Fault Analysis and Diagnosis of Downhole Traction Robot Hydraulic System

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Abstract

Fault diagnosis of downhole traction robot has characteristics of special mechanical structure, complicated working condition and lack of research data. In this paper, a method of fault analysis and diagnosis of tractor hydraulic system based on model is presented. The failure mode and mechanism of key components in telescopic hydraulic system are analyzed. The fault diagnosis of hydraulic system is proposed based on the mathematical model of hydraulic component. Based on AMESim, the fault model of hydraulic system is established, and the diagnosis of single fault and multifault are simulated, which can collect the fault data and the specific diagnosis process. To carry forward the engineering application, the simulated internal leakage system in cylinder is set up and schemes of fault diagnosis are carried out, which prove that the diagnosis is consistent with theoretical

analysis and simulation. The research on fault analysis and diagnosis of the downhole traction robot hydraulic system not only lays theoretical basis for the tractor fault detection, but also provides guidance for the construction and implementation of the diagnostic system.

Keywords: Fault analysis and diagnosis, downhole traction robot, hydraulic system, mathematical model.

1 Introduction

With the development of horizontal well technology, downhole traction robot has been widely used in drilling, logging and other underground operations [1–3]. Durability and reliability in tractor operations are increasingly challenging, because of high temperature and high pressure environment. Therefore, it is significant to ensure that downhole tractor works normally and stably in extremely complex environments [4–6].

Downhole traction robot has a limited number and complex structure, its reliability is a typical small sample and multi-stage problem, which cannot be evaluated by traditional large sample statistical tests. So, the fault diagnosis for downhole robot should be researched from the point of fault mechanism, which is based on the mathematical model of each component. Also, in this way, a large number of failure data can be collected to provide the basis for the further fault diagnosis. The existing fault diagnosis and methods of traditional hydraulic equipment can provide a good reference for the fault diagnosis of tractor hydraulic system [7–10]. Chen studied the influence in the sizes of overflow valve damping hole on pressure overshoot, transition time and adjusting pressure. Also, some researches on fault injection for machinery hydraulic system are also widely carried out based on the simulation software [11–13]. Zhou carried out a simulation research on hydraulic system leakage based on AMESim, which can be used to judge the location and cause of leakage fault [14]. Zhang analyzes the causes of leakage in the piston pump by taking the eccentric annular gap of the piston pair as the research object. By changing the size of the annular gap, the pressure and flow are simulated, to realize the injection of internal leakage fault [15]. Chen simulated the common fault conditions and collect sample data based on AMESim software, and the BP neural network was applied for fault simulation training and diagnosis test [16].

In this paper, the structure of downhole traction robot and its working principle and operation features are introduced. The telescopic hydraulic

system is selected as the research object, and mathematic models for some key components are established based on the analysis of failure mechanism. Through the application of AMESim, the typical fault models and simulation system can be built to verify the feasibility of fault diagnosis. Finally, in order to verify the practical effect of the fault diagnosis, the experimental system of internal leakage in telescopic cylinder is built, and some trials will be carried out for rapid diagnostic test.

2 Mathematical Model

2.1 Description of Hydraulic System

Figure 1 shows the prototype of downhole traction robot based on one-way locking mechanism. The tractor consists of mechanical structure including two locking mechanisms and one telescopic mechanism, hydraulic system and the controller integrated in the body. The tractor movement is realized by alternating locking between the both locking mechanisms and the expansion of telescopic mechanism.

There are some key components in hydraulic system, including asymmetric hydraulic cylinder which can realize locking and expanding, reversing valve which controls the motion direction of hydraulic cylinder, speed control valve which is responsible for the moving speed, motor and hydraulic pump which provide energy for the whole machine. Because of modular design and similar configuration, hydraulic system in telescopic mechanism is selected
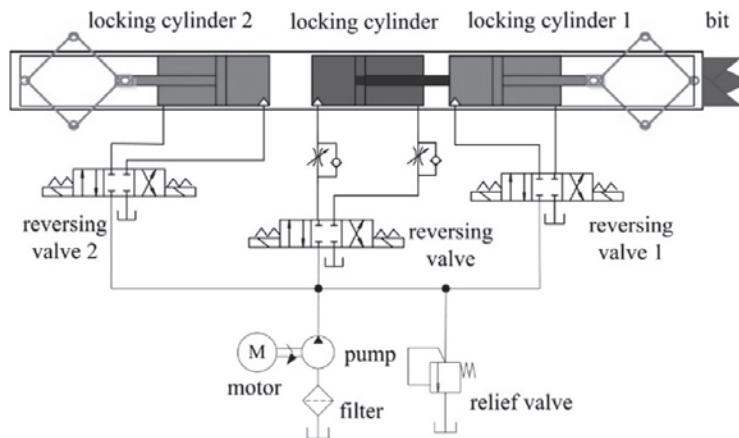

Figure 1   Diagram of downhole traction robot system.

as the object for fault analysis and diagnosis, and the research methods can be applied to the downhole traction robot for the other fault diagnosis.

