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Multi-pulse width modulation control technology for an underground inclination correction hydraulic control system

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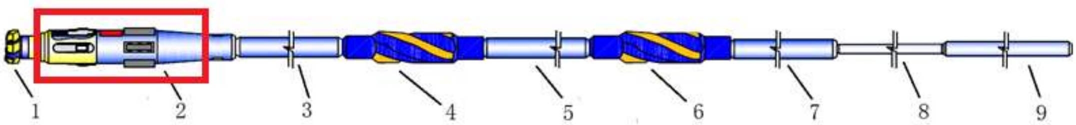
Abstract. Based on continuous adjustment of the underground inclination correction force in a pulse width modulation AADDS (Automaic Anti-Deviation DrillingSystem) automatic vertical drilling tool to address problems such as pulse width modulation induced significant fluctuation of the inclination correction force and instable relative orientation of a well's inclination, the optimization of the continuous control of the underground inclination correction force of this drilling tool is investigated. Two-position two-way electromagnetic valves in a hydraulic control system undergo multiple on/off controls (i.e., multi-pulse width modulation) in a drill rod rotational cycle T (i.e., a modulation cycle) without changing the existing structure, components and parameters of the drilling tool. The system inclination correction cylinder discharges the oil volume obtained in a cycle T multiple time instead of once. Additionally, a spring energy accumulator is added to leverage automatic conversion between hydraulic energy and elastic potential energy to effectively improve the stability of the inclination correction cylinder pressure and inclination correction force. Multi-pulse width modulation parameters are obtained via a mathematical model of a hydraulic control system. When the drill rod rotating speed is 65 r/min and its cycle is 0.923 s, the inclination correction hydraulic control system test shows that the fluctuation amplitude of the inclination correction cylinder modulation pressure via three-pulse width modulation with a spring energy accumulator is only 30% of the value of that via a single pulse width modulation.

1. Introduction

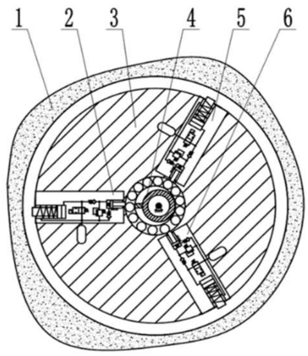
Reference [1] introduced an in-house developed hydraulic control inclination correction system for an AADDS automatic vertical oil drilling tool, which automatically adjusted the drilling tool position and corrected the drilling track when wellbore track deviation occurred during vertical well drilling. This inclination correction system is installed in the lower portion of the drilling tool (Fig. 1) and consists of a mechanical structure, a hydraulic sub-system, and a measurement and control sub-system. This device has three identical hydraulic sub-systems distributed evenly within a floating guided sleeve at a 120°

angle from each other (Fig. 2). The hydraulic pump piston points to the core axis, and the hydraulic cylinder piston rod points to the well wall. The eccentric bearing rotates with the drill rod, drives the movement of the hydraulic pump piston, and provides energy for the hydraulic system. The relief valve controls the system pressure, and the two-position two-way electromagnetic valve controls the direction of the hydraulic cylinder piston movement. The sensor measures the well inclination and tool surface angles, and the controller controls coordination between the three hydraulic cylinders based on predefined logic and real-time measurements. The hydraulic cylinder piston rod is applied to the well wall to generate inclination correction force and complete the inclination correction. Because this system is constrained by underground dimensions and structures, the hydraulic control sub-system control inclination correction force via a two-position two-way electromagnetic valve means the underground inclination correction force of this drilling tool cannot be adjusted continuously.When the inclination correction force cannot be adjusted continuously,there may be a problem that the direction of the inclination correction force of the drill is inconsistent with the relative well inclination direction (or gravity tool surface angle).This problem affects the underground inclination correction efficiency and the well inclination control accuracy of a drilling tool. To address this problem, a method to adjust the inclination correction force continuously by adjusting the pressure in the inclination correction hydraulic cylinder is proposed. On one hand, the continuous adjustment of hydraulic system pressure is normally implemented via a proportional pressure relief valve or servo valve; however, proportional pressure relief and servo valves have stringent medium and environmental requirements and require high power consumption, which are not suitable for a hydraulic control inclination correction system. On the other hand, the hydraulic actuator movement state could be adjusted via a switching valve control [2].A switching valve based on continuous pressure, volume, or actuator displacement control is a digital hydraulic technology. A switching valve using this technology has advantages such as a simple component structure, convenient control, low cost, high efficiency, and high system reliability [3,4,5,6] and has been deployed in systems such as an automotive internal combustion engine, air blower, and engineering machinery [7, 8, 9]. However, an electromagnetic switching valve control actuator has a non-linearity problem and increases pressure fluctuation [10]. High-speed switching valve control is normally based on pulse width modulation (PWM) technology and has been investigated extensively [11, 12, 13]. In view of this, based on the hydraulic theory of hydraulic control inclination correction system for an AADDS automatic vertical oil drilling tool, in this system, we investigated the method of employing two-position two-way electromagnetic valve PWM technology to adjust pressure. Practice proves that this method is feasible. This method supports continuous adjustment of the inclination correction force from the hydraulic control system without changing the structure, dimension, and component configuration of the drilling tool [2]. In this paper, on this basis, the mechanism of inclination correction hydraulic control system pulse width modulation is analyzed, and a multi-pulse width modulation technology is proposed to optimize inclination correction force pulse width modulation and reduce the fluctuation amplitude of the system inclination correction force. This method reduces the fluctuation amplitude of the modulated inclination correction force output to its maximum extent and also provides a new idea for the application of PWM technology.



