Optimization on the Topological Coupling-Throttling Structures for Directional Valves

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Abstract: As for the coupling-throttling effect of multiple grooves and notches on directional spool valves in the process of reversing, A parameterized mathematic model of the coupling-throttling effect for directional valves is proposed in this paper, which uses three basic throttling topological structures (O-shaped, U-shaped and C-shaped) to consist the topological variable space. Specifically, firstly, a bench test was carried out to verify the validation of 3D CFD simulation of the directional valve (on flow and pressure characteristics), which shows a consistent result. Then, on the premise of above, a parametric model of the coupling-throttling effect of multiple grooves and notches on directional valves is established, which accuracy is also proved with CFD simulation; under the constraints of limited topological variables, a topological structure of the coupling grooves and notches is optimized. It can be found from the test results that, the proportional characteristics of the working port is obviously improved, indicating that the parameterized mathematic expression of the coupling-throttling effect can be referred to for the design of such coupling structures.

1. Introduction

The directional valve, with dual functions of direction control and flow control, is a multi-functional integrated valve widely used in construction machinery. Scholars have studied the structural influence of the throttling grooves on spool[1-3]. Many research has been carried out for the opening of a single flow channel of the directional valve, which only apply to two-channel and four-channel direction valves. However, for most six-channel directional valves, there is still a lack of research to describe the influence of coupling-throttling effect between notches on spool on the dynamic characteristics when the valve reversing.

A certain type directional valve is used as an example in this study. A parameterized mathematic model of the coupling-throttling effect for directional valves is proposed in this paper, which is based on three basic throttling topological structures (O-shaped, U-shaped and C-shaped) to consist the topological variable space (referred to as topological variables)[4]. Specifically, firstly, a bench test was carried out to verify the validation of 3D CFD simulation of the directional valve (on flow and pressure characteristics), which shows a consistent result. Then, on the premise of above, a parametric model of the coupling-throttling effect of multiple grooves and notches on directional valves is established, which accuracy is also proved with CFD simulation; under the constraints of limited topological variables, a topological structure of the coupling grooves and notches is optimized on the subject of minimizing the proportional function. It can be found from the test results that, the proportional characteristics of the working port is obviously improved, indicating that the parameterized mathematic expression of the coupling-throttling effect can be referred to for the design of such coupling structures.
2. Simulation and test

2.1 Structure of directional valve
The research object of this paper is a directional valve rotary linkage for a certain type of hydraulic excavator. The sketch of the typical geometric architecture of the valve is shown in Figure 1. When the spool is sliding to the left/right, the P→B/A opening gradually opens; moreover, the P→C opening simultaneously closes. The above process is studied in this paper, and the structure of valve port B and valve port C is designed to meet the expected performance requirements. This approach can also be used in the structural design of other valve ports.

Figure.1 Sketch of the Typical Geometric Architecture of the Valve

2.2 CFD simulation
A widely used direction valve is used as the object of study, and its actual structural dimensions are used as a basis for establishing a CFD model for shunting and throttling during the opening of the direction valve. To simulate steady-state operation when the flow field changes due to spool movement, models at different valve port openings are created and used for calculations, as shown in Figures 2 and 3. Figure 2 shows the simulation model under 2.5mm valve opening; Figure 3 shows the fluid mesh model under 2.5mm valve port opening. During the process of meshing, the complex structure is partially optimized.

Figure.2 the simulation model under 2.5mm opening  Figure.3 the mesh model under 2.5mm opening

With respect to the simulation settings, the constant-flow method and constant pressure-difference method [5-6] can be used to determine the boundary conditions. Considering the working reality and bench test conditions, the constant-flow method was adopted by setting the inlet flowrate as the inlet condition and the static-pressure outlet as the outlet condition. Fluids that are in contact with solids were defined as stationary walls. The remaining details are as follows: a) the fluid was an incompressible Newtonian fluid; b) the hydraulic oil density (ρ) was 890 kg/m$^3$; c) the dynamic viscosity of the fluid (μ) was 0.036 Paꞏs; d) the bulk modulus was 700 MPa; e) the flow in the calculation process was turbulent; f) a standard k-ε model was adopted; g) monitoring points were set near the inlet and outlet to obtain pressure data. The CFD simulation result is shown in Figure 4 and Figure 5.