2.2 Mathematical Model

It is known in previous operations that hydraulic cylinder, speed control valve and reversing valve have a high frequency of failure. Therefore, some typical faults in the three components are analyzed. The corresponding mathematical models are established below.

2.2.1 Model of hydraulic cylinder

In hydraulic cylinder, the most typical fault is leakage, which is caused by a broken seal. Due to the fluid flow between both cylinder cavities, the leakage usually affects the motion of cylinder piston. In the telescopic mechanism hydraulic system, the schematic diagram of cylinder is shown in Figure 2.

Combined with cylinder speed, pressure, the flow equation can be expressed as:

$$\begin{cases} q_1 = A_1 \dot{x} + \dfrac{1}{\beta} V_1(x) \dot{p}_1 \\[3mm] q_2 = A_2 \dot{x} - \dfrac{1}{\beta} V_2(x) \dot{p}_2 \end{cases} \tag{1}$$

where, A_1 and A_2 are the areas of big cavity and rod cavity, respectively, p_1 and p_2 are the pressures of the both cavities. x is the displacement, V_1, V_2 are the volumes of the two cavities, β is the bulk elastic modulus of the fluid.

When cylinder is leaking, the flow equation above is expressed as follow,

$$\begin{cases} q_1 = A_1 \dot{x} + \dfrac{1}{\beta} V_1(x) \dot{p}_1 - q_l \\[3mm] q_2 = A_2 \dot{x} - \dfrac{1}{\beta} V_2(x) \dot{p}_2 + q_l \end{cases} \tag{2}$$
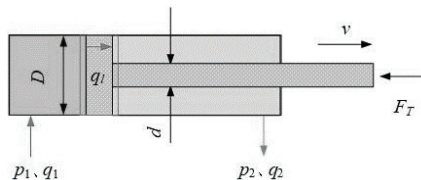

Figure 2   Schematic diagram of telescopic hydraulic cylinder.

where, q_l is the internal leakage.

When working pressure is steady, the formula of internal leakage is obtained.

$$q_l = \frac{A_1 q_2 - A_2 q_1}{A_1 + A_2} \tag{3}$$

Therefore, deviation estimator can be used to detect the leakage in cylinder.

$$\hat{e} = \frac{A_1 q_2 - A_2 q_1}{A_1 + A_2} \tag{4}$$

2.2.2 Model of speed control valve

In hydraulic system of downhole robot, the structure of speed control valve is shown in Figure 3. Because drilling fluid is the transmission medium with many solid particles, speed valve is prone to blockage. Figure 3(b) shows simplified model of speed control valve.

The flow expression in reducing valve is obtained.

$$q_{v1} = C_{d1} W_1 x \sqrt{\frac{2}{\rho}(p_1 - p_2)} \tag{5}$$

where, q_{v1} is the flow through reducing valve, C_{d1} is the flow coefficient, W_1 is the area gradient. x is the opening of the valve port. p_1 is the input pressure. p_2 is the output pressure.

The flow expression in throttling valve is obtained.

$$q_{v2} = C_{d2} W_2 y \sqrt{\frac{2}{\rho}(p_2 - p_3)} \tag{6}$$
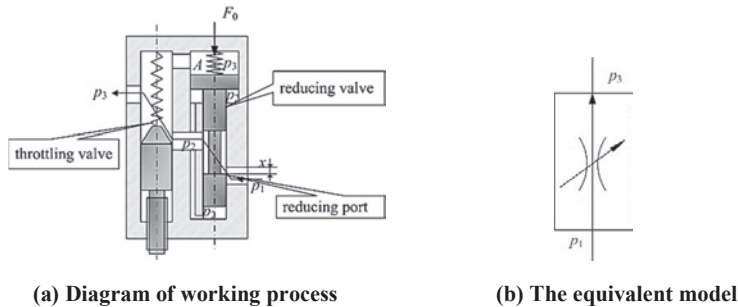

(a) Diagram of working process   (b) The equivalent model

Figure 3   The structure diagram of speed control valve.

where, q_{v2} is the flow through the throttle valve. C_{d2} is the flow coefficient, W_2 is the area gradient. y is the opening of the valve port. p_3 is the output pressure.

