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The Characteristic Analysis of the Electromagnetic Valve in Opening and Closing Process for the Gas Injection System

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Abstract

In this paper, the mathematical model of solenoid valve in the fuel injection system of gas engine is built. Simulation software Matlab/Simulink are employed to analyze the impact which the voltage, number of the coil turns and air gap width may produce to the open and close characteristics of the solenoid valve. The ideal response characteristics are got through the calculation. An optimal scheme which satisfies the operation requirements is put forward. The driving voltage and maintaining voltage are set as 90 V and 21 V; number of the coil turns is 30 N; air gap is determined as 0.6 mm; the opening and closing time are respectively 0.98 ms and 0.8 ms. This paper can be used as a reference for the design of the solenoid valve.

Keywords

Solenoid Valve, Response Characteristics, Matlab/Simulink, Fuel Injection System

1. Introduction

Electronic control injection system has been rapidly developed and widely applied as the important part of gas engine, with advantages of high output power, low fuel consumption and clean emission. It is necessary to analyze the response of the high-speed switch electromagnetic valve for the characteristics affecting the whole engine fuel injection law as the driving structure of high-speed switch electromagnetic valve. Liu Weizhong established the response analysis of high-speed switch electromagnetic valve, but he did not study the influence of various parameters on the open/close response [1]. Li Chunqing established electronic control diesel engine solenoid valve model using the software of GT-suit to study the influence of drive current and spring pre-tighten-

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ing force to the electromagnetic valve on-off characteristic [2]. Dai Jia established the simulation model of pneumatic solenoid valve and analyzed the influence of various parameters on the response characteristic parameters, but the response is not in conformity with the high power, large flow requirements [3]. Ge Wenqing designed a electromagnetic valve with high power and large flow. An experiment was carried out to measure the response characteristics which met the design requirements, but the analysis of the effect of design parameters on the response characteristics was not conducted [4].

To study the drive characteristic of electromagnetic valve, a self-made high power gas spray electromechanical control valve is employed as the research object. The ideal of on-off characteristic parameters is got by observing the different input parameters, impact to the solenoid valve.

2. Electromagnetic Valve Dynamics Simulation Model

Electromagnetic valve electromagnetic part can be simplified to U-shaped structure as shown in **Figure 1**.

According to the electromagnetic valve stem movement regular as shown in **Figure 2**, the stem' mechanical movement can be divided into three processes:

1) Opening process: the high-speed solenoid valve was in the closed state before applying driving voltage to the High-speed solenoid valve under the action of a spring pre-tightening force. After the applying of the driving

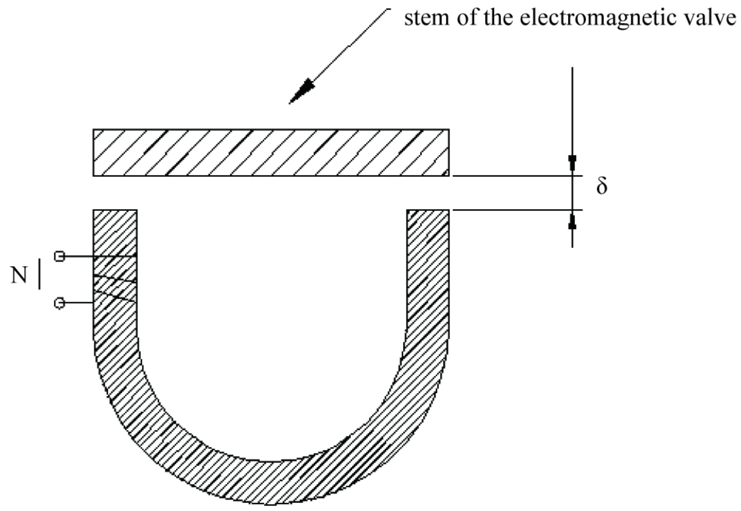

Figure 1. Electromagnetic part.