2.3 CFD and test results
In order to verify the effectiveness of the CFD simulation at any opening of the spool valve, a test device was adopted as same as reference 4. The working port flow-pressure characteristics are obtained through the comparison of the test results with the calculation results for CFD simulation under the same conditions, as shown in Figure 6.
3 Mathematical model

3.1 Single channel throttling model for the direction valve

The single valve port of the direction valve is used as an object to study its throttling model. It can be equivalent to the thin-walled orifice outflow model shown in Figure 6 due to the difference between the flow inlet pipe diameter and the flow outlet pipe diameter in the actual model: equivalent direction valve inlet pipe section at section 1; equivalent direction valve outlet pipe section at section 3, the throttling orifice O equivalent direction valve throttling groove structure.

\[
q = C_d A_0 \frac{2(p_1 - p_2)}{\rho} \\
\rho
\]

Where \( q \) is the flow through the flow channel; \( p_1 \) and \( p_2 \) are pressures at section 1 and contraction section 2; \( C_d \) is the flow coefficient of the throttling orifice; \( A_0 \) is the throttling area of the orifice.

Bernoulli’s equation from stage 1 to stage 3:

\[
\alpha_2 \frac{v_2^2}{2g} + \frac{p_2}{\rho g} = \alpha_3 \frac{v_3^2}{2g} + \frac{p_1}{\rho g} + h_f
\]

Where \( v_2 \) and \( v_3 \) are the flow velocity at flow channel sections 2 and 3 respectively; \( \alpha_2 \) and \( \alpha_3 \) are kinetic energy correction coefficients of contraction sections 2 and 3 respectively, approximately \( \alpha_2 = \alpha_3 = 1 \); \( \rho \) is the fluid density; \( g \) is the gravity acceleration; \( h_f \) is the head loss.

Where \( h_l \) and \( h_m \) are the resistance loss along the way and the local resistance loss respectively.

In accordance with Darcy equation:

\[
h = \lambda \frac{v_2^2}{2g}
\]

Where \( 1 \) is the equivalent pipe length; \( d \) is the equivalent pipe diameter; \( \lambda \) is the resistance coefficient.

Local loss coefficient,

\[
h = (1 - \frac{A_2}{A_3}) \frac{v_2^2}{2g}
\]

\( A_2, A_3 \) are areas of flow channel contraction sections 2 and 3, \( A_2 = A_0 \).

Because the flow continuity equation is as follows:
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\[ A = A v q v \]

After substituting formulas (2), (3), (4), and (5) into formula (2), and ensuring \( \alpha_1 = \alpha_B = 1 \), then it can obtain the following:

\[
\frac{2}{\rho} (p_2 - p_1) = q \left[ \frac{1}{A_2} - \frac{1}{A_1} + \frac{\lambda l}{d A_2} \right] + \frac{1}{A_2} \left( \frac{1}{A_2} - \frac{1}{A_1} \right)^2 \]

(6)

The following can be obtained after transforming the formula (1):

\[
\frac{2}{\rho} (p_1 - p_2) = \frac{q^2}{C_d A_0} \]

(7)

The following can be obtained after substituting equation (7) into equation (6):

\[
q = \frac{A_1}{A_1^2 + (2 + \lambda \frac{l}{d})^2 - 2C_d^2 A_1 A_p} C_d A_0 \frac{2}{\rho} (p_1 - p_2) \]

(8)

Under normal conditions, only the throttling loss is considered in the actual model. Ensure that \( \lambda \frac{l}{d} = 0 \) while the resistance loss along the way is ignored; and substitute \( A_2 = A_0 \) into equation (8) to obtain the throttling formula of the direction valve:

\[
q = C_d A_0 \frac{A_1 A_0}{A_1^2 + 2C_d^2 A_1^2 - 2C_d^2 A_1 A_0} \frac{2}{\rho} (p_1 - p_2) \]

(9)

In the case of a large Reynolds number, the flow coefficient \( C_d \) of the thin-walled orifice varies in a small range, ensure that \( C_{d1} \) and \( C_{d2} \) are between 0.6 and 0.62.

It can be seen from formula (9) that the throttling area curve in the process of spool opening is of vital importance to the flow and pressure characteristics of the direction valve.

3.2 Reversing coupling throttling model

According to the working principle of the direction valve, the coupling-throttling principle during the reversing process is shown in Figure 7. The oil enters from the main valve port P, and then flows out from the working port B and the midway oil return port C respectively after passing through the throttling groove.