Ignoring the friction between the spool and valve body, force balance on reducing valve spool can be expressed.

$$K_w(x_1 - x) = A(p_2 - p_3) + F_0 \tag{7}$$

where, K_w is the spring stiffness, x_1 is the pre-compression of spring; A is the effective area on spool. F_0 is the stable hydraulic force.

$$F_0 = 2C_{d1}C_vW_1x(p_1 - p_2) \tag{8}$$

Combining Equations (5), (6), (7) and (8), flow expression in the speed control valve is got as follow.

$$q_{v0} = C_{d2}W_2y_0\sqrt{\frac{2}{\rho}\frac{K_wx_1}{A}}\left[\frac{1 - x/x_1}{1 + 2C_vC_{d2}^2W_2^2y^2\cos\theta/(AC_{d1}W_1x)}\right]^{1/2} \tag{9}$$

For a specific speed control valve, the offset x of the reducing valve spool is far less than the pre-compression x_1 of the spring, $C_{d2}^2W_2^2y^2 \ll AC_{d1}W_1x$, so q_{v0} can be expressed as $C_{d2}W_2y_0\sqrt{\frac{2}{\rho}\frac{K_wx_1}{A}}$.

The fault in the speed control valve changes the value opening y and effect the steady flow. So, the difference between the theoretical flow q_{v0} and the actual flow q_v can be used as the deviation estimator to detect the blockage failure.

$$\hat{e} = q_{v0} - q_v = C_{d2}W_2y_0\sqrt{\frac{2}{\rho}\frac{K_wx_1}{A}} - q_v \tag{10}$$

2.2.3 Model of reversing valve

According to the actual operation, the main faults of reversing valve include the insufficiency of spool opening and internal leakage Schematic diagram of the reversing valve in the telescopic hydraulic system is shown in Figure 4. Port P is the high pressure port, and port T is the low pressure port. Port A and port B connect the two cavities respectively. Figure 4(b) is the diagram of computational model, which is used to establish the mathematical model.
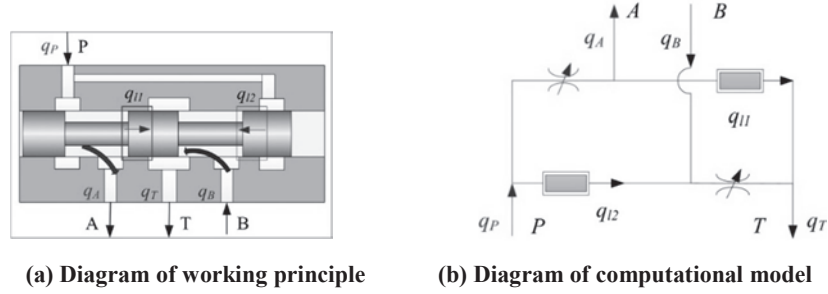
(a) Diagram of working principle   **(b) Diagram of computational model**

Figure 4   Schematic diagram of the reversing valve.

2.2.3.1 *The internal leakage diagnosis*

When the leakage occurs, the flow of reversing valve can be expressed.

$$q_P = q_A + q_{l1} + q_{l2} \tag{11}$$

$$q_T = q_B + q_{l1} + q_{l2} \tag{12}$$

$$q_A + q_{l1} = C_{d1}W_1x_1\sqrt{\frac{2}{\rho}(p_P - p_A)} \tag{13}$$

$$q_B + q_{l2} = C_{d2}W_2x_2\sqrt{\frac{2}{\rho}(p_B - p_T)} \tag{14}$$

Combining Equations (11) and (12),

$$q_{l1} + q_{l2} = q_P - q_A = q_T - q_B \tag{15}$$

So, the leakage estimator can be selected.

$$\hat{e} = q_P - q_A \tag{16}$$

Due to the low accuracy when using two flow signals at the same time, it can be judged by combining the pressure signal.

So, the leakage can also be expressed.

$$q_{l1} = C_{d1}W_1x_1\sqrt{\frac{2}{\rho}(p_P - p_A)} - q_A \tag{17}$$

The leakage estimator is obtained below.

$$\hat{e} = C_{d1}W_1x_1^0\sqrt{\frac{2}{\rho}(p_P - p_A)} - q_A \tag{18}$$

2.2.3.2 *The spool opening diagnosis*

The insufficiency of reversing valve opening causes throttling. Using the actual output pressure and input pressure, the theoretical flow can be calculated. Therefore, the fault can be analyzed by the difference between the theoretical flow and the actual flow.

