Simulation Study on Solenoid Valve of Hydraulic Control Unit

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Abstract. In the research and development and improvement of the wet double-clutch automatic transmission, the hydraulic control unit has always been the focus of attention in the industry, and the working characteristics of the solenoid valve will directly affect the control effect of the hydraulic control unit, which in turn affects the quality of the vehicle's shifting action. [1]This article is based on a hydraulic control unit, using its rich component library on the AMESim software platform, according to the working principle of the solenoid valve, the simulation model of various types of solenoid valves in the hydraulic control unit is established, and the exploration design module is used to identify the various parameters in the valve that are not easy to obtain directly are identified based on genetic algorithm, and the parameters in the model are optimized; then the S function is generated through the interface in AMESim, and each solenoid valve is simulated with the help of the numerical calculation ability of Matlab to obtain The simulation results of the solenoid valve working process are presented.[2, 3].

Keywords: Simulation of solenoid valve, Working principle of solenoid valve.

1. HCU and solenoid valve introduction
An automatic gearbox developed by an automobile company with seven forward gears and one reverse gear. The hydraulic control unit is a main working module equipped with the gearbox. [4, 5]The hydraulic control unit of this model has three main functions: first, The wet dual clutch driving the automatic transmission is combined and disengaged; second, it controls seven forward and one reverse gears for shift operation; third, adjusts the lubrication cooling flow of the gear shaft and clutch. The hydraulic principle diagram of the hydraulic control unit is shown in Figure 1.1 below.
Figure 1.1. Hydraulic principle diagram of hydraulic control unit

As can be seen from the figure, there are ten solenoid valves in the hydraulic control unit, namely four shift control valves, two gear shift pressure control valves, two clutch actuator pressure control valves, and a main pressure control valve and a clutch cooling flow control valve. [6]

The hydraulic principle diagram shows that the solenoid valve is the core component of the hydraulic control unit to play the system function. It not only directly controls the oil pressure of the gear shift oil circuit and the clutch actuator, but also controls the pressure and flow of the oil circuit related to cooling and lubrication by controlling the pilot control pressure of the mechanical hydraulic valve and cooperating with the mechanical valve.

2. Related Theory of Solenoid Valve

In this article, we plan to model and study each solenoid valve in the hydraulic control unit, and conduct simulation experiments on the working process.

The structure and functions of the ten solenoid valves of the hydraulic control unit are similar. [7, 8] The position of the solenoid valve inlet and outlet ports is determined by the proportional solenoid to control the position of the spool, and then the flow direction or flow/pressure of the hydraulic oil is controlled. [9]

![Input and output of solenoid valve](image)

The main components and working form of the solenoid valve are shown in Figure 2.1 above.
As shown in Figure 2.2 above, the spool receives the left electromagnetic force output by the control coil and the proportional electromagnet, and moves to the right to overcome the friction damping and the right spring force, changing the flow of hydraulic oil. Obviously, the movement control process of the spool is a typical spring-mass-damping mechanical system. According to Newton's law of motion, the equation can be obtained:

$$F_E - F_f - C \dot{x} - kx = m\ddot{x}$$  \hspace{1cm} (1)

In the above formula (1), $F_E$ is the electromagnetic force, $C$ is the damping coefficient of the movement; $k$ is the stiffness coefficient of the return spring; $m$ is the mass of the spool moving member; $x$ is the displacement of the spool; $F_f$ is the liquid force, mainly consists of three parts.

1) Steady-state hydrodynamic

When the hydraulic oil flows through the solenoid valve, the movement state of the hydraulic oil changes. The force acting on the spool is the steady state hydrodynamic force $F_1$, which conforms to the following formula:

$$F_1 = 2AC_p\Delta p \cos \theta$$  \hspace{1cm} (2)

In the above formula (2), $A$ is the area of the valve port; $C_p$ is the flow coefficient of the hydraulic oil at the solenoid valve port; $\Delta p$ is the pressure drop of the hydraulic oil inside and outside the valve port; $\theta$ is the jet angle of the valve port.

