Effect Analysis of Leakage in the Middle Position and Improvement of an O-type 3-position-4-way Directional Valve with the Spool Structure

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Abstract. Although the middle position of the O-type 3-position-4-way directional valve with the spool structure is not the working position of the valve, the performance of the middle position is also one of the considerations in the system design. The leakage characteristics of the middle position affect the correctness of the final action of the external load. Leakage effects of the middle position on the action of load under 3 common working conditions were analysed. The results showed that the position of the load actuator moved towards the load direction because of the leakage. The larger the leakage, the faster the response, and the faster the moving speed; the different gaps between different valve ports aggravated the previous phenomenon. The use of a pair of pilot-operated check valves in series and a parallel bypass valve at the inlet and outlet of the actuator could effectively improve the actual cut-off effect of the directional valve.

1. Introduction
The O-type 3-position-4-way directional valve with the spool structure is a typical directional valve, which has a simple structure, clear function and wide application in hydraulic systems. The left and right positions of the valve are working positions, and the middle position is non-working position. Considering the sliding demand of the valve spool and the inevitable manufacturing error in actual products, there exist gaps between the valve spool and the valve body, and the resulting leakage is also inevitable. Researches showed that, in addition to the fitting gap, factors such as medium temperature and working pressure also affected the leakage of the directional valve [1-3]. If the load needs to maintain a specific state in the middle position, considering the effect of aging, the impact of leakage can’t be ignored. Shock and vibration are studied when the directional valve is in the middle position [4]. In this paper, the effect of leakage on a cylinder actuator in the middle position of this kind of directional valve was analysed, and some suggestions for improvement were put forward.

2. Effect analysis
Some major parameters of the valve spool and the valve body of a directional valve were designed. The nominal diameter of the valve was 20mm and the working pressure was 10MPa. The following analysis was based on the design above. AMESim was adopted for the simulations (Figure 1), and different working conditions were considered (Table 1).

Some settings were made to simplify the analysis.
The valve spool was forced by a displacement input to switch the working position. The specific execution way was ignored, that is to say, the execution way could be manual, electromagnetic, or hydrodynamic.

The cylinder was continuously subjected to an external load in a specified direction, which could be considered as the self-weight of the moving parts of a lifting and lowering device.

![Diagram of simulations](image)

Figure 1. AMESim diagrammatic of simulations.

Table 1. Descriptions of different working conditions.

| Conditions | Description of working conditions |
|------------|----------------------------------|
| 1          | a. Connect the hydraulic source, and keep the valve at the middle position all along. |
|            | a. Connect the hydraulic source. |
|            | b. Switch the valve to the working position | 2 |
|            | c. Switch the valve back to the middle position after the cylinder reaches its extreme position. |
|            | d. Keep the valve at the middle position. |
|            | a. Connect the hydraulic source. |
|            | b. Switch the valve to the working position |
| 3          | c. Switch the valve back to the middle position after the cylinder reaches its extreme position. |
|            | d. Disconnect the hydraulic source. |

2.1. Analysis under condition 1

Generally, the flow state of the annular gap between the valve spool and the valve body is considered laminar, and the leakage can be calculated according to the formula of eccentric annular gap leakage as follows [5].

\[
\Delta q = \frac{\pi D \delta^3 \Delta p}{12 \mu l} (1 + 1.5 \varepsilon^2) \tag{1}
\]

Where \(\Delta q\) is the leakage; \(D\) is diameter of the valve spool; \(\delta\) is the gap between the valve spool and the valve body; \(\Delta p\) is pressure difference at both ends of the gap; \(\mu\) is dynamic viscosity of hydraulic oil; \(l\) is sealing length of the gap; \(\varepsilon\) is relative eccentricity of the valve spool. As seen, \(\delta\) affects greatly for the leakage control. There were four gaps in the fitting of valve spool and valve body, which were the gaps between port P and port a, port P and port B, port A and port T, and between port B and port T, which were successively defined as \(\delta_{pa}, \delta_{pb}, \delta_{at}, \delta_{bt}\). The performance of displacement of the cylinder piston was obtained by configuring different \(\delta\) (Figure 2).
The results show that the piston of the hydraulic cylinder moves in the same direction as the external load, and the larger the clearance is, the larger the moving distance is, which can be understood as an unacceptable malfunction of the cylinder piston. It is not difficult to predict that leakage occurs when the valve is in the middle position, which is shown in Figure 3. It indicates that this kind of directional valve cannot be directly applied to the accumulator-type constant pressure hydraulic system. Prolonged leakage brings down the system pressure. At the same time, because of the leakage, the pressure of the two ports A and B of the hydraulic cylinder has increased significantly, rather than the expected zero. The behaviours of the pressure at port A and port B are shown in Figure 4 and Figure 5.
It is also noted that in the initial stage, the step input effect of the external load is greater than that of the leakage, and there is an impact feedback at all the observed parameters. The impact has been proven to occur under all working conditions.