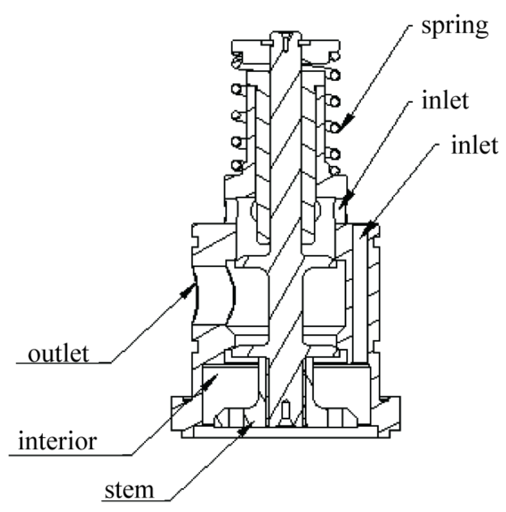

Figure 2. Movement part of the electromagnetic valve.

voltage, Stem began to exercise, until reaching the small gap overcoming the pre-tightening force of the spring after that the value of electromagnetic force is greater than the pre-tightening force of the spring. In order to realize the rapid opening of high-speed, solenoid valve driving voltage need a larger value of high opening driving voltage.

2) Moving process: When the jet at the start of the coil current, current rise. Due to the existence of the inductor the current rising slowly and the electromagnetic rising slowly, when electromagnetic force up to greater than other force, the stem begins moving down, so the gas from the air inlet flow into the lumen. In the process of opening, the magnetic gap gradually reduce, so magnetic resistance gradually reduced. When the solenoid valve in the fully open position, due to the magnetic gap decreases, and the stem reaching the large position, drive voltage converts to maintain the voltage which keep the valve fully opening state at this point, the electromagnetic force acting on the valve stem is still greater than the spring force. Solenoid valve in a fully open position, and the stem in static state theoretically, the resultant force of stem is zero.

3) Reverting process: When the solenoid valve jet has been completed, the coil power outage, due to the self-inductance phenomenon, electromagnetic force doesn't disappear immediately, so the electromagnetic force exists. When the force of the electromagnetic force is smaller than the spring the restoring force of the valve stem begin to rise until closed position [5]-[8].

The working process of the solenoid valve is made up of the process of electricity producing magnetic, magnetic producing force, force producing movements, so the model is a mathematical simulation model by the circuit model, the electromagnetic model and mechanical model.

2.1. Circuit Model

According to the actual situation, this paper made some simplification to the circuit model, not considering the influence of temperature on additional inductance coil and resistance. To overcome the spring pre-tightening force in the process of opening, a larger driving voltage can be input. When the valve is fully open, in order to save power consumption and prevent electromagnetic region temperature affecting to its life, a smaller maintaining voltage can be enter to keep opening process. The voltage can be split two pieces.

$$U = U_R + U_L = Ri + \mathrm{d}\psi/\mathrm{d}t \tag{1}$$

$$U = \begin{cases} U_{\text{peak}} & 0 < t < t_p \\ U_{\text{hold}} & t_p < t < t_h \end{cases} \tag{2}$$

where U_{peak} is the high driving voltage; U_{hold} is the low maintaining voltage; t_p is the time of high driving voltage; t_h is the time of the low maintaining voltage; R is the Equivalent coil resistance; i is the current in the circle; ψ is the total magnetic flux.

2.2. Magnetic Circuit Equation

Considering the influences of electromagnetic materials and the working air gap of magnetic resistance the influence of the change of the magnetic conductor magnetic resistance, permeability of electromagnetic materials is obtained by the fitting of the Silicon steel magnetization curve and not considering the magnetic leakage According to the Kirchhoff's law of magnetic pressure, the equivalent magnetic circuit calculation equation is

$$Ni = H_c L_c + H_\delta L_\delta = \frac{B_c}{\mu_c} L_c + \frac{B_\delta}{\mu_\delta} L_\delta = \frac{\phi}{\mu_r S} L + \frac{\phi}{\mu_0 S} \delta \tag{3}$$

Equations (4), (5) can be inferred from Equation (3)

$$N^2 i = \frac{\psi}{\mu_r S} L + \frac{\psi}{\mu_0 S} \delta \tag{4}$$

$$i = \frac{LH}{N^2 SB} \psi + \frac{\delta}{\mu_0 N^2 S} \psi \tag{5}$$

$$F_e = \frac{\phi^2}{2\mu_0 S} = \frac{\psi^2}{2\mu_0 N^2 S} \tag{6}$$

where δ is the air width gap ($\delta = \delta_0 - x$), δ_0 is the initial gap width, x is the displacement of the stem, B is the magnetic induction intensity, L is the equivalent length of magnetic conductor, N is the number of coil turns, μ_0 is vacuum magnetic permeability, μ_r is the relative permeability, $S$is the area of electromagnets air-gap, F_e is electromagnetic force.

