the driven torsional impact body to produce circumferential torsional impact vibration relative to the torsional transmission intermediary assembly while bearing torque, so as to realize the torsional impact.

The characteristics of the device are as follows. The device can convert the longitudinal vibration into high-frequency torsional impact vibrations, and the number of torsional teeth can be changed according to the requirements of the site to meet the required high-frequency torsional impact vibrations. The working energy of the device comes from the longitudinal vibrations of the drill string, which increases with an increase in the well depth, and also increases the energy, thus reducing the damage caused by the drill string vibrations. The structure of the device is relatively simple, and the use of the process will not cause other harm.

4.3. Bottom-Hole Annulus Drilling Fluid Pressure-Reducing Device Based on Drill String Vibration

According to the field practice, reducing the pressure of the annulus drilling fluid can improve the rock clearing effect at the bit and change the stress state of the rock to be drilled. Scholars at home and abroad have proposed two methods to reduce the bottom-hole annulus drilling fluid pressure. The first method is underbalanced drilling, which improves the drilling efficiency, but is not widely applicable. The second method is to use down-hole tools to reverse the injection of part of the drilling fluid, which is implemented to reduce the bottom-hole annulus drilling fluid pressure. This method does reduce the bottom-hole annulus drilling fluid pressure, but reduces the amount of injected bottom-hole drilling fluid. This device is based on the energy generated by the drill string vibration to realize the bottom-hole annulus drilling fluid pressure reduction, which not only has wide applicability but also sufficient energy. The bottom-hole annulus drilling fluid pressure-reducing device based on drill string vibrations is shown in Figure 7 [41].

The basic structure of the device is as follows. The bottom-hole annulus drilling fluid pressure-reducing device is based on drill string vibrations, including central shaft and central shaft cylinder. The central shaft includes the force transmission shaft and the liquid separating piston. The cylinder in turn connected the spline cylinder, the elastic element protection cylinder, the joint, and the decompression cylinder. The elastic element is arranged between the elastic element protection cylinder and the force transmission shaft. The cylinder liner inside the decompression cylinder is installed outside the liquid separating piston, and the first liquid storage chamber is formed between the joint and the liquid separating piston, and the second liquid storage chamber is formed between the decompression cylinder and the liquid separating piston. The joint is provided with the first inlet channel and the first drainage channel, respectively, connecting the exterior and the first liquid storage chamber. The decompression cylinder is provided with the second inlet channel and the second drainage channel, respectively, connecting the exterior and the second liquid storage chamber. The first inlet channel and the exterior connecting end are provided with the first suction valve. The second inlet channel and the exterior connecting end are provided with the second suction valve. The second drainage channel and the exterior connecting end are provided with the second drainage valve. A stroke limit body is arranged between the force transmission shaft and the elastic element protection cylinder. The upper and lower ends of the elastic element in the elastic element protection cylinder are, respectively, connected with the stroke limit body and the joint.

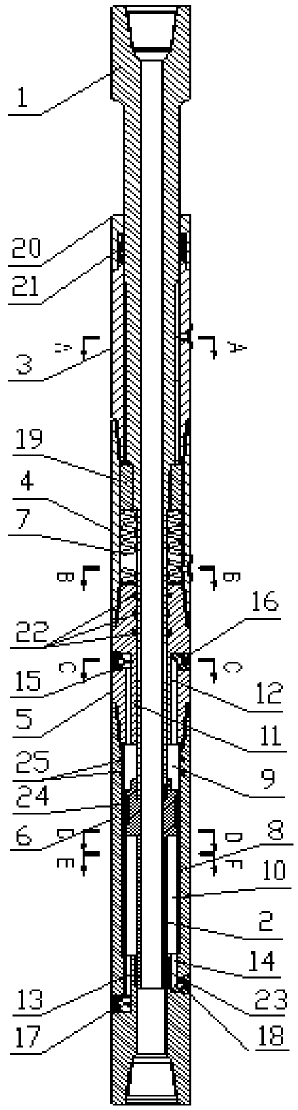


Figure 7. A structure diagram of the bottom-hole annulus drilling fluid pressure-reducing device based on drill string vibrations. 1: force transmission shaft, 2: liquid separating piston, 3: spline cylinder, 4: elastic element protection cylinder, 5: joint, 6: decompression cylinder, 7: elastic element, 8: cylinder liner, 9: first liquid storage chamber, 10: second liquid storage chamber, 11: first inlet channel, 12: first drainage channel, 13: second inlet channel, 14: second drainage channel, 15: first suction valve, 16: first drainage valve, 17: second suction valve, 18: second drainage valve, 19: stroke limit body, 20: seal end cap, 21: seal assembly, 22: joint seal, 23: scraping mud seal, 24: liquid separating piston seal, and 25: cylinder liner seal.

