Research on Influence of Solenoid Valve on Multi-Injection Characteristics of Low Speed Marine Machines

Wenchao Zhu*
School of Energy and Power Engineering, Wuhan University of Technology, Wuhan, China

*Corresponding author e-mail: zhuwenchao5351231@qq.com

Abstract. As one of key components in a common rail fuel injection system, a solenoid valve is used as an execution unit in controlling fuel injection amount, injection timing, injection duration and injection rate, which has a decisive impact on the performance of the common rail fuel injection system, AMESim simulation model of marine low-speed fuel injection system is built and the experimental data were used to verify and optimize the experiment, the simulation model showed that using self-developed fuel injection control valve can achieve multi-injection performance of marine low speed engine, The minimum time of single injection is 1.2ms, the minimum interval between two injections is 1.9ms.

1. Introduction
Marine low-speed diesel engines require not only high response speed but also large flow capacity for the solenoid valve used for fuel injection control because of the large amount of circulating fuel injection. But at the same time improving the solenoid valve circulation capacity and response speed is very difficult. Generally, the large flow characteristics of solenoid valves lead to low response speed, which makes it difficult for the controlled injector to achieve multi-stage injection under a shorter injection pulse width. In this paper, AMESim software is used to build the simulation model of marine low-speed engine fuel injection system, including solenoid valve, hydraulic booster pump, injector, etc. The simulation model is validated by test data. Through the simulation calculation of two key control indexes in dynamic test, the self-developed solenoid valve is analysed. The feasibility of multi-stage injection is achieved by fuel injection system.

2. Simulation model

2.1. Mathematical model
In AMESim simulation, according to the properties and characteristics of liquids, a computational model which meets the accuracy requirements of the system is established, not only relying on mathematical equations, but also considering the influence of the variation of liquid properties on the hydraulic parameters. [1, 2]

(1) The volume chamber module is based on the mass conservation equation of fluid.
\[
\frac{dP}{dt} - Q_0 \left( \frac{1}{\exp \left( \int_0^P \frac{dP}{B} \right)} \right) \frac{B}{V} dt = 0
\]

\(dP\) is Liquid pressure change, \(P_a\); \(\exp \left( \int_0^P \frac{dP}{B} \right)\) is dimensionless calculation factor; \(Q_0\) is actual volume flow, \(\text{m}^3/\text{s}\); \(B\) is bulk modulus, \(P_a\); \(V\) is volume, \(\text{m}^3\); \(dt\) is time change, \(\text{s}\).

(2) The orifice module is based on the energy conservation equation.

\[Q = C_q^{\text{max}} \sqrt{\frac{2 |\Delta P|}{\rho}} \text{sign} (\Delta P)\]

\(Q\) is quantity of Liquid, \(\text{kg} / \text{m}^3\); \(C_q^{\text{max}}\) is Maximum flow coefficient; \(\Delta P\) is Pressure difference between both ends, \(P_a\); \(\rho\) is Fluid density, \(\text{kg} / \text{m}^3\).

(3) Fluid valve port based on momentum conservation equation.

\[f = 2C_q \cdot a \cdot \Delta P \cdot \cos \theta_f\]

\(C_q\) is Dimensionless discharge coefficient, \(a\) is Circulation area, \(\text{m}^2\); \(\Delta P\) is pressure change; \(P_a\), \(\theta_f\) is Fluid injection angle.

2.2. Establishment of simulation model

Considering the eddy current effect in the core and armature of the electromagnet, ELTRA’s module is selected, and electromagnetic force data inquiry mode is adopted. At the same time, the parameters such as air gap, turns of reluctance coil are set up in the module [3, 4, 5].

Figure 1. Simulation model of hydraulic pressurized fuel injection system
In the simulation of current control mode of solenoid valve drive circuit, ESCBCTA module in AMESim is used to construct H-bridge drive circuit. The simulation model can accurately follow the set value of the coil current when the load inductance changes continuously. The faster the response speed of the electromagnet, the smaller the error of the control current simulation model. Figure 1 shows the simulation model of the whole hydraulic pressurized fuel injection system.

3. Experiment on high speed response characteristics of solenoid valve

The electromagnetic valve performance test-bed is used to simulate the working environment of servo oil in the injector. The minimum response time $T_1$ of the spool stability in a single cycle of the solenoid valve in the test represents the rapid opening and closing capability of the solenoid valve in a single injection. The shortest interval time $T_2$ of the control signal in multiple cycles of the solenoid valve represents the pre-injection and multi-injection capability of the solenoid valve in actual operation.

3.1. Experimental scheme

Setting test conditions: pole external diameter 35 mm, pole internal diameter 16 mm, line diameter 0.67 mm, coil turns 20 turns, operating frequency 10 Hz, control chamber height 3 mm, oil return pressure 2 bar. The control variable method is used to study the influence of four factors such as working clearance, residual clearance, reset spring force and working pressure of solenoid valve on the minimum response time $T_1$ of the spool stability and the control signal interval $T_2$ of the solenoid valve and seek to meet the optimal value of $T_1$ and $T_2$.

3.2. Experimental result

Table 1 shows that the values of $T_1$ and $T_2$ are the smallest in group 10, but the effect of spring preload on $T_1$ is not obvious. A small spring preload will make the spring restoring force insufficient and lead to the return port cannot be completely closed, excessive spring preload will lead to the solenoid valve opening influence time prolonged, or even unable to open solenoid valve.

