

Research on Hydraulic Performance of Downhole Traction Robot in Oil Field

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Abstract. one hydraulic telescopic downhole traction robot is developed to increase its drawing ability and motion performance. The basic mechanical structure of tractor is introduced. Continuous movement mechanism and concrete implementation are analyzed. The robot traction performance is researched based on the analysis of support characteristic. The mathematical models of the hydraulic system are established for hydraulic component performance analysis. The simulation on tractor hydraulic system is obtained, and the synchronicity and periodicity of the whole machine movement are analyzed.

1. Introduction

In recent years, the application of in-pipe robot become more and more widely, especially in oil field. An in-pipe robot called Downhole Traction Robot (the following abbreviated as *DTR*) is a kind of in-pipe robot which can accomplish special tasks in the oil underground environment and have the capacity for independent operation [1-2]. The *DTR* can realize the movement of logging and drilling equipment in horizontal well [3].

So far, main types divided from the drive way are rotating-wheel traction robot, motorized tracks robot, corkscrew design robot and the telescope in-pipe robot [4]. The earliest *DTR* is developed by Statoil, Maritime oil well and Welltec company, which has accomplished the first underground cables driving test at sea in 1996 [5]. In 2000, Western Well Tool launched a new full hydraulic driving tractor called Microhole Drilling telescopic Tractor [6], which has very strong power than any other tractors, but the complex hydraulic integrated design reduces the tractor reliability. In 2010, a unilateral self-locking mechanism was developed by SHANG. The mechanism enables the *DTR* to move quickly in one locomotion direction and to keep self-locking with the pipe wall in converse, realizing a high load capability beyond the friction limitation.

Due to the small size and hole narrow space limit, the most tractors are used by motor and screw drive resulting in negative influence, such as complicated structure, low mechanical efficiency and maintenance difficulty. Therefore, the latest development trend of *DTR* is to design the simple mechanism and reliable driving method to realize the powerful drawing ability.

One hydraulic drive telescopic *DTR* is developed in this paper. Hydraulic system is optimized on the basis of the advantages and disadvantages in the existing traction robot hydraulic system. On the analysis of *DTR* walking mechanism, the simulation on tractor hydraulic system and key hydraulic parts are obtained by the use of software, which can provide theoretical basis for design and development to *DTR*.



2. Structure and Movement Mechanism

2.1. Basic Structure of DTR

The drilling fluid driven telescopic *DTR* is designed for special requirements in horizontal well drilling condition, as shown in Figure 1, the robot composes of three parts including front hydraulic crutch (abbreviated as *FHC*), back hydraulic crutch (abbreviated as *BHC*) and hydraulic control unit (abbreviated as *HCU*). Each hydraulic crutch includes walking hydraulic cylinder, supporting hydraulic cylinder and three support claws put each other into 120 degrees in the well hole.

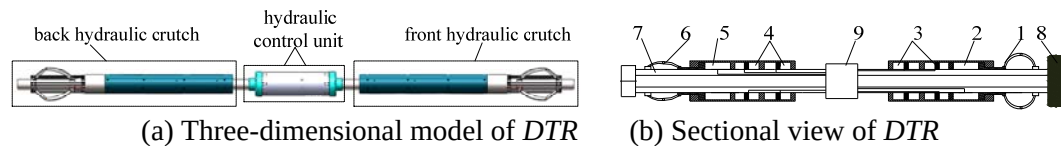


Figure 1. Structure diagram of *DTR*

1- front support claws, 2- front support hydraulic cylinder, 3- front walking hydraulic cylinder, 4- back walking hydraulic cylinder, 5- back support hydraulic cylinder, 6- back support claws, 7- center pipe, 8- drilling, 9- hydraulic control unit.

2.2. Movement Mechanism of DTR

DTR can realize continuous movement through periodic contraction and expansion of front and back crutches. Mechanism is shown in Figure 2, where the tractor right is selected as front end.

In the initial state, front support claws and back support claws was contracting; as the tractor starts in state 1, the high pressure hydraulic (abbreviated as *HPH*) flow to front support hydraulic cylinder leading to the front support claws hold tight the well wall, also *HPH* flow to the left cavity of the front walking hydraulic cylinder to accomplish the movement of the piston and center pipe; at the same time, the back support claws maintain contracting state because of the low pressure hydraulic, *HPH* flow to the right cavity of the back walking hydraulic cylinder to realize the movement of *BHC* relative to the center pipe. In state 2, *HPH* flow to the back support hydraulic cylinder and the left cavity of the back walking hydraulic cylinder, which leads to the expansion of the back support claws and the movement *S* of center pipe, also the front support claws maintain contracting state because of the low pressure hydraulic, *HPH* flow to the right cavity of the front walking hydraulic cylinder to realize the movement.

