Optimization of the High-speed On-off Valve of an Automatic Transmission

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Abstract. The response time of the high-speed on-off solenoid valve has a great influence on the performance of the automatic transmission. In order to reduce the response time of the high-speed on-off valve, the simulation model of the valve was built by use of AMESim and Ansoft Maxwell softwares. To reduce the response time, an objective function based on ITAE criterion was built and the Genetic Algorithms was used to optimize five parameters including circle number, working air gap, et al. The comparison between experiment and simulation shows that the model is verified. After optimization, the response time of the valve is reduced by 38.16%, the valve can meet the demands of the automatic transmission well. The results can provide theoretical reference for the improvement of automatic transmission performance.

1. Introduction

High-speed on-off valve is a new type of digital control hydraulic element [1]. In automatic transmission, high speed on-off valves play a lead role in the hydraulic buffer control of the vehicle shift clutch and directly determine the automatic control performance of planetary gear systems in the hydraulic transmission. At present, the main problem in the hydraulic control system is that the fast response performance of the high speed on-off valve is not reach the standard required since its design technique is bad. Because of this problem, control capability and the performance of the hydraulic control system in automatic transmission are greatly influenced.

In recent years, optimization of solenoid valves has been paid more and more attention [2-7]. Zhang Sheng-chang from Shanghai Jiaotong University has proposed a high speed solenoid valve performance prediction model and iteration algorithm, established hybrid optimization design method of high speed solenoid valve [3,4]. Dai Dong from Nanjing Sci-Tech University optimized the electromagnet parameters of the parallel spool type high pressure pneumatic solenoid valve and shortened the response time by multi - population genetic algorithm [5]. The finite element simulation method of structural dynamic design of ε type high-speed on-off valve electromagnet has brought forward by Xiang Zhong from Zhejiang University [6]. Tao Run has optimized the main parameters that influence the solenoid valve response time of the pressure valve and pressure reducing valve of the ABS braking system by genetic algorithm and shortened the response time [7]. But the above research works are mainly optimizations of the structural parameters of the electromagnet and do not involve the circle number, the working stroke parameter optimization. And the optimization of high-speed on-off valve of the automatic transmission is rarely reported.
In this work, the joint simulation model was built for the high-speed on-off valve in a certain automatic transmission. To reduce the response time, an objective function based on ITAE criterion was built and the Genetic Algorithms was used to optimize the key factors related to the dynamic response characteristic including circle number. So this work will offer technical support and theoretical reference for the development of a high-performance high-speed on-off valve.

2. Constitution and principle

![Figure 1. Schematic diagram of high-speed on-off valve](image)

The structure of a certain high-speed on-off valve is shown in Figure 1. It is mainly composed of a pole shoe, coil spring, ball, a valve body and a valve seat. The high-speed on-off valve is a two position – three way and normally closed valve. Electromagnetic force generated when the coil is energized, the steel ball overcomes the spring force and moves to the left under the electromagnetic force and hydraulic pressure, so the left oil drain port is blocked, the oil from the P port flows out of the outlet by the ball, and then flows to other valves or equipments. When the coil power is out, the electromagnetic force disappears, the spring restoring force moves the ball to the right, so the ball againsts the seat, oil drain port opens, and hydraulic oil accumulated in the gas gap flows back to the tank through the drain port.

3. Modeling and verification of joint simulation model

Ansoft Maxwell and AMEsim software have a strong complementarity [8-11]. In this work, Ansoft Maxwell and AMEsim softwares were combined to establish a dynamic performance simulation model in this work.

3.1. Ansoft Maxwell simulation model

The simulation model of the high speed on-off valve is established using Ansoft Maxwell software as shown in Figure 2. Valve body, pole shoe, coil shell and ball, etc. magnetic materials were modeled. The loop material was set to copper, alve body, pole shoe and ball were set to Steel, and air model was set to air. The air gap length of high speed on-off valve is 0.6mm. With external circuit functions of Maxwell, the excitation of the winding was realized using field circuit coupling finite element calculation. High level voltage is 12V, the low level voltage is 0V, power on time is 20ms, and pulse voltage cycle is 40ms.
3.2. United simulation model

Figure 2. Ansoft Maxwell simulation model of high speed on-off valve

The united simulation model of high speed on-off valve dynamic performance is shown as Figure 3. Each submodel in the simulation model was selected according to the specific structure of the high speed on-off valve and working principle [12]. In Figure 3, the submodel 1, 2 are used to define the characteristics of hydraulic oil and magnetic material properties. In electromagnetic model, the control signal model 3 and voltage source model 4 are used to simulate the control voltage signal. EMLT40 submodel 5 is used to simulate electromagnet. The ball quality is simulated by mass model 6, displacement sensor model 7 is used to simulate displacement sensor, spring module 8 is used to simulate spring and the ball valve sub model 9 is used to simulate spool and valve seat. According to the working principle of the high speed on-off valve, when the coil is powered, the ball moves to the left, block the oil drain port, so add a ball valve submodel 10 in the simulation model. Damping hole model 11 is used to simulate damping hole. Pressure source model 12 is used to simulate fuel supply pressure. Variable orifice model 13 is used to simulate load pressure. Tank model 14 is used to simulate tank. The electromagnet simulation results of Maxwell Ansoft software were catalogued in data tables that can be called by AMEsim software. Then, read the data tables into the simulation model by electromagnetic module EMLT40. So Maxwell Ansoft and AMEsim Softwares united simulation was realized.

