

Optimal Design of Multi-section Proportional Directional Valve Throttle Grooves with Artificial Neural Networks

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Abstract. This paper presents a method for design multi-section proportional directional valve Throttle grooves with ANN method, which aims at getting a better flow stability. There exists a coupling matter during the opening and closing process between the throttling notches, so that it's difficult to parameterize the complex flow field characteristics C_d and the structure boundary of the spool grooves. However, in this paper, an ANN was built with data from CFD results, while the typical structural parameters (U type, the O-type and C-type), operating parameters was input vectors, the discharge coefficient as output vectors. Meanwhile, all of the needed data is taken from the three-dimensional CFD analysis, which are organized properly and verified by a bench scale test on a rig. Then, with throttling stiffness as optimization objective to evaluate flow stability, an optimal design process is carried out to optimize the structure of coupling grooves with ANN models and genetic algorithm. Ultimately, the optimized structure is verified better by the physical test on test rig, therefore, the significance of design method is proved.

1 Introduction

As the main power distribution element of the hydraulic excavator system, which is an open loop system, the multi-section proportional directional valve plays a vital role in the stability and reliability of the system. In the opening and closing process, there is multi-notch coupling throttling effect, while the mapping relationship between the topological structure of the throttling groove and its complex working conditions is difficult to parameterize. Due to the interaction of fluid and solid, the solid boundary affects the flow field performance directly.

As for the difficulty to realize the parameterization of flow field characteristics C_d during the design process of the multi-section proportional directional valve, many achievements have been made by researchers. With the help of the development of computer and computational fluid dynamics, JIANG Tao etc. realized the dynamic 3-D CFD simulation of complex structure sliding vane [1], and also tried to apply Neural Network Model into the process of the valve design. Wang Anlin [2-3] used the method of numerical fitting to fit the parameter C_d and reynolds number Re . Cavitation and the flow forces in hydraulic proportional directional valves by the means of experimental and numerical analysis [4-5] have been carried out by AMIRANTE R etc. As for the flow force acting on the spool

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of sliding valve, LISOWSKI E etc. [6-7] have made many efforts on the simulation method and realized the pressure compensation in a multi-section proportional directional control valve.

For the above analysis, this paper has taken a certain type of multi-section proportional directional valve as an example, based on the rig test to verify the validity of the three-dimensional CFD analysis and the means of artificial neural networks for prediction of discharge coefficient, to optimize the coupling groove s structure with the aim of better throttling stability. As a result, an ANN has been built with data from CFD results, while the structural parameters (U type, the O-type and C-type), operating parameters as input, the discharge coefficient as output. The effectiveness of optimization result has been verified.

2 object of research

2.1 The mechanism of the coupling throttling notches

In this paper, a certain type of multi-section proportional directional valve, which has been widely used in hydraulic excavator system to conduct the swing condition, is taken as the research object. One part of the pressure flow passes through the A port to the executing agency, and the other pressure oil passes out port C through the middle passage to the return tank.

Above all, the coupling flow satisfies the following:

$$Q = Q_1 + Q_2 \quad (1)$$

Where Q is the total flow inputting from port P , Q_1 is the flow flowing out port A , Q_2 is the flow flowing out port C .

$$Q_1 = C_{d1}A_1\sqrt{\frac{2(P - P_1)}{\rho}} \quad (2)$$

$$Q_2 = C_{d2}A_2\sqrt{\frac{2(P - P_2)}{\rho}} \quad (3)$$

Where C_{d1} is discharge coefficient of the throttle notch from port P to port A , C_{d2} is discharge coefficient of the throttle notch from port P to port C , A_1 is the throttling area about port A , A_2 is the throttling area about port C , P is the pressure in port P , P_1 is the pressure in port A , P_2 is the pressure in port C , ρ is the density of the fluid.

2.2 The design variable space

There are three types grooves used in this paper, which is O, C and U types. The spatial distribution is shown in Figure 1, and the same structure is distributed symmetrically around the circumference of the spool.