2.3. Equation of Mechanical Motion

Electromagnetic valve of the valve stem is under spring force, electromagnetic force and the gas pressure. In the process of movement, gas pressure is rather complex, involving the distance between the valve stem and valve seat, the diameter of the valve stem and the pressure change of the air in the cavity in the process of ejection. In this paper, the gas pressure simplified to two force natural gas to stem F_r and gas resistance F_D, and the force of gas on the valve stem can be simplified into a constant gas resistance. F_D can be simplified as $D\dot{x}$ is viscous damping coefficient; $\dot{x}$ is the velocity of the stem; the spring force is $kx + F_0$; k is the stiffness of spring; F_0 is the spring pre-tightening force; $\ddot{x}$ is the acceleration of the stem; m is the quality of the stem. So the equation of motion is

$$F_e = ma + F_K + F_0 + F_D - F_r = m\ddot{x} + kx + F_0 + D\dot{x} - F_r \tag{7}$$

3. Simulation Calculation and Analysis

As the solenoid valve is a typical nonlinear dynamic system, the software Simulink is employed to establish the mathematical model in this paper. The output of the response characteristic which changing by the parameter can be got through this method. Furthermore, the picture of the electromagnetic force, current and the displacement of the stem can be got. In **Figure 3**, some worlds present some special means, such as:

$$k_1 = \frac{1}{\mu_0 N^2 S},\ k_2 = \frac{1}{2\mu_0 N^2 S},\ k_3 = \frac{1}{2N^2 S},\ k_4 = \frac{1}{NS}$$

3.1. Influence of Driving Voltage Value

The voltage in this paper can be spitted into two parts, respectively named high driving voltage and low maintaining voltage. Due to the driving voltage has influence to the open process and low maintaining voltage has influence to the process of shutting down, the influence of voltage to the solenoid valve can be obtained. When keeping the driving voltage at 21 V. The displacement curve of the stem is **Figure 4** and the opening response time curve is **Figure 5**.

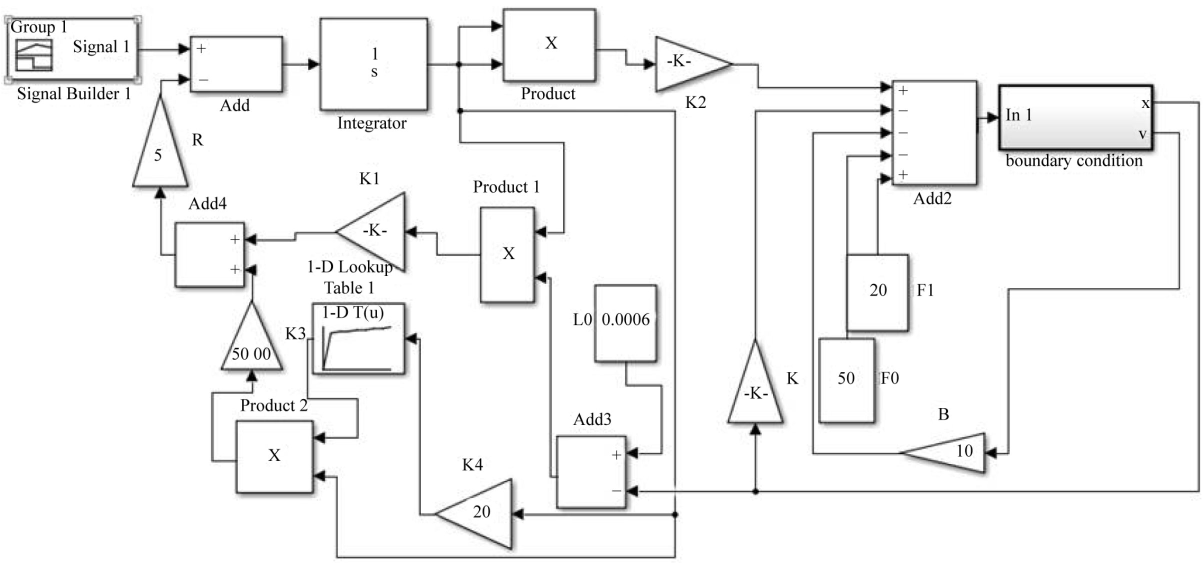

Figure 3. Simulation model.

