Design & Simulation of a Superimposed Hydraulic Back Pressure Valve with Adaptive Back Pressure

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Abstract. A superimposed hydraulic back pressure valve with adaptive back pressure was designed. The back pressure of the valve changes as the diving depth of underwater vehicles changes, and is always higher than outboard environmental pressure by an adjustable value, preferred 0.5MPa, to avoid leakage of environmental medium to the inboard hydraulic system. The valve was designed in a pilot-operated style with a flat valve port of main valve. Variable damping plugs were used to easily regulate the dynamic performance of the valve. And an isolation device was adopted to isolate the contact between the inboard and outboard media. The static mathematic models of the valve were established and simulations were carried out. The simulation results show the valve has good pressure stability and flow adaptability, and its back pressure changes with the change of outboard pressure well.

1. Introduction
For hydraulic systems of underwater facilities with outboard hydraulic users, the power unit and main system pipes are always arranged inboard of underwater vehicles. It is important to avoid leaks of environmental medium to the systems. In order to prevent seawater or lakewater from penetrating into the system through outboard actuators, a back pressure valve is usually connected in series in system circuits to set the pressure in return tubes higher than outboard environmental pressure. Under the effect of internal and external pressure difference, seawater or lakewater can be blocked out of the vehicles even if there are leaks through outboard actuators or pipe joints. The environmental pressure varies with the diving depth of the vehicles. The general method is to set the back pressure of the valve to be fixed and slightly higher than environmental pressure of the maximum diving depth. In this case, there exists a large amount of situations of the back pressure much higher than environmental pressure which would cause large loss of system energy and large return throttling noise through the valve.

This paper presents a superimposed hydraulic back pressure valve whose back pressure changes as the diving depth of underwater vehicles changes and is always higher than outboard environmental pressure by an adjustable value. The valve also operates well with a flow range up to not less than 100L/min. According to the physical structure of the valve, the schematic diagram was obtained, static mathematic models were established, and simulation work was carried out.

2. Structure design
The valve was based on a hydraulic back pressure valve with a large flow range \cite{1}. Some typical features retained to maintain the large flow range. A pilot valve was applied to release the manual regulation force, the port of main valve adopted a form of flat valve to reduce the effect of steady jet force and thereby expand the flow range, and variable damping plugs were used to compensate for the
underdamping of the hydraulic system. Several other improvements were made to satisfy the demand of good following performance of the back pressure relative to environmental pressure [2][3].

a. Environmental pressure was introduced into the spring chamber of pilot valve as a balancing pressure. So the cracking pressure of pilot valve could be calculated based on the sum of pilot spring force and environmental pressure. The cracking pressure accounted for a large proportion of the back pressure, and at last the back pressure of the valve followed the changes of environmental pressure.

b. An isolation device was located between the pilot valve and outboard environment to isolate environmental medium. A damping plug provided on the passage between spring chamber of pilot valve and the isolation device helped to absorb pressure shocks and oscillations at ends of the plug.

c. A drain passage was provided on the body of the isolation device corresponding to the middle portion of the piston. It allows the environmental medium that leaks through the piston to pass through the drain preferentially rather than entering the hydraulic system.

d. An adjustable main damping plug was placed inside the main valve spool, and the dimension of main valve was effectively reduced.

e. The isolation device and the pilot valve were mounted on the main valve body in a superimposed way. The structure and function of each component were relatively independent, which meant it was convenient to use and maintain.

Then the detail sketch diagram of the back pressure valve could be obtained (as seen in Figure 1).

Figure 1. Cross-section of the valve

Figure 2. Diagrammatic of the valve

3. Static mathematic models

Figure 2 shows the principle diagrammatic of the valve. Table 1 shows the physical significances of variables referred in the equations. Then the mathematic models could be obtained [3]~[5].