The normal opening is x_1^0, and the opening coefficient is α ($0 \leq \alpha \leq 1$), When the opening is $x_1 = \alpha x_1^0$, the actual flow at port P is obtained.

$$q_P = C_{d1} W_1 x_1 \sqrt{\frac{2}{\rho}(p_P - p_A)} = C_{d1} W_1 \alpha x_1^0 \sqrt{\frac{2}{\rho}(p_P - p_A)} \qquad (19)$$

So, the deviation estimator of the flow can be expressed.

$$\hat{e} = q_{P0} - q_p = C_{d1} W_1 x_1^0 \sqrt{\frac{2}{\rho}(p_P - p_A)} - q_p \qquad (20)$$

By selecting the flow deviation estimator, it is possible to judge whether there is any fault in reversing valve, but it cannot be determined whether the specific fault is caused by internal leakage or opening insufficiency. Therefore, it is necessary to judge the fault type according to the other changes from pressure and flow. In general, when leakage occurs, the pressure in valve becomes lower, when opening fault occurs, the pressure in valve becomes higher.

3 Simulation

Based on mathematical models of typical components, the fault analysis and diagnosis of hydraulic system is simulated. According to the working principle, the simulation models based on AMESim are established, as shown in Figure 5.

The simulation models mainly include hydraulic cylinder, speed control valve, reversing valve and relief valve. The related parameters are shown in Table 1.

3.1 Analysis of Single Fault

3.1.1 Internal leakage in cylinder

The clearance between the cylinder and the piston is set from 0 mm to 0.4 mm, and the simulation results are shown in Figure 6. When supplied by a fixed displacement pump, the flows rate at port A and port B are shown
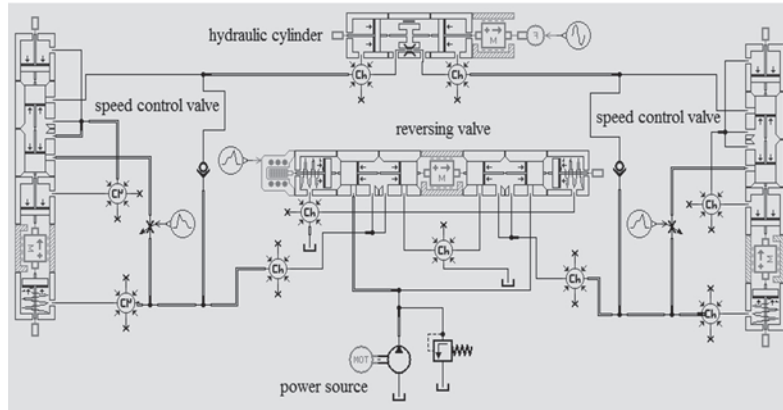
**Figure 5** Simulation models of telescopic hydraulic system.

Table 1 The settings of parameters in simulation models

Parameter	Value
Maximum working pressure	10 Mpa
Maximum load	5400 N
Shaft speed of motor	1000 rev/min
Pump displacement	5.5 cc/rev
Piston diameter	40 mm
Rod diameter	20 mm
Length of piston stroke	170 mm
Maximum flow rate at reversing valve	8 L/min
Orifice diameter of speed control valve	5 mm

in Figure 6(a). The flow rate difference is obtained by formula 4, as shown in Figure 6(b). It indicates that internal leakage increases as clearance increases, and the expanding speed of piston decreases with the increase of clearance. Conversely, if the flow rate difference is known, the value of clearance in the hydraulic cylinder can be diagnosed.
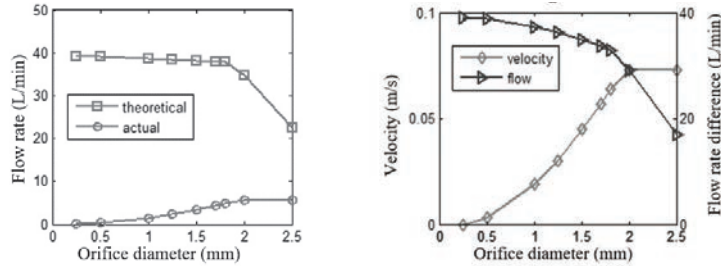
3.1.2 Blockage in speed control valve

In the blockage simulation, the orifice diameter in speed control valve ranges from 0 mm to 5 mm. The flow rate varies with changes of orifice diameter, as shown in Figure 7. The theoretical flow rate can be obtained by injecting fault pressures to the normal valve, as shown in Figure 7(b). By calculating the difference between theoretical flow and actual one, the flow difference is obtained, as shown in Figure 7(b). In addition, the velocity of piston keeps
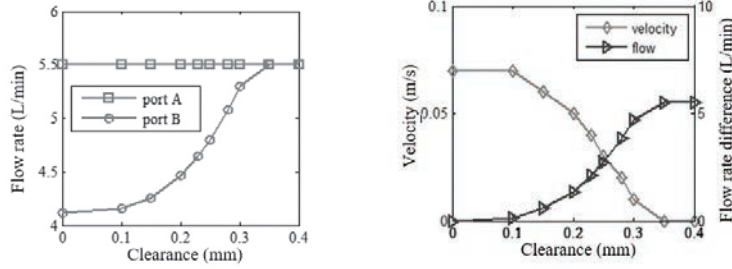
(a) Flows rate at port A and port B   (b) Flow rate difference and velocity of cylinder piston

Figure 6   Related curves of internal leakage in cylinder.