1 - drill bit; 2 - AADS guided tool; 3, 5, 7, and 8 - drill collars; 4 and 6 - stabilizers; 9 - drill rod

Fig. 1 Basic structure of a dual-stabilizer vertical guided well drilling system

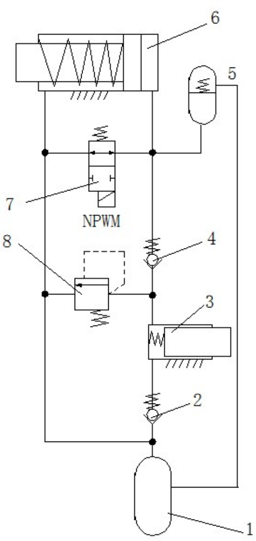


1 - well wall; 2 - integrated hydraulic block A and its hydraulic system; 3 - floating guided sleeve; 4 - core axis; 5 - integrated hydraulic block B and its hydraulic system; 6 - integrated hydraulic block C and its hydraulic system

Fig. 2 Hydraulic system of an AADDS guided tool

2. Principle of pulse width modulation for a hydraulic control inclination correction system

Fig. 3 shows the schematic diagram of the hydraulic principle for an inclination correction system with a spring energy accumulator. In the diagram, the piston of hydraulic pump 3 is driven by an eccentric bearing embedded in the drill rod. The eccentric bearing converts the drill rod rotation into piston linear movement. The piston works with the cylinder reset spring, unidirectional oil suction valve 2, and unidirectional oil discharge valve 4 to complete the single piston pump oil suction and discharge. In Fig. 3, relief valve 8 limits the maximum pressure from the piston pump, and this pressure corresponds to the maximum inclination correction force from inclination correction cylinder 6. Two-position two-way electromagnetic valve 7 is a system control component. When the electromagnetic valve is off, the inclination correction cylinder has no output. A Peltry compensation oil cylinder is used to prevent mud from entering the hydraulic system, to balance the underground annulus pressure, and to provide piston pump oil suction capability.



1 - Peltry compensation oil box; 2 - unidirectional oil suction valve; 3 - single piston pump; 4 - unidirectional oil discharge valve; 5 - spring energy accumulator; 6 - inclination correction hydraulic cylinder; 7 - electromagnetic valve; 8 - relief valve