The working process of the device is as follows. When the drill string vibrates downward, the central shaft is pressed down, and the elastic element is compressed by pressure, the second suction valve of the second liquid storage chamber is closed, the second drainage valve is opened, the liquid in the second liquid storage chamber is discharged, the first liquid storage chamber produces negative pressure, the first suction valve is opened, the first drainage valve is closed, and the liquid in the first liquid storage chamber increases. At this time, the bottom-hole annulus drilling fluid flows upward rapidly, and the bottom-hole annulus drilling fluid pressure decreases. When the drill string vibrates upward, the central shaft rises, the elastic element is reset, the second liquid storage chamber produces negative pressure, the second suction valve is opened, the second drainage valve is closed, the second liquid storage chamber turns into the liquid, the bottom-hole annulus drilling fluid pressure is reduced, the first suction valve of the first liquid storage chamber is closed, the first drainage valve is opened, and the fluid is lifted up. The above process is reciprocated to realize the impulse pressure reduction in the drilling fluid in the bottom-hole annulus during the up and down vibrations of the drill string.

The characteristics of the device are as follows. The force generated by the drill string vibration is used as energy, the up and down movement of the device is realized by using elastic elements, and the pressure reduction in the ring hole drilling fluid is realized by using the change in the fluid direction in the two fluid storage chambers. The vibrations of the drill string and the generated energy increase with the increase in the well depth, and the continuous use can be achieved without treatment of the circulating media. The drilling operation can be carried out even if part of the tool is damaged, which reduces the harm caused by the vibration of the drill string. The device has the advantages of simple structure and stable performance. It does not need other specific drilling tools to cooperate with it when it is applied. The operation and construction of the device are the same as conventional drilling.

5. The Future Development Prospects of Speed-Raising Devices

At present, the amount of oil and gas development in the shallow strata is constantly decreasing, and domestic and foreign petroleum exploration and development gradually turn to the research and exploration of deep and ultra-deep wells, while the deep strata are faced with more complex problems, such as the complex lithology and energy supply of rock breaking. A variety of down-hole speed-raising devices have been designed at home and abroad to solve these problems. At present, some of the devices have been effectively applied and obtained good benefits. It can be seen that the development of speed-raising tools should pay more attention to the development characteristics of drilling engineering.

(1) The energy source and equipment diversification problem of drilling devices with an increasing ROP. Most of the current mainstream drilling speed tools reduce the energy of circulating media. With the increase in well depth, the energy decreases, and the ROP increase effect will also be weakened. Therefore, it is necessary to find more suitable energy to provide devices with an increasing ROP. Because of the complexity and diversity of formation lithology, the speed-raising methods are different, so it is necessary to develop a variety of new speed-raising devices and integrate them organically. (2) The drilling energy distribution problem. When the energy is used in the underground, and applied to all kinds of down-hole tools, such as the rotary punch drilling tool, which converts the hydraulic energy of the drilling fluid into an axial impact on the bit, the screw drilling tool converts the hydraulic energy of the drilling fluid into tools, such as bit speed. If the energy is properly distributed, the work efficiency can be greatly improved. (3) The problem of the cooperative use of down-hole devices with an increasing ROP. Down-hole power drilling tools are the most widely used tools in various oil fields, but the speed-boosting devices cannot be used in conjunction with down-hole power drilling tools, and the application is partially limited. If they can be used in conjunction with each other in the future, the direction of down-hole devices with an increasing ROP will be further developed. (4) The structure simplification problem of devices with an increasing ROP. Underground space with the increase in well depth will gradually shrink, but a worse environment can complicate the mechanical structure to failure. So, on the basis of securing the drilling speed, the structure of drilling devices with an increasing ROP for the drilling tool or a new speed tool design should be simplified. (5) The miniaturization problem of drilling tools. Under the condition of deep and ultra-deep wells, due to the long borehole trajectory, the existing speed-raising device faces the problem of the torque becoming too long when working underground, which will bring risks to drilling. Therefore, it is of great significance to shorten the size of the speed-raising device. (6) The problem of risk reduction during the use of drilling devices with an increasing ROP. No matter what kind of tool with an increasing ROP, it has a service life limit, and there will also be many emergencies. When the tool with an increasing ROP fails down-hole, avoiding any impacts

to normal drilling is very important to control the occurrence of down-hole risks. (7) The problem of reducing the cost of drilling technology with an increasing ROP. The design of down-hole speed-raising tools should not only meet the requirements of speed raising, but also reduce the drilling cost as much as possible. Otherwise, the research will not be of great significance.

6. Conclusions and Understanding

(1) In the modern international energy economic structure, the oil industry is a very important component, and at present, the development of oil and gas is paying more and more attention to the exploration of deep oil and gas.

(2) The low drilling speed and the weakening of energy transfer with the increase in well depth are two of the main problems that we face now.

(3) According to the field test results, the vibration reduction and pressurization devices that have actually been used can increase the penetration rate by more than 30%, and the tool life exceeds 200 h. This can meet the actual needs of the site.

(4) Using the kinetic energy generated by the vibration of drill string can not only solve the problem of energy supply, but also solve the problems of vibration destroying drilling tools and reducing rock breaking efficiency.

(5) The research and development (R&D) and application of these six devices in this paper have improved the drilling speed of deep and ultra-deep wells, and weakened the harm caused by drill string vibrations, laying a foundation for the development of drilling speed-increasing devices in the future.

(6) The technology of using drill string vibrations to improve drilling speed provides a new idea for deep well speed increases. We should speed up the pace of research in this direction, and make more reasonable use of down-hole energy.

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