2) Dynamic hydraulic power

When the opening of the valve port changes, the flow of hydraulic oil through the solenoid valve will change so that the force acting on the valve core is the dynamic hydraulic force $F_2$, which is in accordance with the following formula:

$$F_2 = \rho l \frac{dg}{dt}$$  \hspace{1cm} (3)

In the above formula (3), $\rho$ is the density of hydraulic oil flowing through the solenoid valve; $l$ is the flow of hydraulic oil through the solenoid valve; $\frac{dg}{dt}$ is the rate of change of the valve port flow at this time.

3) Hydraulic pressure
The force of the hydraulic oil's own pressure acting on the end surface of the spool is the hydraulic pressure, which conforms to the following formula:

\[ F_3 = pA' \]  \hspace{1cm} (4)

In the above formula (4), \( p \) is the pressure of the fluid in the solenoid valve; \( A' \) is the projected area of the end face of the spool.

So there are:

\[ F_f = F_1 + F_2 + F_3 \]  \hspace{1cm} (5)

Regarding the electromagnetic force in (1), according to Kirchhoff's law, the voltage in the control coil has the following relationship:

\[ U = iR + \frac{d\varphi}{dt} \]  \hspace{1cm} (6)

In the above formula (6), \( U \) is the voltage input to the control coil; \( i \) is the current input to the control coil; \( R \) is the resistance of the coil; \( \varphi \) is the flux linkage around the coil.

The current density of the magnetic field generated by the coil is:

\[ J = \frac{Ni}{A} \]  \hspace{1cm} (7)

In the above formula (7), \( J \) is the current density of the coil magnetic field; \( A \) is the cross-sectional area of the coil.

Combining Maxwell's electromagnetic equations in differential form:

\[
\begin{cases}
\nabla \times H = J \\
\nabla \times E = -\frac{\partial B}{\partial t} \\
\n\nabla \cdot B = 0
\end{cases}
\]  \hspace{1cm} (8)

In the above formula (8), \( \nabla \) is the Hamiltonian, \( \nabla \equiv \frac{\partial}{\partial x} \hat{i} + \frac{\partial}{\partial y} \hat{j} + \frac{\partial}{\partial z} \hat{k} \); \( H \) is the magnetic field strength; \( E \) is the mild electric field; \( B \) is the magnetic induction strength.

According to the relevant definition of electromagnetics, there are

\[
\begin{cases}
\nJ = \sigma E \\
B = \mu \mu_0 H
\end{cases}
\]  \hspace{1cm} (9)

In the above formula (9), \( \sigma \) is the electrical conductivity of the coil; \( \mu \) is the magnetic permeability of the coil; \( \mu_0 \) is the vacuum permeability.

According to Ampere's Law:

\[ J = \nabla \times H - \sigma E \]  \hspace{1cm} (10)

So the current density in the coil is:

\[ J = \frac{Ni}{A} \]  \hspace{1cm} (11)
In the above formula (11) $N$ is the number of turns of the coil; $A$ is the cross-sectional area of the coil.

According to the energy equation of the electromagnetic field, we can get

$$F_E = \frac{N^2 \mu^2 A l}{2 \mu_0 l^2}$$  \hspace{1cm} (12)

In the above formula (12), $l$ is the width of the electromagnetic air gap of the solenoid valve. It can be seen from the above formula that the electromagnetic force output is basically proportional to the input current when the solenoid valve size and material parameters are determined.

In the steady state, the combination of the valve core and the return spring 1-12, 1-1-5 can be obtained:

$$\sum F = F_1 + F_3 + F_E = 0$$  \hspace{1cm} (13)

In the above formula (13), under the good lubrication of hydraulic oil, $F$ static friction force can be basically ignored, then there is

$$pA' = 2AC_v \Delta p \cos \theta + \frac{N^2 \mu^2 A l}{2 \mu_0 l^2}$$  \hspace{1cm} (14)

The above formula (14) is the relationship between the output pressure of the solenoid valve and the input current.