Fig. 3 Hydraulic principle of a hydraulic control inclination correction system

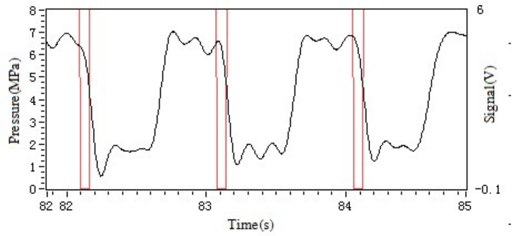
Although in principle, when the fluid entering the inclination correction cylinder is regulated by an electromagnetic valve as shown in Fig. 3, the inclination correction force from the inclination correction cylinder can be adjusted continuously in a certain range, due to a peculiarity of this hydraulic control system, it is very difficult to implement pulse width modulation in this system. First, different from a constant oil source in a conventional high-speed switching valve proportion control system, the operation cycle of a piston pump in this system is a drill rod rotation cycle (approximately one half cycle of oil suction and one half cycle of oil discharge). Therefore, the pump output volume is a cyclic pulse, which increases the fluctuation of the system pressure. Second, the switching valve response speed has a significant impact on the control result; however, the electromagnetic valve in this system is not a switching valve specialized for pulse width modulation. As the power supply of the electromagnetic valve is a dry battery, to ensure at least 240 hours of continuous operation underground, the electromagnetic valve driving power is limited to 0.3 W, which means that the electromagnetic valve cannot achieve a quick response and large control volume. Third, to reduce the response requirements for the high-speed switching valve, the saturated zone, and the dead zone non-linearity of the controlled variable, multiple high-speed switching valves should be deployed in every control edge; however, constrained by volume and energy supply, this system cannot be implemented, which increases control difficulty. The fourth point is, as the inclination correction cylinder volume is small, the inclination correction force from the inclination correction cylinder is very sensitive to a variation of fluid in the cylinder.

the basic idea of pulse width modulation proposed for the system in Fig. 1 is as follows: the system pulse width modulation cycle is set to the drill rod rotation cycle T; at a point at the half cycle of the piston pump oil discharge, the electromagnetic valve is turned off for a predefined period Δt ($\Delta t < T/2$) to release all the hydraulic oil from the oil pump in the discharge phase back to the oil cylinder, thus controlling the inclination correction force from the inclination correction cylinder near a predefined amplitude. In this case, Δt is related to the target modulation pressure of the inclination correction cylinder or the predefined inclination correction force. When the system structure and parameter are determined, the value can be calculated accurately. Of course, in actual system operation, the actual inclination correction force for this Δt may be different from the calculated value. However, actual underground drilling primarily focuses on continuous control of the drilling tool inclination correction force; the requirement for accuracy of the inclination correction force has lower priority.

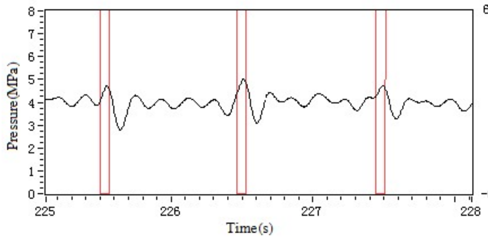
3. Principle of electromagnetic valve multi-pulse width modulation

3.1. Single pulse width modulation

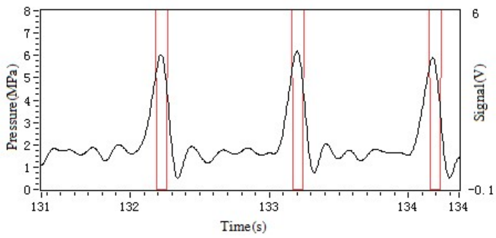
The current PWM method employs single pulse width modulation, i.e., only one pulse signal is generated in a single pulse width cycle. The basic idea of electromagnetic valve pulse width modulation is to create an equivalent opening for an electromagnetic valve core by applying a high frequency pulse width signal to an electromagnetic valve coil and changing the valve equivalent opening by adjusting the pulse width signal duty cycle [5, 14, 15]. However, this conventional PWM method is not applicable to the hydraulic control inclination correction system in this paper. The above analysis shows that the purpose of system pulse width control is not to create a valve core opening, but to release oil from the oil pump in a rotation cycle back to the oil cylinder via an electromagnetic valve. Therefore, compared with current fluid system PWM, the pulse width modulation of an inclination correction hydraulic control system has the following characteristics: (1) the pulse width modulation signal frequency is very low, approximately one to four Hz corresponding to the drill rod rotating speed; (2) the pulse width signal pulse width is determined by the target modulation pressure of the inclination correction cylinder; and (3) in a pulse width modulation cycle, the electromagnetic valve off-pulse position has a significant impact on the inclination correction force fluctuation amplitude. When the target modulation pressure is four MPa and the modulation cycle is one second, the electromagnetic valve off-pulse signals are at the initial, middle, and final stages of the oil pump oil suction phase. The test curves of the inclination correction cylinder modulation pressure variations are shown in Figs. 4(a), (b), and (c). The figures show the off-pulse effect is the best around the center of the oil discharge section.