Therefore, the experimental data of the third group meet the requirements of stable operation of the system, the minimum response time $T_1$ of spool stability in single injection is 2.3ms, and the minimum time interval $T_2$ between the two control signals of spool stability in multiple injection is 1.8ms.

| Test sequence number | working clearance $G$/mm | residual clearance $G_c$/mm | reset spring force $F$/N | Working pressure $P$/MPa | $T_1$/ms | $T_2$/ms |
|----------------------|--------------------------|-----------------------------|------------------------|-------------------------|----------|----------|
| 1                    | 0.25                     | 0.08                        | 100                    | 30                      | 3.21     | 1.61     |
| 2                    | 0.3                      | 0.08                        | 100                    | 30                      | 2.58     | 1.70     |
| 3                    | 0.35                     | 0.08                        | 100                    | 30                      | 2.30     | 1.80     |
| 4                    | 0.4                      | 0.08                        | 100                    | 30                      | 3.11     | 2.19     |
| 5                    | 0.35                     | 0.04                        | 100                    | 30                      | 2.82     | 2.31     |
| 6                    | 0.35                     | 0.12                        | 100                    | 30                      | 3.02     | 1.70     |
| 7                    | 0.35                     | 0.16                        | 100                    | 30                      | 3.19     | 1.60     |
| 8                    | 0.35                     | 0.08                        | 64.7                   | 30                      | 2.47     | 2.72     |
| 9                    | 0.35                     | 0.08                        | 85.8                   | 30                      | 2.4      | 2.41     |
| 10                   | 0.35                     | 0.08                        | 132                    | 30                      | 2.21     | 1.70     |
| 11                   | 0.35                     | 0.08                        | 100                    | 27.5                    | 2.81     | 1.98     |
| 12                   | 0.35                     | 0.08                        | 100                    | 25                      | 2.65     | 1.95     |
| 13                   | 0.35                     | 0.08                        | 100                    | 22.5                    | 2.54     | 2.0      |
| 14                   | 0.35                     | 0.08                        | 100                    | 20                      | 2.47     | 1.84     |
4. Study on multi-stage injection characteristics of electronically controlled fuel injection system

4.1. Simulation calculation scheme

(1) Minimum pulse width for single injection of solenoid valve

The control signal is a monopulse signal with an amplitude of 50A, and its pulse width is a batch simulation object parameter. The simulation time is 0.01s, and seven batch simulation values of pulse width are established. The range of simulation values is 0.9ms-1.5ms, and the step size is 0.1ms.

(2) Multiple injection minimum time interval

Set the control signal as two same normal high and low voltage control signals, control pulse width is 20ms, establish five batch simulation values of pulse width, the range of values is 1.5-2.3ms, step size is 0.2ms.

4.2. Analysis of simulation results

(1) Minimum pulse width for single injection of solenoid valve

As shown in Fig.2, when the control pulse width is 1.2ms, the spool of the solenoid valve is stable and the minimum response time is 3.1ms. If the control pulse width is less than 1.2ms, the control time is too short, so that the pressure in the control chamber cannot be reduced to zero. Considering the response delay caused by the change of the control cavity volume in the simulation calculation, the simulation results lag behind the experimental data by 2.3ms.

(2) Multiple injection minimum time interval

Short injection interval will lead to needle valve not fully seated that the next injection. It can be seen from the fuel injection characteristic curve of Fig.3. When the injection interval is less than 1.9ms, the first injection process and the second injection process are basically completed at one time, and the multiple injection cannot be achieved. Although the response delay is caused by the volume change of the control chamber, the delays of the pressure opening and closing responses cancel each other, so the simulation results are in good agreement with the experimental data of 1.8ms

Figure 2. Control of pressure characteristic curve in chamber
Figure 3. Characteristic curve of fuel injection quantity

5. Conclusion
The AMESim software is used to simulate the fuel injection system. Through the structure and working principle of the fuel injection system, the AMESim simulation model including high-speed solenoid valve, hydraulic booster pump and injector is established. The accuracy of the AMESim model is verified by comparing with the performance test data of the solenoid valve. The minimum time of spool stabilization for single injection is 1.2ms and the spool stabilization time is 3.1ms. The minimum time interval of control signal is 1.9ms when multiple injection spool is stable.

References
[1] Wang Chengyong. Simulation and Research on the Injection Performance of RT flex60C Common Rail Fuel [D]. Harbin Engineering University, 2011.
[2] Su ming, Chen lunjun. Study on dynamic and static characteristics of electromagnetic high-speed switch solenoid valve based on AMESim [J]. Hydraulic and pneumatic, 2010 (02): 68 - 72.
[3] Liyun F, Liming W, Bingqi T, et al. Study on fuel injection quantity characteristics of the electronically controlled two-valve fuel injection system for multi-injection [J]. Journal of Harbin Engineering University, 2012, 33 (6): 702 - 708.
[4] Glass O, D Han-Kwan. On the controllability of the relativistic Vlasov–Maxwell system. Journal de Mathématiques Pures et Appliquées, 2015.103 (3): 695 - 740.
[5] Schechter M. Fast Response Multipole Solenoids, SAE Technical Paper 820203, 1982.