According the above prerequisites, the topology variable space $\mathbf{X}=[\mathbf{Xa}, \mathbf{Xc}]$ are proposed basing the original model, that \mathbf{Xa} are the design variable space for the port A , and the \mathbf{Xc} is the design variable space of the port C . As shown in Figure 1, the parameters of port A , the O-type groove can be expressed by the parameter r_1 ;the U-type can be expressed by the r_2 , and L_2 should keep a limit because of the continuity of the throttling groove; the C-type can be made by the a Parameter r_3 and r_2 ; that is, $\mathbf{Xa}=[r_1, r_2, r_3, L_2]$; Among the parameters of port C ; the U-type on can be expressed by parameter r_4 , and L_3 should keep constant because of the total displacement of the spool ; C-type one can be r_5 by parameter, $\mathbf{Xc}=[r_4, r_5]$. The design space of the swing valve topology is $\mathbf{X}=[\mathbf{Xa}, \mathbf{Xc}]=[r_1, r_2, r_3, L_2, r_4, r_5]$.

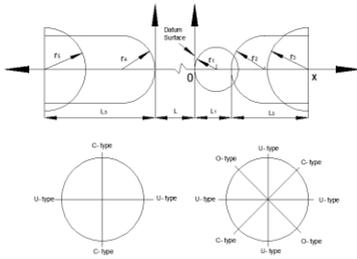


Figure 1. Topology diagram of the swing valve

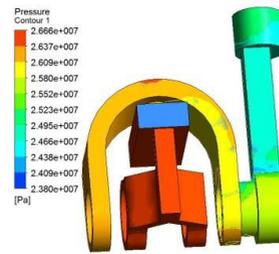


Figure 2. The pressure diagram of CFD result

3 CFD analysis and test

The multi-groove coupling throttling effect of multi-way valve is studied with the three-dimensional CFD technique[3, 6-7] being used to accurately describe the valve cavity flow field. At the same time, in order to verify the effectiveness of simulation methods, it is necessary to design corresponding tests to prove the accuracy and rationality of the three-dimensional CFD simulation.

3.1 CFD simulation models and settings

The three-dimensional model is established with the base of the actual valve port structure which refers to the template of a kind of commercial multi-way valve swing. With this as the object, the boundary conditions of the inlet and outlet are flow and outlet pressure for the fluid domain in the flow field. The fluid state setting for the calculation process is defined as: 1) the fluid is Newtonian fluid and incompressible; 2) the hydraulic oil density ρ is 890 kg/m^3 , the dynamic viscosity μ is $0.036 \text{ Pa}\cdot\text{s}$, the bulk modulus κ is 700 MPa ; 3) the fluid state is turbulence, the standard $k-\epsilon$ model is used; 4) The spool displacement is from the zero opening position, in order of 0.2, 0.5, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5.2mm; 5) Setting port A pressure p_{out} to 25Mpa, port C pressure to 6Mpa, inlet flow Q_{in} to 250L/min. The simulation model and the calculation result cloud diagram are shown in Figure.2, and the flow curve of simulation result is shown in Figure. 4.



Figure3. The diagram of test system

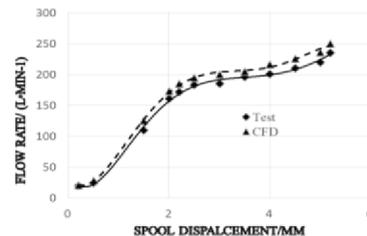


Figure 4. The contrast of the test result and the CFD result

3.2 Experimental verification of CFD simulation

To verify the effectiveness of the CFD simulation throttling at any position of valve opening [1-3], a system is required to accurately control and measure the displacement of the spool and adjust the pressure at the inlet and outlet of the tested valve. As shown in Figure.3, a test system is set up to measure the throttling characteristics of the swing work port. The schematic diagram includes the main pump, the tested multi-way valve swing, the loading valve, the spool micro-displacement control device, and the oil return measurement system.