(a)



(b)



(c)

Fig. 4 Effect of off-pulse position on modulation pressure

3.2. Multi-pulse width modulation

When the drill rod rotating speed is determined, the oil volume from the piston pump in a rotation cycle is fixed. When the electromagnetic valve opens (off), the oil in the oil pump and inclination correction cylinder will be discharged via the electromagnetic valve and the cylinder pressure declines. When the electromagnetic valve closes (on), the oil in the oil pump enters the inclination correction cylinder directly and the cylinder pressure rises. Therefore, single pulse width modulation always leads to a significant fluctuation in pressure in the hydraulic cylinder [5, 10]. However, if oil from the oil pump is discharged several times, the pressure fluctuation in the inclination correction cylinder will effectively be reduced. When the spring energy accumulator is added, the conversion between hydraulic energy and elastic potential energy in the spring energy accumulator reduces the pressure fluctuation. This is the multi-pulse width modulation method that is elaborated in the following sections.

References [16~19] mentioned a pulse number modulation (PNM) method to build a digital hydraulic system. References [17, 18] proposed a method to replace a control edge of a proportional pressure relief valve with N switching electromagnetic valves, i.e., N switching valves replaced a proportional direction valve for the corresponding volume and pressure. Reference [17] proposed integration of pulse number modulation and pulse frequency modulation (PFM). PFM is used for low volume, while PNM is used for high volume. Therefore, the number of switching valves is effectively reduced, while the valve control system maintains high volume resolution. The method in references [17~19] explains the concept of multi-pulse width modulation. The switching valve in Fig. 3 is replaced by n identical parallel electromagnetic valves and each valve undergoes single pulse width modulation; however, the position of each valve off-pulse signal in the pulse width cycle and the width of each pulse do not have to be identical. In this way, oil from the oil pump is released in n rounds in a rotation cycle. Furthermore, if the pulse width and off position of each valve are adjusted properly so that an electromagnetic valve can complete n rounds of identical on/off in a pulse width modulation cycle, then the function of n parallel electromagnetic valves is integrated into a single switching electromagnetic valve. This is multi-pulse width modulation theory for an inclination correction hydraulic control system. That is, in a drill rod rotational cycle, n off-pulse signals are generated for switching an electromagnetic valve and each pulse signal guarantees a reliable closing of the electromagnetic valve before the next off-pulse signal; then, this hydraulic control system is an n pulse width modulation (NPWM) control system.

Fig. 5 shows a schematic diagram of a three-pulse width modulation signal; i.e., in a pulse width modulation cycle, three off-pulses are generated, whose widths are $\Delta t_1=t_2-t_1$, $\Delta t_{,2}=t_4-t_3$, and $\Delta t_3=t_6-t_5$. In the diagram, U and U_m are the drive voltages of the electromagnetic valve coil and the maximum voltage signal, respectively, and xv and xvm are the valve core displacement and the maximum valve core displacement, respectively.

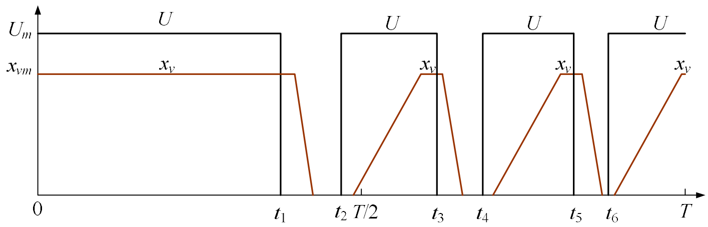


Fig. 5 Three-pulse width modulation synthesis signal

3.3. Determination of an off-pulse parameter

Fig. 5 shows that when the target modulation pressure of the inclination correction cylinder fluctuation upper and lower bounds have identical amplitudes, the fluctuation amplitude of the target modulation pressure reaches its minimum level. In multi-pulse width modulation, in addition to ensuring equal upper and lower fluctuation amplitudes for each off-pulse induced target modulation pressure, the fluctuation amplitude of each off-pulse induced target modulation pressure should be equal; i.e., if the target modulation pressure is P_c, then $\Delta P_c =|\Delta P_{ci}|=|-\Delta P_{ci}|$ (i=1, 2, …, n). Next, three-pulse width modulation in Fig. 5 is used as an example to investigate how to determine off-pulse widths Δt_i (i=1, 2, 3) and off-pulse initial positions t_1, t_3, and t_5.