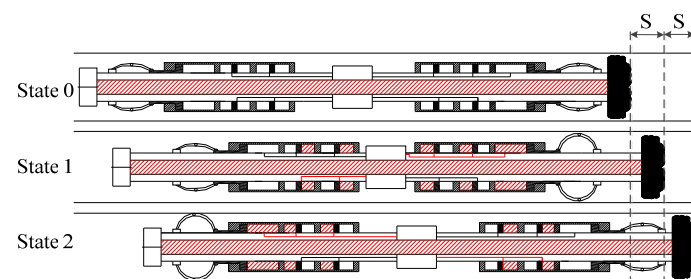


Figure 2. Diagram of continuous movement mechanism

The specific *DTR* movement process is as follows: Firstly the drilling fluid introduced through the center pipe used for drill rig is filtered through the filter unit, forming the hydraulic medium of system to enter into *HCU*. As the pressure is greater than P_0 , the hydraulic can flow into the main valve which is in state of the *B1*, *B2* conduction, as shown in Figure 3. Through *B1* port, the *HPH* flow into the front support hydraulic cylinder and the left cavity of front walking hydraulic cylinder. The front support claws maintain expanding state and holding tight well wall because of the high pressure hydraulic. The *HPH* in the left cavity of front walking hydraulic cylinder drive front piston and center pipe moving forward, and the *LPH* flow out through *B2* port.

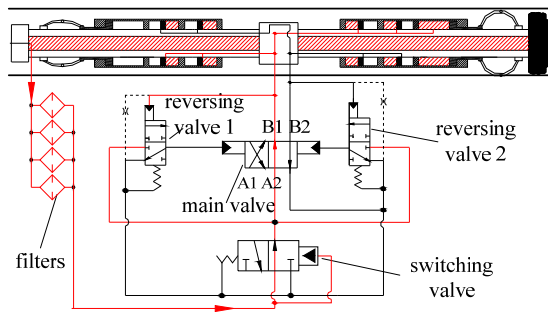


Figure 3. hydraulic system in state 1

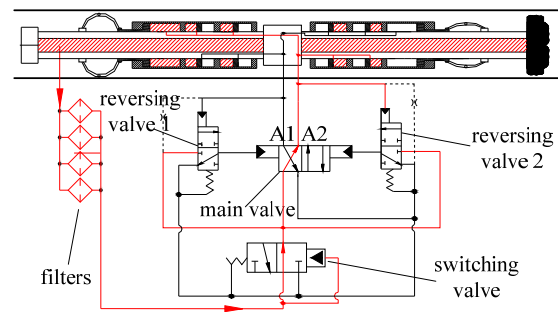


Figure 4. hydraulic system in state 2

At the end of the stroke phase, the pressure in the left cavity of front walking hydraulic cylinder increases dramatically. As the pressure increases to P_1 , reversing valve 1 conducts to drive main control valve switch conduction location, that's B1, B2 fall into shut, A1, A2 in the conduction. Then the *HPH* flow into the corresponding cylinders to continue the next action, as shown in Figure 4. Since then, the movement process of *BHC* is the same as the working process of the *BHC*. So the above actions, *DTR* can realize continuous movement under the full hydraulic pressure driven.

3. Mathematical Model of *DTR* Hydraulic System

This section is set to establish hydraulic components mathematical model, mainly including the flow continuity equation and momentum differential equation of the component.

3.1. Characteristic of Flow Pressure

Directional control valve flow pressure characteristic equation:

$$q_v = C_c C_v \cdot A_v \sqrt{\frac{2\Delta P}{\rho}} = C_d \cdot A_v \sqrt{\frac{2\Delta P}{\rho}} \quad (1)$$

Where, q_v is the flow of valve body hole, C_c is the shrinkage coefficient, C_v is the velocity coefficient, C_d is the flow coefficient, A_v is the flow area of the port.

The flow continuity equation of hydraulic cylinder:

$$Q_c = \frac{A_c x_c}{E} \frac{d(P-T)}{dt} + A_c \frac{dx_c}{dt} \quad (2)$$

Where, Q_c is the flow into the cylinder cavity, E is the liquid bulk modulus, A_c is circular cross section area on the piston rod, x_c is the displacement of the piston.

3.2. Motion Differential Equation Analysis

Movement differential equation of directional valve spool:

$$M_v \frac{d^2 x_v}{dt^2} = \sum P_v - F_{fv} - F_{nv} - F_{sv} - F_{pv} \quad (3)$$

Where, M_v is the quality of directional valve spool, x_v is the displacement of directional valve spool, P_v is the fluid pressure acting at directional valve spool, F_{fv} is the viscous resistance acting at the spool.

Movement differential equation of hydraulic cylinder piston rod:

$$M_c \frac{d^2 x_c}{dt^2} = \sum P_c - F_{fc} - F_{nc} \quad (4)$$

Where, M_c is the quality of piston rod, P_c is the liquid pressure acting at piston, F_{fc} is the viscous resistance acting at piston, F_{nc} is the friction force in the piston.

Ignoring some minute quantities, further motion differential equations for the hydraulic cylinder piston rod is got:

$$M_c \frac{d^2 x_c}{dt^2} = P_B A_c - P_a A_c - B \frac{dx_c}{dt} \quad (5)$$

4. Simulation for Hydraulic System

In this section, the hydraulic system of *DTR* is simulated. Where, the *DTR* working state is as following: motor speed is 1000 *RPM*, output flow of quantitative pump rate of is 80 L/min, two walking hydraulic cylinder stroke are 150 mm, the diameter of piston is 120 mm, the diameter of piston rod is 90 mm, and the traction load is set to 50000 N.