(1) Force balance equation of pilot spool:

\[ p_p A_p = k_p (x_p + x_{ps}) + c_p d_p x_p \sin 2\beta \cdot p_p + p_i \cdot A_{ps} \]  

(2) Force balance equation of main spool:

\[ p_m A_m = k_m (x_m + x_{ms}) + c_m d_m \sin 2\alpha \cdot p_m + p_p \cdot A_{ms} \]  

(3) Force balance equation of piston of isolation device:

\[ p_i A_i = p_i A \]  

Where \( A_p = \pi d_p^2/4 \), \( A_{ps} = \pi d_{ps}^2/4 \), \( A_m = \pi d_m^2/4 \), \( A_{ms} = \pi d_{ms}^2/4 \).

| \( A_m \) | Effective area of main throttle | \( k_p \) | Stiffness of pilot spring |
|---------|-------------------------------|---------|--------------------------|
| \( A_p \) | Effective area of pilot throttle | \( p_m \) | Pressure before main throttle |
| \( A_{ms} \) | Effective area of main spring chamber | \( p_p \) | Pressure before pilot throttle |
| \( A_{ps} \) | Effective area of pilot spring chamber | \( p_i \) | Pressure in pilot spring chamber |
Assume \( d_m = d_{ms} \), \( d_p = d_{ps} \), \( \alpha = 90^\circ \), then equation (1) ~ (3) could be rewritten to (4) ~ (6).

\[
P_m = \frac{p_v}{A_p} \left( k_m (x_m + x_{m0}) \right)
\]

(4)

\[
P_m = p_v + \frac{k_m (x_m + x_{m0})}{A_p}
\]

(5)

\[
P_m = p_v + \frac{k_m (x_m + x_{m0})}{A_p} = p_v + \Delta p
\]

(6)

Suppose \( x_{m0} \gg x_m \), \( x_{p0} \gg x_p \), and \( A_p \gg c_p \pi d_p x_p \sin 2\beta \), then the back pressure could be estimated as follows:

Equation (7) indicates that the back pressure \( p_m \) is always a little higher than environmental pressure \( p_v \) by a specific value \( \Delta p \) which is set by the parameters of main spring and pilot spring.

4. Simulation analysis

Figure 3 shows the simulation diagrammatic. AMESim was adopted for the simulation analysis. Some assumptions were made to simplify the simulation models.

- Drain port pressure was negligibly small and set zero.
- Gravity was ignored.
- Frictions during the movement of spools were ignored.
- The density of environmental medium (seawater or lakewater) kept constant as the diving depth of the underwater vehicle changed.

4.1. Pressure stability and flow adaptability analysis

The performances of pressure before main throttle under a large range of flowrate through the main throttle were analysed. The step excitation system return flowrate \( q_{in} \) varied every 1 seconds from 10L/min to 20L/min, 50L/min, 100L/min, and 50L/min, 20L/min, 10L/min. Figure 4 and Figure 6
show the changes of back pressure under different diving depths when the pressure difference $\Delta p$ is respectively set 0.5MPa or 1.0MPa. Table 2 shows the back pressures after stabilization in different stages.

![Figure 4. Changes of $p_m$](image1)

![Figure 5. Changes of piston displacement](image2)

![Figure 6. Changes of $p_m$](image3)

![Figure 7. Changes of piston displacement](image4)

Table 2. Values of steady $p_m$ under different situations.

| Return flow/L.min$^{-1}$ | Stage1 | Stage2 | Stage3 | Stage4 | Stage5 | Stage6 | Stage7 | Average | $k$  |
|--------------------------|--------|--------|--------|--------|--------|--------|--------|---------|------|
| 10                       |        |        |        |        |        |        |        |         |      |
| 20                       |        |        |        |        |        |        |        |         |      |
| 50                       |        |        |        |        |        |        |        |         |      |
| 100                      |        |        |        |        |        |        |        |         |      |
| 50                       |        |        |        |        |        |        |        |         |      |
| 20                       |        |        |        |        |        |        |        |         |      |
| 10                       |        |        |        |        |        |        |        |         |      |
| -                        |        |        |        |        |        |        |        |         |      |
| $\Delta p=0.5$MPa        |        |        |        |        |        |        |        |         |      |
| depth=0m                 | 0.495  | 0.495  | 0.498  | 0.501  | 0.498  | 0.495  | 0.495  | 0.497   | 1.35%|
| depth=100m               | 1.500  | 1.500  | 1.502  | 1.504  | 1.502  | 1.500  | 1.500  | 1.501   | 0.27%|
| depth=200m               | 2.506  | 2.506  | 2.507  | 2.509  | 2.507  | 2.506  | 2.506  | 2.507   | 0.14%|
| $\Delta p=1.0$MPa        |        |        |        |        |        |        |        |         |      |
| depth=0m                 | 1.001  | 1.001  | 1.003  | 1.005  | 1.003  | 1.001  | 1.001  | 1.002   | 0.49%|
| depth=100m               | 2.006  | 2.007  | 2.008  | 2.010  | 2.008  | 2.007  | 2.006  | 2.007   | 0.18%|
| depth=200m               | 3.012  | 3.012  | 3.013  | 3.015  | 3.013  | 3.012  | 3.012  | 3.013   | 0.11%|