Fig. 6 shows the variation of inclination correction cylinder modulation pressure versus pulse width signal corresponding to Fig. 5. In the diagram, (t_1, t_2), (t_3, t_4), and (t_5, t_6) show that the inclination correction cylinder and the energy accumulator discharge oil via the electromagnetic valve; thus, the pressure declines. Additionally, the minimum pressure is equal. ($T/2$, t_3), (t_4, t_5), and (t_6, T) show that the oil pump and energy accumulator fill the inclination correction cylinder with oil; the inclination correction cylinder pressure rises, and the maximum pressure is equal. To achieve the pressure modulation result in Fig. 6, the pulse width modulation parameter should be determined based on the volume-pressure and dynamic characteristics of the hydraulic control system. The basic method to determine an off-pulse parameter is introduced in the following section.

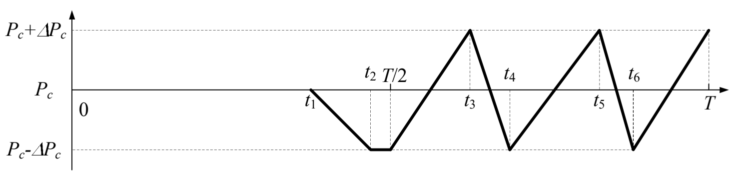


Fig. 6 Three calculations of the pulse width modulation parameter

To facilitate the problem description and simplify analysis, factors such as pump, valve, cylinder, and energy accumulator leakage within the system are not considered. Additionally, the effect of electromagnetic valve on/off delay and hysteresis is not considered. In the oil discharge phase of a rotational cycle, the volume from a single piston pump is as follows:

$$Q_p = A_p \dot{X}_p = -A_p L\omega \sin \omega t \quad (T/2 \le t < T) \tag{1}$$

Where A_p is the piston end area, m^2; L is the eccentricity of the eccentric bearing, m; and ω is the rotating speed of the drill rod, rad/s.

During inclination correction cylinder pressure modulation, the inclination correction cylinder piston is against the well wall and there will only be a tiny deformation. The spring energy accumulator's spring generates corresponding elastic deformation. The spring energy accumulator and the inclination correction cylinder are treated as a single element. Therefore, the flow equilibrium equation of this element is as follows:

$$Q_g = A_g \dot{X}_g + \frac{V_g}{\beta e} \dot{P}_g + A_a \dot{X}_a + \frac{V_a}{\beta e} \dot{P}_g \tag{2}$$

The equilibrium equation of the inclination correction cylinder is simplified as follows:

$$A_g P_g = K_e \Delta X_g + K_g X_g \tag{3}$$

The equilibrium equation of the energy accumulator is simplified as follows:

$$A_a P_g = K_a X_a \tag{4}$$

In (2), (3), (4), Q_g is the overall flow of the inclination correction cylinder rod-less chamber and energy accumulator, m^3/s; P_g is the pressure in the inclination correction cylinder rod-less chamber equal to the pressure in the spring energy accumulator chamber, MPa; A_g is the operational area of the inclination correction cylinder rod-less chamber, m^2; V_g is the compression volume of the rod-less chamber, m3; βe is the equivalent oil elastic modulus, MPa; X_g is the piston displacement, m; Xgm is the maximum piston displacement, m; $\Delta X_g = X_g - X_{gm}$ is the displacement increment of the piston rod after it is against the well wall, m; K_e is the equivalent stiffness of the piston rod, N/m; K_g is the stiffness of the inclination correction cylinder reset spring, N/m; A_a is the operational area of the energy accumulator piston, m^2; V_a is the volume of the spring energy accumulator chamber, m3; and Ka is the stiffness of the energy accumulator spring, N/m.

The electromagnetic valve does not contain a reset spring and has small mass. Therefore, the dynamic process of this valve is not considered. The valve flow equation in the power-off section is as follows:

$$Q_v(t) = C_d A_v \sqrt{2P_g / \rho} \quad (t \in (t_1, t_2) \cup (t_3, t_4) \cup (t_5, t_6)) \tag{5}$$

Where Q_v is the flow from the valve to the oil cylinder, m^3/s; C_d is the valve flow coefficient; A_v is the valve area, m^2; and ρ is the oil density, Kg/m^3.