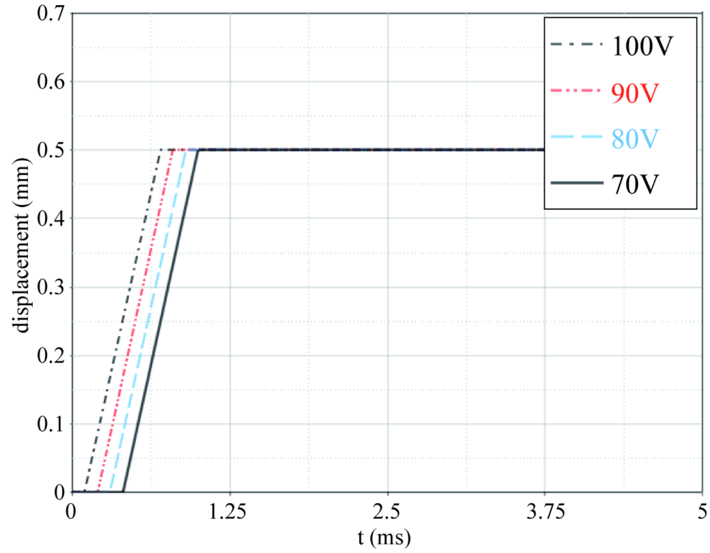

Figure 4. Opening process of the stem in different driving voltages.

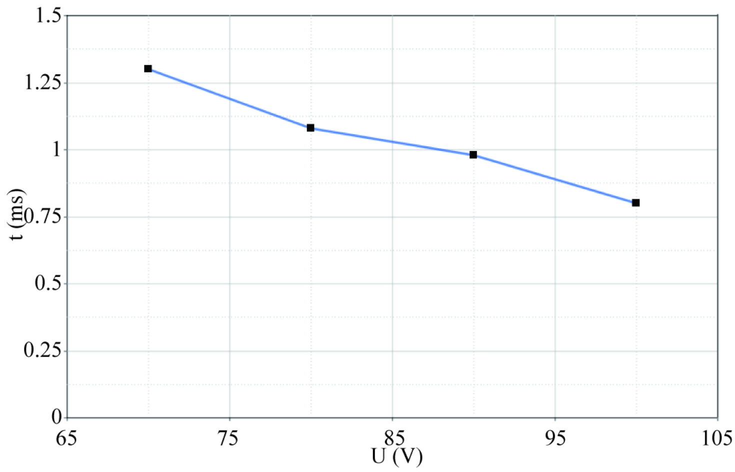

Figure5. Opening response time in different driving voltages.

As the maintaining voltage is constant at this time, the close response time is constant. When the voltage is 100 V, the opening response time is 0.8 ms. With the decrease of the voltage value, response time increases, when the voltage to 90 V, the response time is 0.98 ms, when the voltage decreases to 80 V, the response time rose to 1.08 ms, when the voltage to 70 V, the response time is 1.12 ms. Therefore we can get a litter response time by enhancing the voltage, but high driving voltage lead to a high velocity between the tem and the seat and reduce the life of the solenoid valve and increase power consumption. When driving voltage meets the job requirements, we should choose a low maintaining voltage as far as possible. The driving voltage is selected as 90 V. The close response in details we can get from **Figure 6**.

Due to the driving voltage is constant, the open response time is 0.98 ms. While maintaining the higher the voltage, the current in coil is reduced in lower velocity and stem will close delay which is shown in **Figure 7**. Above all, when low maintaining voltage meets the job condition, high maintaining voltage leads power consumption and extend the closing time.

3.2. Influence of Number of Coil Turns

With the same current, the more of the number of coil is, the greater of the magnetic induction intensity is. The greater of the electromagnetic force is, the shorter of the response time of opening is.

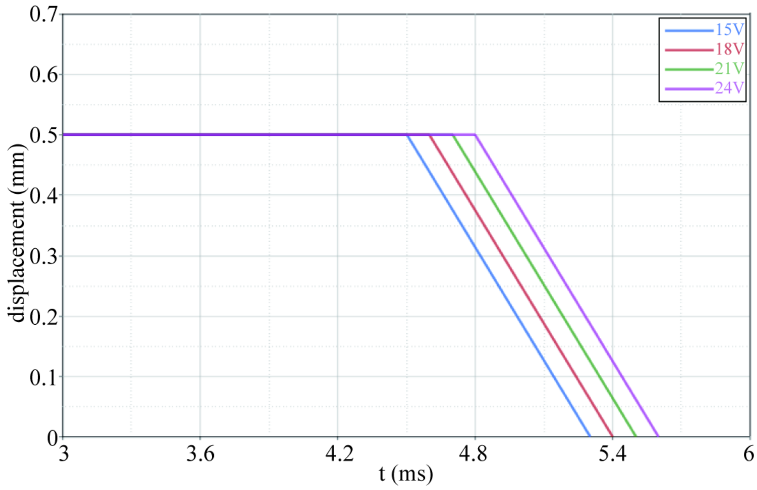

Figure 6. Closing process of the stem in different maintaining voltages.

