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Design of a Novel Electro-hydraulic Drive Downhole Tractor

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Abstract. In order to improve the traction ability and the work efficiency of downhole tractor in oil field, a novel electro-hydraulic drive downhole tractor was designed. The tractor’s supporting mechanism and moving mechanism were analyzed based on the tractor mechanical structure. Through the introduction of hydraulic system, the hydraulic drive mechanism and the implementation process were researched. Based on software, analysis of tractor hydraulic drive characteristic and movement performance were simulated, which provide theoretical basis for the development of tractor prototype.

1. Introduction
With the rapid development of horizontal well in petroleum exploration, it’s becoming more and more difficult to carry down logging and other instrument to well [1-2]. As the tool for transporting the underground instrument, the downhole tractor has been paid more and more attention and developed gradually [3].

The downhole tractor is also called horizontal well crawling robot, which can carry logging and drilling instrument to move in horizontal well, and the tractor power usually comes from itself or the drilling fluid[4]. In 1996, the cable wheel tractor was developed by Statoil, Maritime well services and Welltec. As the two most advanced tractors, SmarTract and Sondex are playing an important role in horizontal well development[5-6].

However, in the face of the complex oil well environment, the tractor has two key problems, how to raise the traction ability and how to move fast and steadily inside the pipe. Currently most tractors are driven by motors, which simplify the design, but reduce the drag ability and the speed. Some tractors are hydraulic driven, which selects the servo valve and proportional valve as the control component. Due to the stringent requirements of the hydraulic medium purity, this type increases the tractor operating costs and the accidents in the hydraulic system. At the same time, the small opening area of traditional valve usually causes the pressure loss and produces so much heat in the system to reduce the reliability of the tractor. Therefore, how to improve the traction ability, realize the steady walking and ensure operation security have become the key problems to develop the tractor.

In this paper, a new type of electro-hydraulic drive downhole tractor is proposed based on the analysis of the product and research before. The paper firstly introduces the mechanical structure of the tractor, analyzes the locking principle of the supporting mechanism and the moving principle of walking mechanism. Then the hydraulic system of the tractor is introduced and its hydraulic drive and control mechanism were analyzed. Finally, the walking process of the tractor is studied based on software, which researched the characteristics of hydraulic drive and the performance of the whole machine.

2. Mechanical Structure and Moving Principle
The mechanical structure of the horizontal well tractor is shown in figure 1, including the main body of the tractor and two moving mechanism modules which contain reciprocating cylinder 1, reciprocating cylinder 2 and supporting cylinder respectively. The cylinder body of supporting cylinder is connected to the piston rod of reciprocating cylinder 1. The piston rod of reciprocating cylinder 2 and the piston rod of the supporting cylinder are hinged to the supporting arm respectively.

Figure 1. Schematic diagram of tractor structure

2.1. Locking Principle of Supporting Arm

The mechanical locking principle of the supporting arm is shown in figure 2. The CAM is in contact with the pipe wall at point B under the torsional spring pretension force, O is the rotation axis of the CAM, \( F \) is the positive pressure of the CAM on the wall, \( \alpha \) is the angle between \( OB \) and positive pressure \( F \), \( \beta \) is the equivalent friction coefficient of the roller and the inner wall of the pipe. As \( \tan \alpha < \beta \) is satisfied, when the mechanism is under the action of \( F_1 \), the CAM turns away from the pipe wall, and the mechanism can move to the right overcoming the friction resistance. When the mechanism is under the action of \( F_2 \), CAM is rotating in the direction of the wall of extrusion, and the positive pressure and friction between the CAM and the wall is increasing, then the mechanism locks the inner wall of the pipe.

Figure 2. Diagram of supporting arm locking principle

2.2. Continuous Propulsion Principle

Figure 3 shows the schematic diagram of the continuous propulsion principle of downhole tractor. In initial state of figure 3(a), supporting arms are located at both ends of main body.