It is obvious that there is only one off-pulse in the oil suction area. Therefore, as long as t_2-t_1<T/2 is satisfied, t_1 can be determined in (0, T/2) beforehand; t_2~t_6 are calculated via formulae (1)~(4). In the following section, the calculation of Δt_1 is used as an example.

When the inclination correction cylinder rod-less chamber pressure decreases by ΔP_c from P_c, the displacement increment of the inclination correction cylinder piston is calculated via formula (3).

$$\Delta x_g = A_g \Delta P_g / K_e \tag{6}$$

When the inclination correction cylinder rod-less chamber pressure decreases by ΔP_c from P_c, the displacement increment of the energy accumulator piston is calculated via formula (4).

$$\Delta x_a = A_a \Delta P_g / K_a \tag{7}$$

Based on formulae (2), (5), (6), and (7), there is:

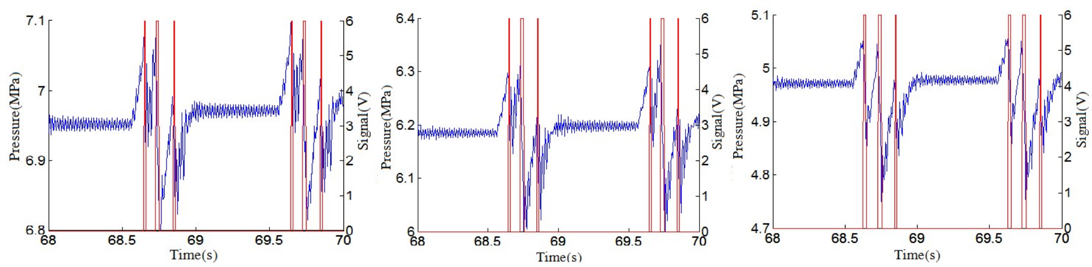
$$t_2 = t_1 + \frac{\sqrt{\rho}\Delta P_g}{C_d A_v \sqrt{2P_{g0}}} \left(\frac{A_g^2}{K_e} + \frac{A_a{}^2}{K_a} + \frac{V_0}{\beta_e} \right)$$

i.e.,

$$\Delta t_1 = \frac{\sqrt{\rho}\Delta P_g}{C_d A_v \sqrt{2P_{g0}}} \left(\frac{A_g^2}{K_e} + \frac{A_a{}^2}{K_a} + \frac{V_0}{\beta_e} \right) \tag{8}$$

Where P_{g0} is a value between P_c and P_c -ΔP_c that satisfies the integral mean value theorem and can be approximated as P_{g0}=P_c -$\Delta P_c/2$, and V_0 is the combined volume of the inclination correction cylinder and the energy accumulator operational chamber.

The rotating speed of the eccentric bearing in the inclination correction hydraulic integrated block is 60 r/min; the pulse width modulation cycle is 1 s; the relief valve pressure is set to 7.3 MPa; the energy accumulator piston diameter is 25 mm; the spring stiffness is 70 KN/m; the pre-compression is 1.2 mm; the maximum allowed piston stroke is 60 mm; and the maximum piston displacement is 50 mm. Figs. 7(a), (b), and (c) show the simulation curves of the inclination correction cylinder pressure when the target pressures are 7 MPa, 6 MPa, and 5 MPa, respectively. The curves show that after the energy accumulator is added, three-pulse width modulation technology reduces the pressure fluctuation to 0.3 MPa.



(a) (b) (c)

Fig. 7 Numerical simulation of pressure curves for three-pulse width modulation

Due to various factors in an actual inclination correction hydraulic control system such as leaks, delays, hysteresis, and parameter variations, an off-pulse parameter cannot be calculated accurately. Therefore, actual operational results may be different from the expected results, which are analyzed in the following section via testing.

4. Multi-pulse width modulation test and analysis

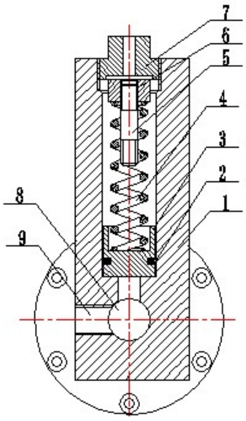
4.1. Overview of test equipment

To verify the feasibility of the multi-pulse width modulation method and the pressure stabilizing effect of the energy accumulator, test equipment for inclination correction hydraulic system performance simulation is built (Fig. 8). This system consists of a support stand, a guided hydraulic system, a transmission system, and a measurement and control system.