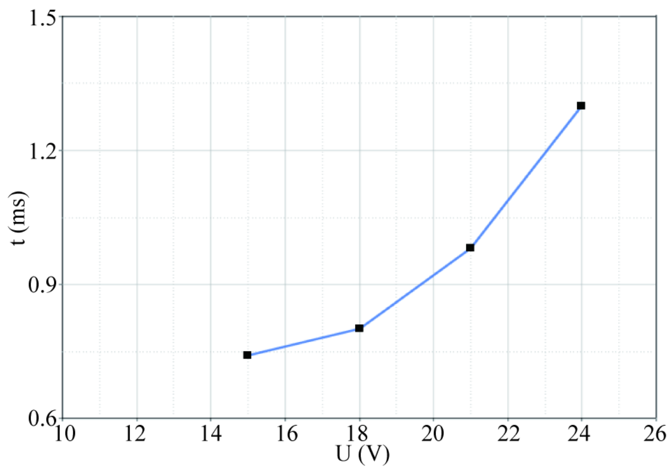

Figure 7. Closing response time in different maintaining voltages.

According to the actual situation, the number of the coils selected for the paper is 30, 40, 50, and 60.The influence of different number of the coils can be observed in **Figure 8** that the more of the coil number is, the higher of the peak electromagnetic force is, what's more, the opening time of the stem is accelerated. In **Figure 9**, when the current is off, the more of the coil is, the slower the electromagnetic force decreases, which impacts the closing time of the stem.

3.3. Influence of Air Gap Width

The electromagnetic valve air gap width δ includes two parts the displacement of the stem x and the residual gap width δ_0, when the valve is fully closed, the electromagnetic valve air gap is equal to the sum of the residual gap width and the displacement of the stem, when fully closed the electromagnetic valve air gap is equal to the sum of the residual gap width. As the displacement of the stem has an impact on the flow flux, the biggest displacement should not change, now we analyze what influence of the different values of the residual gap width will have on the character of electromagnetic valve, the value we choose for the residual gap width is 0.1 mm, 0.2 mm and 0.3 mm.

In **Figure 10**, with the increasing of the air width, the electromagnetic force grows rapidly. When the low maintaining voltage is constant, the bigger the air gap width is, the litter the force is

In **Figure 11**, when the displacement of the stem is constant, the smaller of the air gap width is, the shorter of the closing time is.

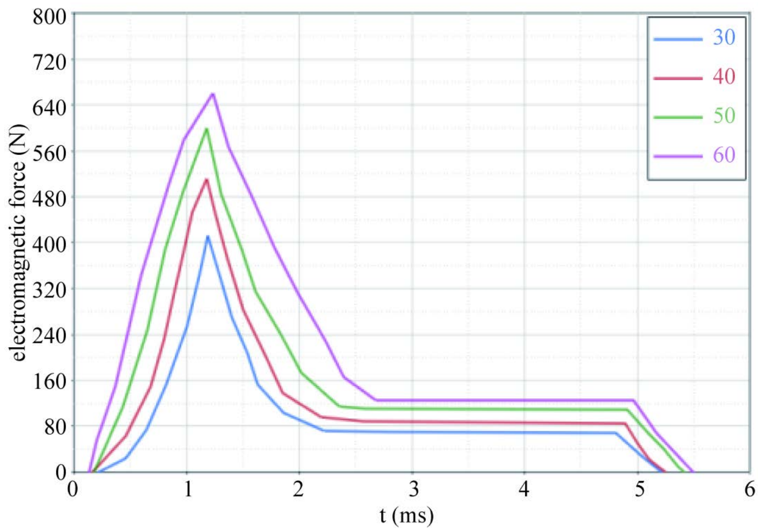

Figure 8. Electromagnetic force in different number of coil.