(a) Curves of theoretical flow and actual flow (b) Curves of flow rate difference and velocity

Figure 7   Related curves of blockage in speed control valve.

increasing as the orifice diameter increases. The maximum velocity remains 0.07 m/s when the diameter reaches 2 mm. As can be seen, the flow deviation and velocity can be used as the basis for fault location for speed control valve.

3.1.3 Opening in reversing valve

As shown in Figure 8, the opening coefficient of the reversing valve ranges from 0 to 1. Through direct measurement, the actual flow is measured and the value is shown in Figure 8(a). The theoretical flow rate can be obtained by injecting the actual pressures to the mode.

Figure 8(b) shows the deviation of the flow rate in reversing valve. The value decreases with the increase of opening coefficient, which indicates the fault become less, the curve of piston velocity indicates that the speed becomes larger as opening coefficient increases, and it cannot increase after the opening coefficient reaches 0.5. All the above information can be used as the basis for fault diagnosis for reversing valve.
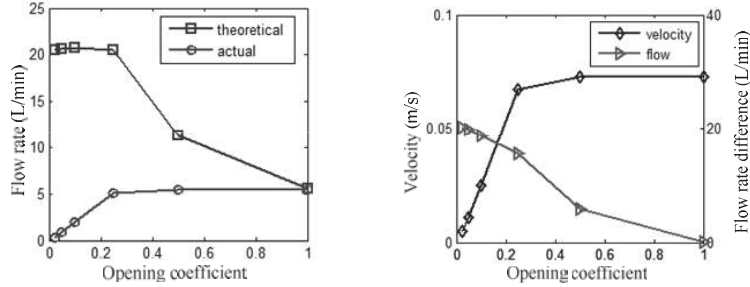
(a) Curves of theoretical flow and actual flow (b) Curves of flow rate difference and velocity

Figure 8   Related curves of reversing valve in opening fault.

Table 2   The settings of parameters in the fault series

Item	Opening Coefficient	Orifice Diameter	Cylinder Clearance
Series 1	30%	2.5 mm	0.25 mm
Series 2	20%	3.5 mm	0.15 mm
Series 3	60%	1.5 mm	0.2 mm

3.2 Multiple Faults Simulation and Diagnosis

To verify the applicability of fault diagnosis, the simulation of hydraulic system which contains multiple faults is carried out. In the case, the fault modes include: the insufficient opening of reversing valve, the blockage of speed control valve and the internal leakage in cylinder. The faults parameters are shown in Table 2.

Among the above faults, the opening fault in series 2 is the worst, and series 3 is the lightest. Also, the blockage of speed control valve in series 3 is the worst, the internal leakage in series 1 is the worst. According to the principle of fault diagnosis, all the faults in the system should be diagnosed and the fault severity of each component should be distinguished.

3.2.1 Simulation results

The simulation results of three fault series are shown in Figures 9 and 10. Figure 9 depicts the displacements of cylinder piston, the solid line is the curve of the system without fault, and the other three lines are the curves of piston motion in three fault series, respectively. It can be seen that all the motion of three series reach the predetermined position later than that of normal system, which means failures. By further measurement, the flow curves of different series are obtained, as shown in Figure 10. In the normal
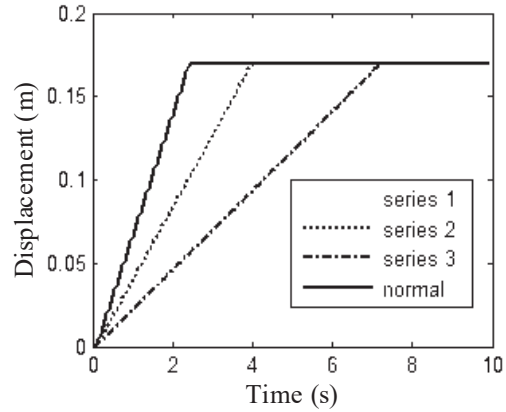
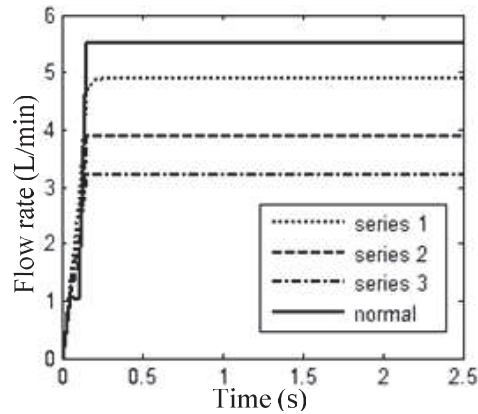**Figure 9**   Displacements in different series.