The following can be obtained from the fluid continuity:

\[
Q = q_B + q_C \]

(10)

Where \( Q \) is the inlet flow, \( q_B \) is the flow of the working flow channel P-B, \( q_C \) is the flow of the midway flow channel P-C. The throttling formulas of flow channels P-B and P-C can be obtained in accordance with formula (9):

\[
q_B = C_{d,B} \frac{A_{o,B} A_{o,B}}{A_{o,B} + 2C_{d,B} A_{o,B}^2 + 2C_{d,B}^2 A_{o,B} A_{o,B}} \frac{2(p_i - p_{1,B})}{\rho} \]

(11)

\[
q_C = C_{d,C} \frac{A_{o,C} A_{o,C}}{A_{o,C} + 2C_{d,C} A_{o,C}^2 + 2C_{d,C}^2 A_{o,C} A_{o,C}} \frac{2(p_i - p_{3,C})}{\rho} \]

(12)

Where \( C_{d,B} \) and \( C_{d,C} \) are throttling groove flow coefficients of the working flowing channel P-B and midway oil return flow channel P-C; \( A_{o,B} \) and \( A_{o,C} \) are outlet cross-sectional areas passing through the working flow channel P-B and midway oil return flow channel P-C, which are determined values in this study; \( A_{o,B} \) and \( A_{o,C} \) are valve port throttling areas passing through the working channel P-B and midway oil return flow channel P-C; \( p_i \) is the inlet pressure; \( p_{1,B} \) and \( p_{3,C} \) are the load pressure of working port B and the back pressure of midway oil return port C; \( \rho \) is the oil density.

Due to the small change in valve port flow coefficient, \( C_{d,B} \) and \( C_{d,C} \) are taken as 0.62, representing the throttling coefficient of the thin-walled orifice under turbulent flow state. \( A_{o,B} \) and \( A_{o,C} \) are affected by the structure and opening of the valve port. Since the positions of two valve ports are relatively fixed, and the opening of one valve port can reduce the opening of the other valve port. Based on the opening of the working valve port, the flow area of the valve port within the displacement stroke of
the spool can be obtained by the structural parameters.

3.3 Analytic verification of multi-valve throttling-coupling

According to reference 4, the fluid flow area of the two valve ports are obtained. Figure 8 shows the flow area curves of port B and port C during the reversing transition.

![Figure 7 Coupling-throttling](image1)

![Figure 8 Flow area](image2)

![Figure 9 Mathematical and CFD results](image3)

It can be seen from Figure 9 that the results of mathematical model are consistent with the CFD simulation results, which can express the continuous change in the flow and pressure characteristics with the opening of the valve.

4. Structural topological optimization design

4.1 Topological variable space

The design in this paper is based on the study of the prototype model, in which three basic forms of throttling groove structure are adopted: O-shaped, U-shaped and C-shaped, which is shown in Figure 10. The distribution of the throttling groove on the outer circumferential surface of the spool is not considered temporarily.

The distance $l_1$ and $l_2$ are taken as the constant value. Then the design variable $z = \{x_1, x_2, r_1, r_2, r_3, r_4\}^T$ is obtained. The construction of such six-dimensional topological variable space as the design variable simplifies the complex problem of large degree of freedom of the actual structure, and makes it possible for the further design and calculation.

![Figure 10 The structural diagram of throttling grooves](image4)

![Figure 11 Comparison of flowrate result](image5)

4.2 Optimization

In this paper, proportional characteristics was taken as the evaluation criterion for flow stability, which was defined as following formula 13.

$$f(X) = \frac{\partial q_B}{\partial X}$$  \hspace{1cm} \text{(13)}

In which, $\min (f(X))$ is the subject function, the $q_B$ is the flow rate through the working port.

4.3 Result verification

The processed structure after optimization is tested, and then the results are compared with the test results before optimization. Figure 11 shows the comparison of flowrate with original structure, Table...
1 shows the structural parameters comparison before and after optimization. It can be seen from the figure that the trend of flow characteristics after optimization is better than the original one. However, the inlet pressure characteristic has been also greatly improved.

| Table 1 structural parameters before and after optimization. |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| x1 (mm) | x2 (mm) | r1 (mm) | r2 (mm) | r3 (mm) | r4 (mm) |
| Before | 2 | 2 | 2 | 1.45 | 2 | 1.5 |
| After | 2.999 | 2.735 | 2.735 | 2.173 | 1.763 | 2.758 |

5 Conclusion
The following conclusions are obtained:
1). A parameterized mathematic model of the reversing process is established, solving the large amount of calculation of CFD method and discontinuity of calculation results in the reversing process.
2). The optimization function model is established to optimize the coordinate variables of the throttle structure of the coupling valve port in the transition process of the multi-channel directional valve

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