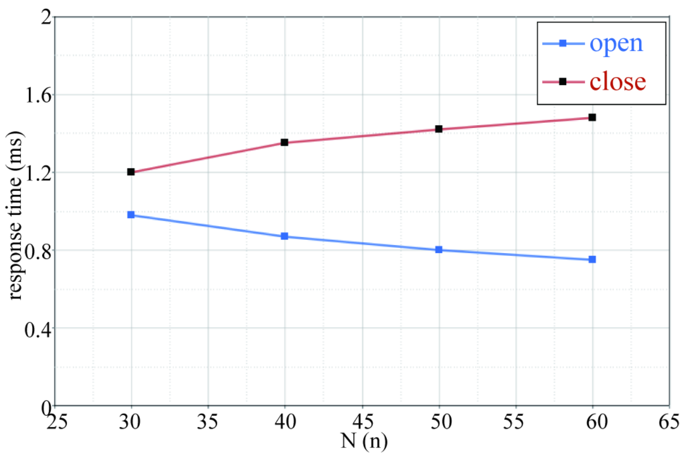

Figure 9. Response time in different number of coil.

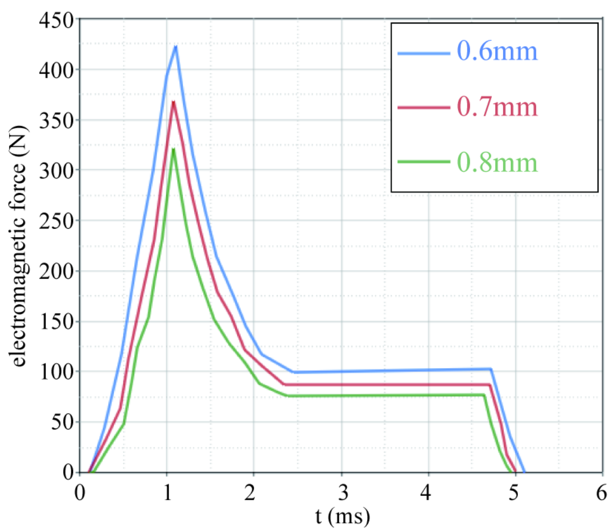

Figure 10. Electromagnetic force in different air gap width.

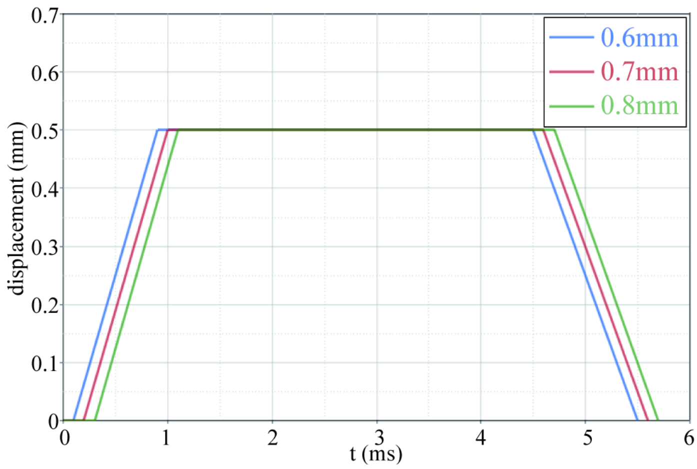

Figure 11. Displacement of the stem in different air gap width.

4. Optimal Case

After observing the effects of various parameters on the on-off characteristic, the ideal on-off characteristic parameters of the parameters is got at last, namely $U_{peak} = 90$ V, $U_{hold} = 21$ V, $N = 30$, $\delta_0 = 0.6$ mm.

5. Conclusions

The mathematical model of Circuit, magnetic circuit and mechanical motion is established using the simulation software Simulink after the brief introduction and analysis of the electromagnetic valve. The influence of the design parameters on the opening and closing process of the electromagnetic valve is analyzed in quantitative in details about Voltage, the number of coil turns and the air gap width. During analysis, the voltage is split into two parts. The parameter of impact to electromagnetic valve we choose for the high driving voltage is 100 V, 90 V, 80 V and 70 V, and the same situation to other is that 15 V, 18 V, 21 V, 24 V to low maintaining voltage, 0.5 mm, 0.6 mm and 0.7 mm to the air gap width and 30 V, 40 V and 50 V to the number of the coil turns.

At last an optimal solution is selected for the dynamic simulation respectively $U_{peak} = 90$ V, $U_{hold} = 21$ V, $N = 30$, $\delta_0 = 0.6$ mm. This case which the opening response time is 0.98 mm and the closing response time is 0.95 mm meets the job demand.

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