For the simulation scheme and test system, the following settings (As shown in Table 1) are made for the test verification.

Table 1. The test setup and system parameters.

test setup		system parameters	
Displacement of the Spool /mm	0.2,0.5,1.5,2,2.5,3,3.5,4,4.5,5.2	Maximum displacement	112 ml/r
P _{out}	25 MPa	Rated pressure	35Mpa
Q _{in}	250L/min		

The experimental result is compared with the CFD simulation result so that the flow characteristics of the work port are obtained. The research shows that the CFD simulation and the test results of the flow characteristics of the work port have similar trends, so it can be considered that the CFD method can better simulate the actual work of the directional valve within the allowable range of error. The conclusion is consistent with the literature [2], this proves that the three-dimensional CFD simulation technique can be equivalent to bench test to some extent.

4 Mapping model and optimization

On the basis of the bench test to verify the effectiveness of three-dimensional CFD analysis, combined with the orthogonal test method, the structure parameters, working parameters combination and the mapped data of the throttle coefficient of the three types of throttling grooves structures are obtained respectively by the orthogonal test method, and then, the training samples of the ANN model are realized respectively. The neural network expressions of structural parameters, working conditions and throttling coefficients of port A and C are presented.

4.1 orthogonal test scheme and the ANN model

Table 2 is the orthogonal test table of port C, for example, table 3 is the orthogonal test table of port A. During the design process of orthogonal arrays, we need to satisfy the continuity of structure, and there are the following constraints in the orthogonal test table:

Table 2. The orthogonal test table of port C

Sample	r4/mm	r5/mm	level	factor	r4/mm	r5/mm
1	1.2	2	9	2	2	2
2	1.2	1.6	10	2	1.6	1.6
3	1.2	2.4	11	2	2.4	2.4
4	1.2	2.8	12	2	2.8	2.8
5	1.6	2	13	2.4	2	2
6	1.6	1.6	14	2.4	1.6	1.6
7	1.6	2.4	15	2.4	2.4	2.4
8	1.6	2.8	16	2.4	2.8	2.8

Table 3. The orthogonal test table of port A

Sample	r1/mm	r2/mm	r3/mm	L2/mm	Sample	r1/mm	r2/mm	r3/mm	L2/mm
1	0.9	1.2	1.6	3.2	9	1.2	2.4	2.4	3.2
2	1.2	1.6	1.6	3.6	10	0.9	2	2.4	3.6
3	1.5	2	1.6	4	11	1.8	1.6	2.4	4
4	1.8	2.4	1.6	4.4	12	1.5	1.2	2.4	4.4
5	1.8	2	2	3.2	13	1.5	1.6	2.8	3.2
6	1.5	2.4	2	3.6	14	1.8	1.2	2.8	3.6
7	1.2	1.2	2	4	15	0.9	2.4	2.8	4
8	0.9	1.6	2	4.4	16	1.2	2	2.8	4.4

According to the combination of each structure in the above orthogonal test table, the simulation model of the opening of the valve is 0.2,0.5,1.5,2,2.5,3,3.5,4,4.5,5.2mm in turn. For each model, the flow rate boundary is set 5, 55,105,155,205,255L/min.

The simulation results are processed through computer programming: the throttling area function A_1, A_2 of each structure of each structure is obtained, and the throttling coefficient of each group of simulation is calculated with the throttling formula $C_{di} = \frac{q_i}{A_i} \sqrt{\frac{\rho}{2\Delta p_i}}$.

As shown in Figure 5, A is a neuron network model of port A with [r1, R2, R3, L2, Xv, Q1] as input, [Cd1,A1] as output; Figure 6 shows a neuron network model of port C with [r4, r5, Xv, Q2], [Cd1,A1] as output. For the total data, 15% of the data points were randomly extracted for use in testing. The remaining data points were used as training patterns. Both of the ANN models were one hidden layer, and the number of neurons in the hidden layer of the ANN model for port A and port C is 9 and 7.