4. Optimization of High-speed On-off Valve

4.1 Mathematical model of optimal design

The selectivity and practicability of ITAE criterion are relatively good. ITAE criteria can reflect the comprehensive control performance of the system [12]. In order to achieve quick response
requirement, the response time of the high-speed on-off valve is an important index in the dynamic design and is related to the error of transient displacement response. The objective function based on the ITAE criterion is the integral of the time between the actual output and the desired output. The objective function can take into account the high speed on-off valve response time and transient error. Therefore, the objective function of the optimization has established as equation (14):

$$J = \int_{0}^{\infty} t |e(t)| dt$$  \hspace{1cm} (14)

$$e(t) = S(t) - S_0(t)$$  \hspace{1cm} (15)

Where, $e(t)$ is the error between the actual displacement and the desired displacement of the ball when step drive voltage inputting system, $S(t)$ is the actual displacement of the ball; $S_0(t)$ is the desired displacement of the ball.

In the simulation model, $S_0(t)$ is calculated by the driving voltage, proportional element 15 and delay link 16, $S(t)$ is measured by displacement sensors, the displacement error $e(t)$ is obtained by comparison point 17.

From the above analysis, the optimization objective of the problem is to minimize the $J(x)$. Circle number, spring preload, spring stiffness, the quality of the ball, working air gap five parameters are optimized variables. High speed on-off valve optimization design mathematical model is as follows:

$$\text{min } J(X)$$

$s.t.$

$$X = (N, F_{10}, K, m, \delta)$$

$$X \in \Omega$$

$$X_{\text{min}} \leq X \leq X_{\text{max}}$$

Where, $X$ is the optimization variables; $N$ is the circle number; $F_{10}$ is spring preload; $K$ is spring stiffness; $m$ is the quality of the ball; $\delta$ is working air gap; $\Omega$ is design domain; $X_{\text{min}}$ and $X_{\text{max}}$ are lower bound and upper bound of optimization variables respectively. Considering the structure of the valve and actual working conditions of the automatic transmission, the constraint conditions including the circle number, spring preload, spring stiffness, the ball quality, working air gap are provided respectively as follows:

- 700 turn $\leq N \leq 1300$ turn
- 27 N $\leq F_{10} \leq 33$ N
- 12 N/mm $\leq K \leq 18$ N/mm
- 0.006 kg $\leq m \leq 0.014$ kg
- 0.5 mm $\leq \delta \leq 0.7$ mm

### 4.2 Optimization result analysis

AMESim genetic algorithm module was used to optimize. The population quantity of genetic algorithm was set to 100, the crossover probability was set to 80%, the variation rate was set to 10%, and the number of generations was set to 50. Parameters before and after optimization are compared in Table 1. In order to facilitate processing, the optimized parameters are modified. The analysis results show that the correction of parameters of high-speed on-off valve has little impact on response time. The comparisons of displacement response curves before and after optimization are shown as Figure 5. The opening response time is reduced from the original 8.2 ms to 6.2 ms, and closing response time is reduced from the original 12.5 ms to 6.6 ms. The total response time is decreased by 38.16% and meets the requirements of fast response performance. As shown in Figure 6., the maximum electromagnetic force is reduced from 39 N to 37 N, it doesn't fall much. The electromagnetic force is still able to meet the requirements of the work.

| Parameters     | circle number / turn | spring preload / N | spring stiffness N/mm | the quality of the ball / g | Working air gap / mm | opening response time / ms | Closing response time / ms |
|----------------|----------------------|--------------------|-----------------------|-----------------------------|----------------------|---------------------------|---------------------------|
| Original parameter | 1000.00              | 30.00              | 15.00                 | 10.00                       | 0.60                 | 8.20                      | 12.50                     |
| Optimized parameters | 703.28               | 29.94              | 16.00                 | 7.61                        | 0.64                 | 6.20                      | 6.50                      |

Table 1. Comparison of parameters before and after optimization.
5. Conclusion

A joint dynamic performance simulation model of the high-speed on-off valve was built by use of AMESim and Ansoft Maxwell software. The model has realized the coupling of electromechanical, liquid and magnetic. The experimental data verified the reliability of the model.

To shorten the response time, the ITAE Criterion was used to create the optimization objective function and the genetic algorithm was used to find the optimal solution. The main factors affecting performance of the high speed on-off valve has optimized. Through the optimization, the opening response time is reduced from the original 8.2ms to 6.2ms, and closing response time is reduced from the original 12.5ms to 6.6ms. The total response time is decreased by 38.16%.

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