Figure 10   Flow curves in different series.

system, the flow rate into hydraulic cylinder is 5.5 L/min, which is not accessible to the other three faults series.

Comparing Figure 9 with Figure 10, we find that the flow rate in series 1 is greater than that in series 2, but the speed in series 1 is lower than that in series 2. So, it shows that the severity of the fault in the series is not certain, and this problem must be solved by testing specific component in each series.

3.2.2 Component diagnosis

All the curves of reversing valve flow rate in three series are shown in Figure 11. When the theoretical flows minus the actual flows respectively,
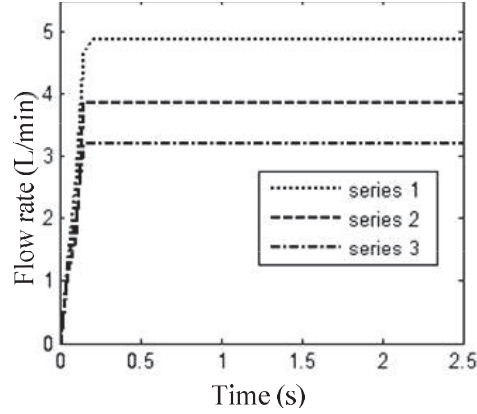
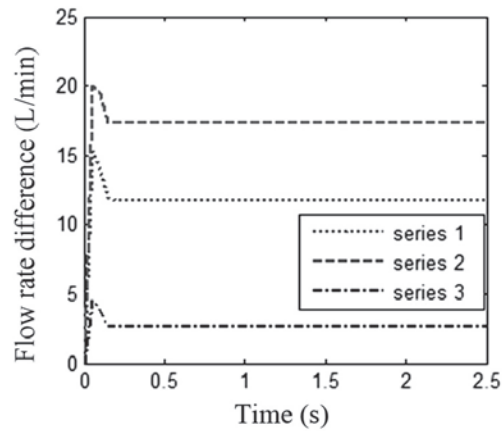**Figure 11**   Flow rate at port P in reversing valve.

Figure 12   Flow rate difference in reversing valve.

the three series flow deviations are shown in Figure 12. The figure shows that the maximum deviation is produced in series 2, which means the maximum failure, and series 3 has the least deviation, which is the lightest fault. This diagnosis is also consistent with the initial settings of fault severity.

Similar to the diagnosis and analysis of reversing valve, the difference curves of the theoretical flow rate and the actual one in the speed control valve is obtained, as shown in Figure 13. According to the numerical value, it can be seen that series 3 has the most serious faults, series 1 is lighter and
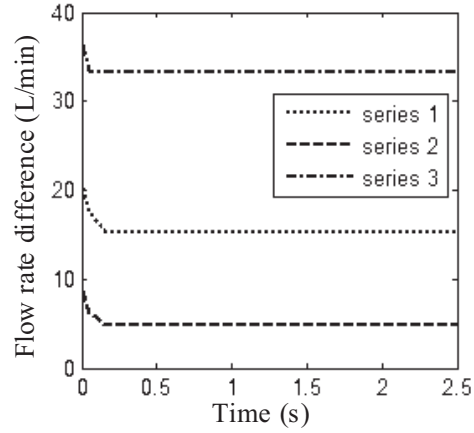
Figure 13 Curves of flow rate difference in speed control valve.
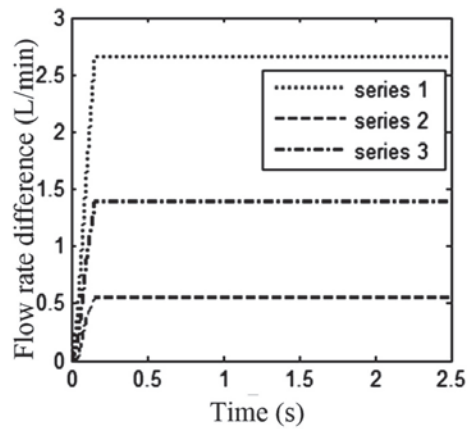

Figure 14 Curves of flow rate difference between the ports in cylinder.

series 2 is the lightest, which fully conforms to the previous setting of orifice diameter in speed control valve.

According to the internal leakage flow formula, the flow rate difference of hydraulic cylinder leakage is calculated, as shown in Figure 14. As we can see from the figure, in series 1, the internal leakage 2.64 L/min is the largest. In series 2, the leakage 0.55 L/min is the smallest, which is consistent with settings of the cylinder clearance.