In addition, according to the two basic equations in fluid mechanics—the continuity equation and the Bernoulli equation, the relationship between the flow rate and the pressure at the outlet of the solenoid valve can be derived

$$q = C_v A_0 \sqrt{\frac{2\Delta p}{p}}$$  \hspace{1cm} (15)

In the above formula (15), $\Delta p$ is the pressure difference of the hydraulic oil on both sides of the solenoid valve inlet and outlet, $A_0$ is the opening area of the solenoid valve oil outlet, satisfy

$$A_0 = W x_R$$  \hspace{1cm} (16)

In the above formula (16), $W$ is the area gradient of the solenoid valve oil outlet, which is related to the shape of the solenoid valve outlet; $x_R$ is the opening of the valve port, which is related to the displacement of the valve port and spool.

This article focuses on the relationship between the output properties of the solenoid valve hydraulic oil and the current input of the solenoid valve control coil. Through the above theoretical derivation and analysis, the relationship between each parameter of the solenoid valve and its output is established. When modeling and solving with the help of a computer, it is necessary to focus on the structural parameters of the solenoid valve mentioned above to improve the accuracy of the simulation.

### 3. Solenoid valve modeling and simulation

In this paper, AMESim (Advanced Modeling Environment for Simulation of engineering systems) is used to establish the model of the solenoid valve. At the same time, with the help of Matlab's powerful numerical calculation capabilities, the output of the solenoid valve is simulated during actual work.

[10.11]
The electromagnetic valve is divided into two parts from the overall structure: electromagnetic part and mechanical hydraulic part. The drive circuit starts to work first, and then the control signal generates a magnetomotive force in the electromagnetic part of the solenoid valve, and the electromagnet generates a corresponding electromagnetic force, which in turn affects the spool of the solenoid valve, and controls the opening and closing state of the valve port. A certain flow and pressure can be generated at the output port of the solenoid valve. [12, 13]

The mechanical hydraulic component model uses the hydraulic component design library and related components in the mechanical library for modeling. Using the spool, mass, and spring push rod to simulate the remaining components of the mass spring damping system, a mathematical model of the clutch actuator oil pressure control valve shown in Figure 3.1 is established. [14, 15]

![Figure 3.1. Model of clutch actuator oil pressure control valve](image)

The electromagnetic part of the oil pressure control valve of the clutch actuator uses the proportional electromagnetic module in the electromagnetic library (EM, Electro Mechanical) file of the AMESim hydraulic simulation platform.

The design exploration module of AMESim hydraulic simulation platform provides two design exploration algorithms: nonlinear quadratic programming algorithm and genetic algorithm. Comparing the two, the genetic algorithm is more time-consuming but more accurate. In this paper, the genetic algorithm is selected to explore the design space.

The genetic algorithm is designed and proposed according to the evolutionary laws of nature. The basic idea is based on the principle of survival of the fittest. For solving more complicated combinatorial optimization problems, genetic algorithms are more able to obtain ideal optimization results than some conventional optimization algorithms.

The relevant parameters of the solenoid valve need to be set as shown in Table 3.1 below.

| Component            | Parameter            | Approximate Range | Unit |
|----------------------|----------------------|-------------------|------|
| Proportional electromagnet | Coil turns          | 1000-2000         | turns|
|                      | Coil resistance      | 1-20              | Ω    |
|                      | Initial air gap      | 5-10              | mm   |
| Spool                | Piston diameter      | 2-5               | mm   |
|                      | Push rod diameter    | 2-10              | mm   |
|                      | Mass                 | 0.01-1            | kg   |
| Spring               | Stiffness coefficient| 1-5               | N/mm |
|                      | Preload              | 1-5               | N    |
When performing parameter identification, first find out the data to determine the known parameters of each component in the solenoid valve model, and set these parameters in the parameter mode. According to relevant information, the data shown in the following table is known.