Fig. 8 Test equipment for inclination correction hydraulic system performance simulation

Support stand: The support stand fixes the guided hydraulic and transmission systems. Guided hydraulic system: The guided hydraulic system is a complete set of guided tools vertically installed on the support stand. Transmission system: The transmission system primarily consists of a frequency convertor, a three-phase asynchronous motor, a decelerator, a transmission axis, and a cam mechanism. The frequency convertor controls the motor's rotating speed; the transmission axis connects the decelerator with the cam mechanism and drives the cam rotation; the cam outer circle has contact with a single piston pump in the guided hydraulic system and drives the linear movement of the piston. Measurement and control system: The measurement and control system mainly consists of a computer, data collection card, pressure sensor, and switching power supply.

A computer is used as the controller, which includes an in-house developed control program for signal processing, parameter setting, signal generation, test data monitoring, and storage. The pressure sensor measures the pressure in the rod-less chamber and converts the pressure to an electric signal, whose measurement range is 0~10 MPa and whose output is 0~5 V. The data collection card NI6221 converts the electric signal from the pressure sensor to a digital signal that the computer can process and converts the control value from the control program (zero or one) to an electric signal (0 or 6 V) that the electromagnetic valve accepts. The pressure stabilizing energy accumulator is based on the spring structure. Fig. 9 shows a diagram of the energy accumulator structure. The spring energy accumulator consists of an energy accumulator cavity, piston, spring, and screw cap. The piston and cavity are sealed via a Glyd ring®. The piston diameter and spring stiffness are the same as the simulation parameters, and pre-compression is adjustable. Fig. 10 shows an image of the spring energy accumulator. In the test, the energy accumulator is installed on the inclination correction cylinder cap; the oil inlet is connected to the inclination correction cylinder rod-less chamber; and the pressure sensor is connected to the energy accumulator spring-less chamber.



1 - energy accumulator cavity; 2 - Glyd ring®; 3 - piston; 4 - spring; 5 - screw; 6 - cushion block; 7 - plug; 8 - oil inlet; 9 - pressure sensor installation hole

Fig. 9 Structure of a small spring energy accumulator

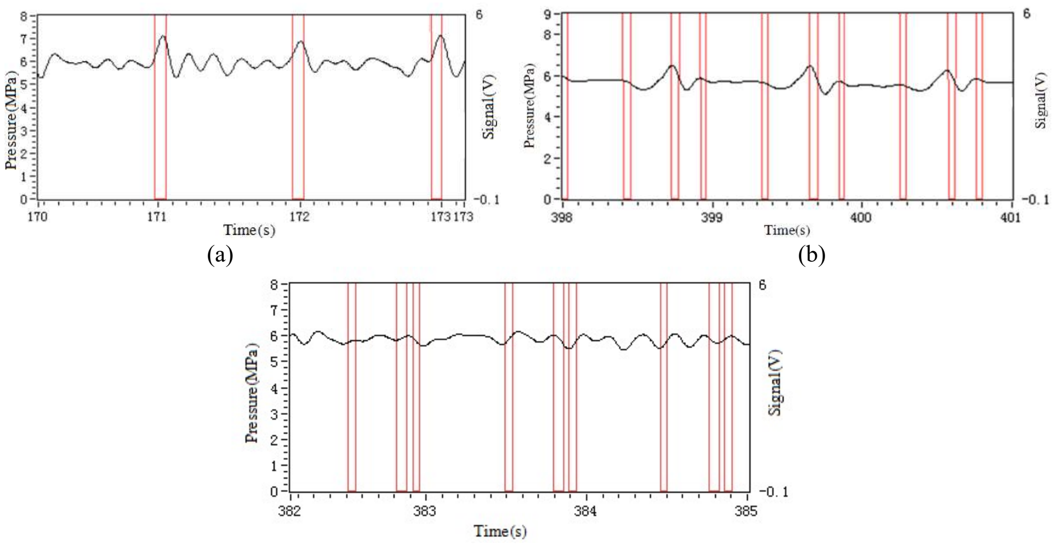
Fig. 10 Image of the energy accumulator during a test