Figure 3 (b) is the work step 1, the both supporting arms move toward the middle. As the right supporting arm is pulled by the left force, its CAM turns clockwise and locks the wall. Under the reaction force, the main body of the tractor is pulled by the right reciprocating cylinder 1 and moving forward \( \Delta L \). As the left supporting arm is pulled by the right force, its CAM turns counterclockwise and releases the wall, the left supporting arm moves towards the right relative to body.

Figure 3 (c) is the work step 2, the both supporting arms move toward the opposite. As the left supporting arm is pulled by the left force, its CAM turns clockwise and locks the wall. Under the reaction force, the main body of the tractor is pulled by the right reciprocating cylinder 2 and moving . As the right supporting arm is pulled by the right force, its CAM turns counterclockwise and releases the wall, the right supporting arm moves towards the right relative to body.
It can be seen that the main body of the tractor moves forward two \( \Delta L \) at work step 1 and step 2, so that the rapid and efficient movement of the tractor can be realized.

3. Hydraulic System and Control Scheme

The hydraulic system is shown in Figure 4, including pump 4, the overflow valve 41 and several high frequency switch valves, SV 5i (i=1,2,3…8). The switch valve loop unit consists of two reciprocating hydraulic branches #1, #2 and two supporting hydraulic branches #3, #4.

By repeating the steps above, the tractor can achieve continuous motion.

4. Simulation and Discussion
Based on the analysis of mechanical structure and hydraulic drive mechanism of the tractor, the moving process is simulated by software. Setting the load of the tractor is 3000N, and the frictional force of each supporting mechanism is 300N. The piston diameter of the reciprocating cylinder is 50mm, the piston rod is 15mm, the piston diameter of supporting cylinder is 30mm, and the diameter of piston rod is 10mm.

According to the principle of hydraulic control of the tractor, the signals of switch valves in supporting module are set up, as shown in figure 5. According to signal period of the switch valves in two supporting modules, the action sequence diagram of the switch valves in reciprocating hydraulic branch are set, as shown in figure 6.

As can be seen from figure 5 and figure 6, the signal of each switch valve is the change of the form period of the rectangular wave, and the period is 2s. The signal levels are also switched according to the hydraulic drive principle of the tractor. Since all are the high frequency switch valves, the valve core response frequency are also large enough to ensure the continuity of the traction movement.

The kinematics characteristics of tractor reciprocating mechanism are simulated, as shown in figure 7. The response curve of the switch valves are shown in figure 8.

As shown in figure 7, the displacement curve and flow curve of the right reciprocating cylinder are obtained. The two curve cycles are also 2s, corresponding to the switch valve cycles. The red solid line indicates the reciprocating motion of the piston, and the maximum stroke is 0.4m, then it returns to the initial position at the end of the motion. The internal flow of the cylinder changes periodically and rises rapidly. Figure 8 shows the pressure change in cavities of reciprocating cylinder. As can be seen from the picture, the pressure of the two chambers changes periodically. Because of the function of the high frequency switch valve, the switching speed is fast, ensuring the continuous and steady operation of the tractor.

It is known by the tractor driving principle that the left reciprocating cylinder has the same characteristics. From the above simulation, it can be seen that the proposed electro-hydraulic drive tractor can realize continuous motion, and has better stability and reliability.

5. Conclusion
In this paper, a novel electro-hydraulic drive horizontal well tractor is presented. The embedded mechanical structure is applied to make the whole electro-hydraulic drive tractor more simple and compact, which can increase the pipe crossing performance. The motion principle and the continuous propulsion principle of the tractor are analyzed.

The hydraulic drive system is designed whose supporting mechanisms adopt hydraulic differential control to improve the tractor speed and efficiency. The inlet and outlet of all hydraulic cylinders are independently controlled with high frequency switch valves, which can enhance anti-pollution ability, reduce loss of valve body throttling and improving the reliability. Finally, the kinematics characteristics and hydraulic characteristics of the continuous moving are analyzed based on simulation, which can lay theoretical basis for the development of tractor.

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