$p_m$ curves converge very fast. The settling time of each excitation is less than 0.2s and the values of steady $p_m$ show good flow adaptability. Suppose that the fluctuation of $p_m$ can be computed as follows:

$$k = \frac{Max(p_m) - Min(p_m)}{Average(p_m)} \times 100\%$$

(8)
Then the fluctuations of steady $p_m$ could be described quantitatively in the last column of table, which indicates the valve has good pressure stability. It is also found no matter how the flow fluctuates (rise or fall), the steady $p_m$ before and after the fluctuation is almost the same. Figure 5 and Figure 7 show the piston displacements of the isolation device. The piston displacements are less than 0.4mm under different conditions. It indicates the drain passage set in the middle portion of the piston is practicable.

![Figure 8. Changes of $p_m$](image1)

![Figure 9. Changes of $p_m$](image2)

Figure 8 and Figure 9 show the changes of back pressure under different system return flow conditions through the valve when diving depth is respectively set 0m and 100m. The results show the valve port retains a residual back pressure when the system return flow suddenly decays to zero. The larger the diving depth, the higher the residual pressure; the smaller the return flow, the higher the residual pressure. It could be explained that high environmental pressure and small return flow leave the chamber before the valve a short time to become a closed volume. Therefore, the back pressure is hard to unload. It is considered not a bad consequence for the reason that there remains a certain back pressure even if the flow drops to zero, such as one of system pipes is unexpected broken.

4.2. Characteristics analysis of gradual flow

In practical applications, the return flow is often not stepped, but more likely to be gradual. In this paper, the dynamic response characteristics of the valve under the change of return flow shown in Figure 10 were simulated and analysed, and the results are shown in Figure 11. As seen, when the flow increases linearly from zero until it stabilizes at the maximum flow, the system back pressure quickly converges to the set value. Then when the flow begins to decrease linearly, the back pressure only shows a slight drop and remained constant at last. When the flow slowly reduces to zero and maintains, the back pressure does not fall to zero as expected, but continues to maintain a considerable value. As mentioned above, the residual pressure is considered not a bad consequence, but it is also worth reminding that in some specific situations the system needs to be configured with some functions to quickly unload the residual pressure. At the same time, it is also found the pressure shock is obviously brought down.
4.3. Characteristics analysis of gradual diving depth

Figure 13 shows the dynamic response characteristics of the valve under gradual diving depth situations demonstrated in Figure 12. At the beginning, a normal oscillation of the back pressure occurs, and then the curves converge quickly. Surprisingly, it is found that when diving depth increases or decreases linearly, the back pressure also increases or decreases linearly followingly. Meanwhile, the curves under different return flow circumstances are highly coincident with only the pressure shock peaks being different. The results indicate the valve does have good following performance.

5. Conclusions

Generally, some understandings are obtained for designing of the back pressure valve.

- The back pressure valve has good pressure stability and flow adaptability. It can maintain good pressure stability when system return flow reaches from small to not less than 100L/min.
- The system back pressure through the valve can be synchronized with the change of environmental pressure (corresponding to the diving depth of the underwater vehicles).
- It is noticeable that there exists a residual back pressure before the valve when the return flow reduces to zero gradually. Unloading circuit after the valve should be considered as needed.
The large transient pressure shock occurs before the main throttle especially when the step return flow is large. The pressure shock can be brought down remarkably by releasing the return flow gradually.

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