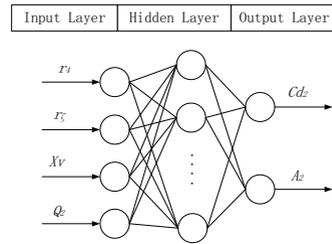
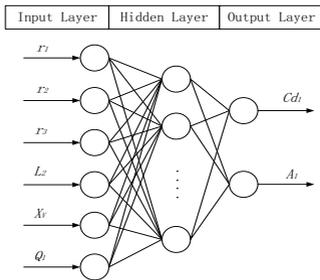


Figure 5. Schematic diagram for the ANN of port A

Figure6. Schematic diagram for the ANN of port C

To evaluate the models accuracies, the root square errors (RMSE), mean absolute errors (MAE) were used. The RMSE sizes the goodness of the fit related to high discharge coefficient values whereas the MAE measures a more balanced perspective of the goodness of the fit at moderate discharge coefficients. The RMSE and MAE are defined as:

$$RSME = \sqrt{\frac{1}{N} \sum_{i=1}^N (Cd_{test, i} - Cd_{predict, i})^2} \tag{4}$$

$$MAE = \frac{1}{N} \sum_{i=1}^N |Cd_{test, i} - Cd_{predict, i}| \tag{5}$$

in which N is the number of data set ; $Cd_{test,i}$ is the original data for testing, which number is i ; $Cd_{predict,i}$ is the prediction data, which number is i.

For the total evaluation,the RSME and MAE for the above ANN models is shown as fllowing table 4.

Table 4. The RSME and MAE for each model in validation period

Model	RSME	MAE
ANN for port A	0.156	0.135
ANN for port C	0.246	0.212

4.2 Optimization of the throttling grooves

During the changing process of the multi-section valve of the hydraulic excavator, various indexes need to be satisfied for the system design. The most typical one is to meet the demand of the throttle robustness for the load change, which means that the multi-section valve should be of good flow stability. Therefore, in this paper, throttling stiffness was taken as the evaluation criterion for flow stability, which was defined as following formula 6.

$$f(X) = \frac{\partial Q}{\partial p} \tag{6}$$

In which, the $f(X)$ is the throttling stiffness, the Q is the flow rate through the working port, and the p is the pressure on the working port as the working load.

However, with throttling stiffness as optimization objective to evaluate flow stability, an optimal design process is carried out to optimize the structure of coupling grooves with ANN models and genetic algorithm, which flow chart is shown as Figure.7, and the significant outcome of the optimization is shown in table 5, in which the F is the optimization objective function.

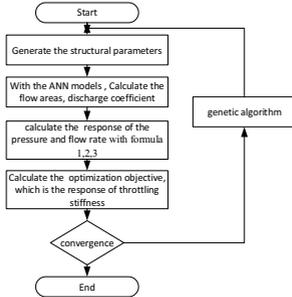


Table 5. The Comparison before and after the optimization

	r1	r2	r3	L2	r4	r5	F
Before	0.5	2.0	2.0	4	2.0	2.0	12.3
After	0.56	1.78	2.38	3.84	1.98	2.34	16.1

Figure 7. Flow chart of the optimization

Ultimately, the optimized structure is verified better by the physical test on test rig, therefore, the significance of design method is proved.

5 Conclusion of the research

Combining the results of the above research, this paper realized the following conclusions:

1) An ANN model is established for variables of design space, parameters of working condition and throttling coefficient, which accurately expresses the mapping relationship between the structure parameters, parameters of working condition and parameter of the flow field characteristics of the multi-section spool valve, avoiding the large scale computing and CFD analysis of large degree of freedom, which purpose is to realize the optimization of topology structure for the multi-section spool valve under the complex working condition.

2) The optimized structure is verified better by the Physical test on test rig, therefore, the significance of design method is proved.

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