4.2. Test procedures and result analysis

In the test, the motor's rotating speed is adjusted via a frequency convertor; the rotating speed of the eccentric bearing in the inclination correction hydraulic integrated block is controlled at approximately 65 r/min; and the pulse width modulation cycle is set to 0.923 s. The maximum pressure in the inclination correction cylinder is controlled by a relief valve at approximately 8 MPa. The test shows that in the hydraulic control system, the electromagnetic valve power-off delay and hysteresis is approximately 10 ms and the power-on delay and hysteresis is approximately 35 ms. Therefore, the actual width of each off-pulse on the electromagnetic valve exceeds 45 ms. A wider off-pulse results in increased oil discharge via the electromagnetic valve and lower target modulation pressure. The following test illustrates the effect of the number of system synthesis pulses and the width of the off-pulse on target modulation pressure in an inclination correction cylinder.

1. Effect of the number of synthesis pulses on the target modulation pressure

Assume the target modulation pressure is 6 MPa. Fig. 11(a) shows the inclination correction cylinder pressure curve for single pulse width modulation; (b) shows the three-pulse width modulation curve without an energy accumulator; and (c) shows the three-pulse width modulation curve with an energy accumulator. The three curves show the test results of single pulse width, three-pulse width modulation without an energy accumulator, and three-pulse width modulation with an energy accumulator.



(a) (b)

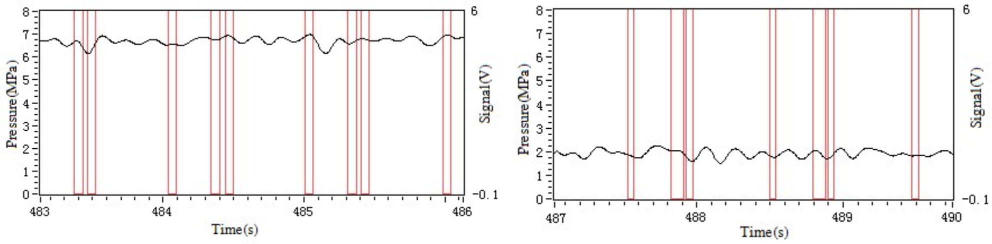
(c)

Fig. 11 Three-pulse width versus single pulse width modulation when Pc=6 MPa

Fig. 11 shows that three-pulse width modulation has significantly smaller maximum pressure fluctuation amplitude than single pulse width. After an energy accumulator is added, the three-pulse width modulation has maximum pressure fluctuation amplitude superior to the three-pulse width modulation without an energy accumulator. Although the target pressure generated by three-pulse width modulation with an energy accumulator has varied fluctuation amplitude, the maximum amplitude of the fluctuation reduces to 30% of the case for a single pulse width.

2. Effect of off-pulse width on target modulation pressure

In Fig. 12(a), the widths of the three off-pulses are 50 ms, 55 ms, and 50 ms. In (b), the widths of the three off-pulses are 50 ms, 90 ms, and 50 ms.



(a) P_c=7 MPa (b) P_c=2 MPa

Fig. 12 Effect of off-pulse width on target modulation pressure

Fig. 11(c) and Fig. 12 show that the off-pulse width of pulse width modulation can be changed to adjust the target modulation pressure continuously; force from the inclination correction cylinder decreases with the increase in the electromagnetic valve power-off period.

5. Conclusion

(1) Multi-pulse width modulation control technology is applied to an inclination correction hydraulic control system of an AADDS automatic vertical drilling tool to achieve continuous control of the

inclination correction force of the drilling tool. When a spring energy accumulator is added, the inclination correction force fluctuation reduces significantly, and the inclination correction control stability is improved. (2) Multi-pulse width modulation technology is a fluid modulation control method that synthesizes multiple single pulse width signals with identical modulation cycles but different duty cycles and pulse width delays into a single modulation signal. This method provides more precise control of a convective system based on the configuration of the original system. (3) Although multi-pulse width signal parameters can be calculated based on a system model, many factors are ignored in the calculation. Therefore, in actual operation, multi-pulse width signal modulation should be adjusted to achieve desirable results. Online optimization of multi-pulse width modulation control needs to be investigated further.

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