4 Experiments

4.1 Test System

There are so few downhole robots, the cost and the time of failure testing for the actual system are high and large. Therefore, some fault is imitated to study fault characteristics and fault diagnosis. In the internal leakage, a throttling valve is set in parallel with the cylinder to simulate the internal leakage with variable sizes. Thus, the internal leakage experiment can be carried out. The schematic diagram of experiment system is shown in Figure 15.

In Figure 15, the experiment system consists of three parts: power source, quick measurement module and hydraulic cylinder. The quick measurement module is used to measure flows and pressures of the inlet and the outlet of cylinder. There are ball valves between both adjacent quick connectors. After placing ball valve in the closed state and connecting flow sensor between both quick connectors, the flow in the pipeline can be measured.

Figure 16 shows diagram of wiring in experiment system. The solid line in the figure represents the hydraulic flow. The power source not only provides pressure and flow for the telescopic mechanism, but also provides energy for the loading system. The dotted line is the signal transmission line, in which the controller sends out instructions to make hydraulic components and sensors work.

Based on experimental principle and connection mode, the internal leakage experiment system is established, as shown in Figure 17.

4.2 Results and Discussions

When the operation is stable, the relevant data is obtained and plotted. In the experiment, the simulating leakage clearance of the cylinder is set
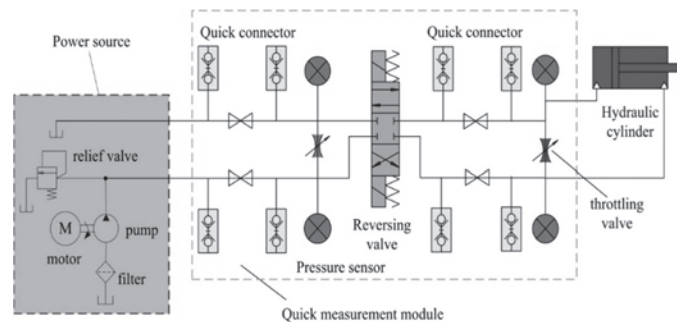

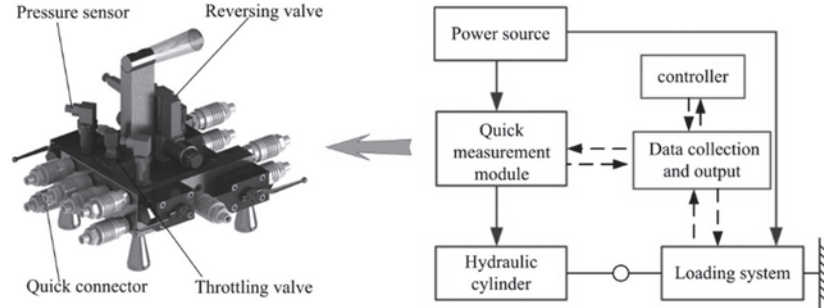**Figure 15**   Schematic diagram of experiment system.

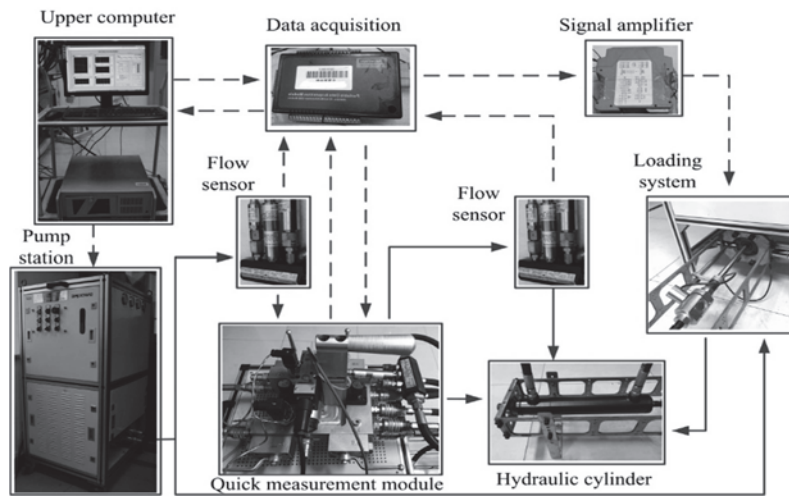**Figure 16**   Diagram of wiring of experiment system.

Figure 17   Physical map of internal leakage experiment system.

by 0 and 0.2 mm, and the corresponding displacements of cylinder piston are shown in Figure 18. In addition, the theoretical curves for the settings of 0 mm and 2 mm are added. It can be seen that when the cylinder has no failure, the displacement in the experiment is almost identical with the simulation displacement, where external leakage and pipe leakage are not considered. When the cylinder clearance is 0.2 mm, the trend of experimental displacement is similar to that of simulation analysis.