2.2. Analysis under condition 2
Simulation results are shown in Figure 6 ~ Figure 9.
It is found that due to the leakage, the pressure at port A of the hydraulic cylinder drops rapidly from the maximum value, and the pressure at port B of the hydraulic cylinder rises rapidly from zero. At this time, the displacement of the hydraulic cylinder piston doesn’t change because the piston already reaches the extreme position. When the pressure difference between port A and port B ports decreases to just overcome the external load, the cylinder piston starts to move from the extreme position to the opposite direction. Meanwhile, it is also clear that the larger the gap, the faster the state changes, that is, the faster the valve responses.

2.3. Analysis under condition 3

As seen in Figure 10 ~ Figure 13, as the hydraulic source is cut off, port P of the directional valve doesn’t leak to port A and port B of the valve, and the effect of leakage from port A and B to port T becomes greater. Different from condition 2, when port B of the valve leaks to port T of the valve, the pressure drops rapidly, which increases the pressure difference between port A and port B of the hydraulic cylinder and pushes back the time when the piston of the hydraulic cylinder starts to move. However, once the movement starts, the effect of leakage is intensified, that is to say, the moving speed of the hydraulic cylinder piston becomes faster. Before the piston of the hydraulic cylinder reaches the extreme position in the other direction, the chamber at port B of the hydraulic cylinder is drawn into negative pressure by the moving piston.
3. Improvement for application

There are different ways to improve the function of middle position of the directional valve in different applications [6-8]. It is expected to keep the position of the load unchanged when the directional valve is in the middle position. Considering the bidirectionality of leakage, the improvement measures need to prevent the hydraulic cylinder from leaking to the directional valve, and also prevent the directional valve from leaking to the hydraulic cylinder. As pair of pilot-operated check valves and a bypass directional valve were adopted. The working principle was shown in Figure 14. The bypass valve and the directional valve worked together. When the directional valve was in the middle position, the bypass valve was in the left position (connecting position); on the contrary, when the reversing valve was in the left position or the right position, the bypass valve was in the right position (cut-off position). Simulations were carried out under condition 2 mentioned above.

By comparing Figure 15 and Figure 6, it is found that even if the directional valve is switched back to the middle position, the displacement of the cylinder piston remains unchanged after reaching the extreme position, regardless of the change of the gap. However, Figure 16 indicates that there is still a smaller leakage through port P of the directional valve. The application of the directional valve in the accumulator-type constant pressure hydraulic system should be fully considered.

Figure 12. Changes of pressure at port B of cylinder when δ changes.

Figure 13. Changes of differential pressure at ports of cylinder when δ changes.

Figure 14. Diagrammatic after improvement.
Figure 15. Changes of displacement of cylinder piston when $\delta$ changes.

Figure 16. Changes of leakage through port P of valve when $\delta$ changes.

In the improvement process, it was considered to keep only the pilot-operated check valves instead of the bypass valve. The results show that when the 4 gaps ($\delta_{pa}$, $\delta_{pb}$, $\delta_{at}$, $\delta_{bt}$) are completely consistent, the hydraulic cylinder piston maintains the position unchanged; when the 4 gaps are not the same, the hydraulic cylinder piston still acts unexpectedly. The results are shown in Figure 17 and also indicate indirectly that the leakage through port P of the valve can be drained back to the oil tank preferentially by setting a bypass valve instead of accumulating at port A and B of the valve to generate pressure, which opens the pilot-operated check valve and makes the reverse cut-off effect of the pilot-operated check valve invalid. In other words, the bypass valve has a positive effect.

Figure 17. Changes of displacement of cylinder piston when $\delta$ changes.

4. Conclusions

Generally, some understandings are obtained for the application of the directional valve.

- Due to the existence of leakage caused by the inevitable fitting gaps between the valve spool and valve body of the directional valve, it is not advisable to directly apply the middle position to keep the load position from moving. The larger the gap, the larger the leakage, and the more difficult it is for the load to keep the position unchanged.

- Try to make the gaps between the valve spool and the valve body consistent. Inconsistent gaps mean that the leakages through the different ports are inconsistent, which would lead to inconsistencies in the pressure, flow and other states of the chambers on both sides of the load, and then make the load tend to move.

- Through the improvement measures of the pilot-operated check valve in series and the parallel bypass valve at the load inlet and outlet, the cut-off function in the middle position of the directional valve can be strengthened at least for the duration of the simulation analysis.
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