Table 3.2. Known parameters

| Parameter                        | Value  | Unit |
|----------------------------------|--------|------|
| Hydraulic oil density           | 831.1  | kg/m³|
| Kinematic viscosity of hydraulic oil | 23.58  | mm/s |
| Spool piston diameter           | 10     | mm   |
| Push rod diameter               | 5      | mm   |
| Coil resistance                 | 10     | Ω    |

Then, according to the relevant data required by the technology, several of these points are input into the design exploration module using the data input function in AMESim. Drag the remaining parameters in Table 3.2 above to the input parameter box, and use the input pressure parameter and the output pressure of the solenoid valve in the simulation as output parameters, and define the difference between the two in the comprehensive output parameter. Then add each input and output to the design exploration module as shown in Figure 3.2 below.

Figure 3.2. Input and output settings

The parameters to be identified are used as the exploration space for design exploration, and the comprehensive output parameter Dif is used as the objective function. Finally, in the research management interface, create a new optimization to explore Optimization, select the genetic algorithm, use the default genetic algorithm parameters, as shown in Figure 3.3 below.
After 20 iterations, the optimal parameters of other components in the solenoid valve model are finally obtained, as shown in Table 3.3 below. At this time, the objective function $D_i$ value is $1.45 \times 10^{-5}$, indicating that at this time, the model of the clutch actuator oil pressure control valve is very close to the ideal state in the technical requirements of the actual solenoid.

| Component          | Parameter       | Approximate Range | Unit |
|--------------------|-----------------|-------------------|------|
| Proportional electromagnet | Coil turns | 1477 | turns |
|                    | Coil resistance | 10 | Ω |
|                    | Initial air gap | 7.3 | mm |
| Spool              | Piston diameter | 10 | mm |
|                    | Push rod diameter | 5 | mm |
|                    | Mass             | 0.02 | kg |
| Spring             | Stiffness coefficient | 1.4 | N/mm |
|                    | Preload          | 1 | N |

After 20 iterations, the optimal parameters of other components in the solenoid valve model are finally obtained, as shown in Table 3.3 below. At this time, the objective function $D_i$ value is $1.45 \times 10^{-5}$, indicating that at this time, the model of the clutch actuator oil pressure control valve is very close to the ideal state in the technical requirements of the actual solenoid.

Insert the interface element with Matlab/Simulink in AMESim, given an input and an output. An additional voltage sensor element is added to convert the pressure signal of the output hydraulic oil to the input signal of the interface module and send the input electrical signal to the output signal of the interface module. The model of the joint simulation of the oil pressure control valve of the clutch actuator is shown in Figure 3.4 below.
After the model of the joint simulation passes through the sub-model mode and the parameter mode, the S function of the simulation system is compiled and generated as shown in Figure 3.5 below.

Call the S function in the Matlab model and set the parameters. In Simulink environment, you need to create an S function module and change its name to the corresponding file name in AMESim, and add an underscore "_". At this time, by using the S function, the entire model in AMESim is added to Simulink, and finally the Simulink control system will be partially simulated. The data obtained after the simulation can be returned to AMESim through the S function. At this time, the simulation curve can be analyzed in AMESim. This whole process realized the joint modeling and simulation of AMESim and Simulink.
In the simulation results in AMESim, check the pressure output of the oil outlet as shown in Figure 3.7 below.

Figure 3.7. Simulation working characteristic curve of the oil pressure control valve of clutch actuator

Set the input current signal of the clutch actuator pressure control valve to I=0.05t. Figure 3.7 shows the curve of the pressure of the clutch actuator oil line pressure control valve with time. It can be seen from the figure that after about 2.8 seconds, the spool of the solenoid valve moves, and an output signal begins to appear at the oil outlet of the solenoid valve. The pressure output curve after 7 seconds is a downward convex curve that approximates a straight line, indicating that the working state of the solenoid valve has good linearity and can achieve precise pressure control.

4. Conclusions
This article uses its rich component library in AMESim, based on the working principle of the solenoid valve, establishes a simulation model of various types of solenoid valves in the hydraulic control unit, and uses the exploratory design module, which is not easy to obtain directly from the solenoid valve. Based on genetic algorithm, the parameters were identified, and the parameters in the model were optimized. Finally, the S function was generated through the interface in AMESim, and the simulation of each control solenoid valve was carried out with the help of the numerical calculation ability of Matlab. Simulation results of the working process.

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