Further verification of the leakage diagnosis is performed, namely, the selected leakage estimator. The experimental estimators are obtained by introducing the flows of hydraulic cylinder ports. When the cylinder is not leaking, the deviation estimators are shown in Figure 19, whose mean
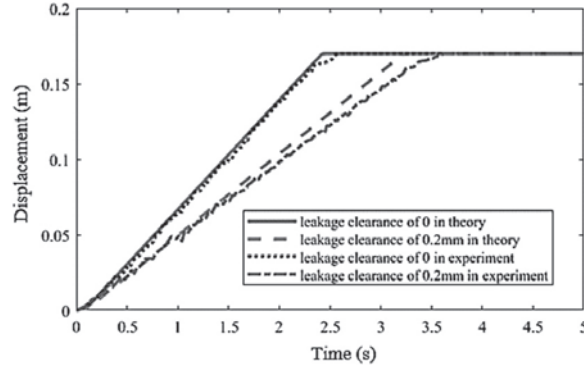
Figure 18   Curves of displacement in the experiment and simulation.
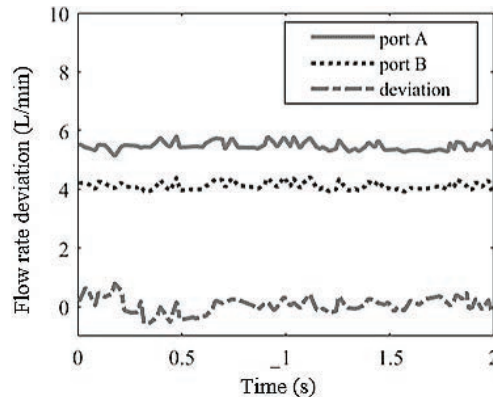

Figure 19   Curves of the flow without internal leakage.

value is about 0 L/min. When the cylinder leakage is 0.2 mm, the deviation estimators are obtained as shown in Figure 20, whose mean value is around 1.5 L/min. The estimators fluctuate because of the effects of noise and other vibrations. Compared with theoretical result, the mean deviation should be near 1.37 L/min, which is less than the experimental value. The reason is that there may be amount of other leakages in the operation, including pipeline leakage and external leakage.

From the experimental data and graphs, the experiment can simulate internal leakage characteristics of the hydraulic cylinder. Moreover, the method of deviation estimator proposed in this paper can correctly locate and diagnose the leakage and severity of the cylinder.
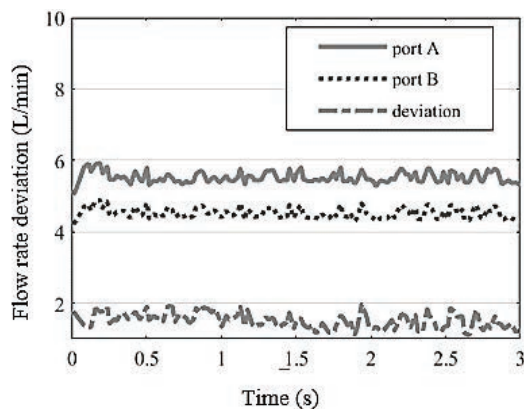
Figure 20   Curves of the flow with internal leakage.

With the leakage experiment, the fault characteristics and data of each leakage dimension can also be collected, which is provided for the fault diagnosis. In addition, based on the similar experiment principle, it can also collect fault characteristic for other hydraulic components including directional valve, speed control valve and even overflow valve, which is helpful to establish the fault information database for the downhole traction robot hydraulic system.

5 Conclusions

In this paper, the fault analysis and diagnosis of downhole traction robot hydraulic system were proposed with some simple but effective arguments and measurements.

The structure of downhole traction robot was introduced, and its working principle and operation feathers were analyzed. With the help of the analysis of failure mode and mechanism in the key components, the fault diagnosis of hydraulic system was proposed based on the mathematical model. Based on simulation, the fault model of downhole traction robot hydraulic system was established, and the diagnosis of single fault and multi-fault were simulated, some fault data and characteristics were found and collected. Experiments of simulated leakage in hydraulic cylinders were established, and schemes of fault diagnosis were carried out, which can validate the feasibility of the diagnostic method.

For future research, the following work is to collect more and more fault data and characteristics on hydraulic components.

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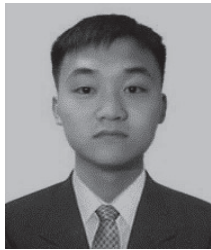
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