4.1. Single Component Analysis

The simulation time is set to 10s, and results are worked out below. Figure 5 is the piston motion curves of walking hydraulic cylinder. The hydraulic cylinder piston do reciprocating motion, whose cycle time is 3.4 seconds and stroke is 150 mm. As curves show that the periodic motion, which proves that *DTR* traction is equal to the load.

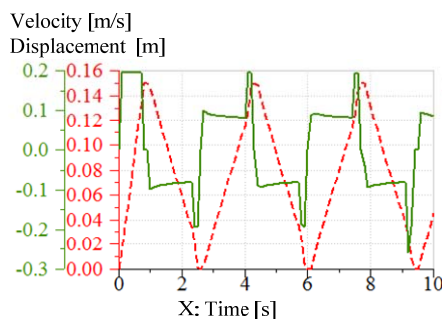


Figure 5. Movement of cylinder piston

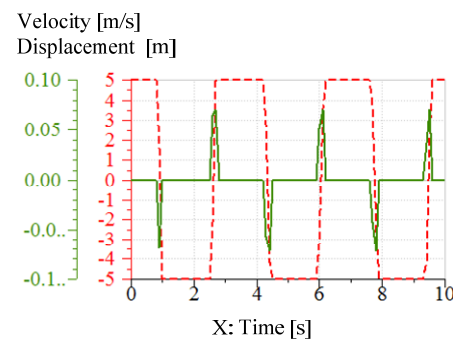


Figure 6. Movement of main valve spool

Figure 5 also shows the kinematics characteristics of *DTR*. The dotted line is the piston displacement curve: the initial displacement of piston is 0 mm, where is in the most left side. The piston starts moving as the high pressure hydraulic flowing. After the displacement is 150 mm, the direction of piston movement changes, piston move back to the position of 0 mm, and keep for the reciprocating movement same as the above process.

The solid line shows the velocity curve of the piston. It can be seen that the tractor speed can reach 0.1m/s as the tractor is stable. The piston of hydraulic cylinder can accomplish switching in a very short time. From what has been discussed above, *DTR* can walk forward continuously through the reciprocating motions of hydraulic cylinders, which can meet the performance index requirements.

In order to explore the switching performance of hydraulic system, the movement curve of main control valve spool is simulated, which can indicate the switching characteristics of the tractor. As shown in Figure 6, the displacement of the main control valve spool is a periodic change, and the displacement (dotted line) is between -5 and 5 mm. As shown in the central solid line, the maximum switching speed (solid line) of the main control valve spool can reach 0.07 m/s, which is good for action sensitivity of the whole tractor.

4.2. Synchronization Analysis

The characteristics of single cylinder and valve are analyzed above, which is not enough to study movement characteristics of *DTR* as a whole. So the alternate action of the two reversing valves and the synchronization feature of two walking hydraulic cylinders will be analyzed below.

Figure 7 shows the pressures of the two walking cylinder port1. By the graph, we can see that the working pressure of two hydraulic cylinders stabilize at about 120 bar, return pressure is about the 16 bar. When the piston rod move at the ends of the hydraulic cylinder, the oil pressure can be up to 150 bar in a short period of time, which can make reversing valve move to result in the main valve reversing.

Finally, the kinematic characteristics of the two walking hydraulic cylinders are analyzed. As shown in Figure 8, driven by hydraulic system, the movements of two piston rod of walking hydraulic cylinder is almost completely synchronized and reversed, which meets the movement demand of *DTR*.

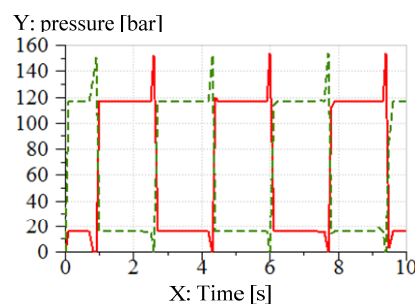


Figure 7. Pressures of walking cylinder

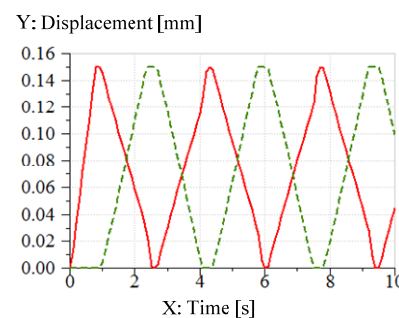


Figure 8. Displacements of walking cylinders

5. Conclusion

A new type of hydraulic drive telescopic downhole traction robot was proposed, and the hydraulic system was optimized. Then the movement mechanism and concrete implementation process of *DTR* were analyzed. The characteristics of hydraulic components and the kinematics hydraulic system were simulated, which indicated that the moving speed of the tractor can reach 0.1m/s and the traction force is 50KN. In addition, the paper simulates the movement of the whole traction robot and the synchronicity of the hydraulic cylinders which can lay the foundation for the prototype development of the *DTR*.

Acknowledgments

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