Simulation of Solenoid Valve Characteristics of Electronically Controlled Fuel System for Diesel Engine

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Abstract. To quantitatively analyze the influence of solenoid valve parameters on their dynamic response characteristics, mathematic models are built based on the electromagnetic theory. Research is carried out using mathematical models, whereby the dynamic response process of the solenoid valve driven by constant voltage is simulated. The four parameters, namely: driven voltage, initial air gap distance, spring preload, and the number of coil turns influence the dynamic characteristics of the solenoid valve. The solenoid valve displacement curves under different parameters are obtained. Theoretically determined relationships between the dynamic response characteristics and the structural and control parameters of the solenoid valve, provide the basis for the parameter matching of the solenoid valve, and the optimized design of electronic control fuel systems.

1. Introduction
The solenoid valve is a key component in the electronic unit pump fuel injection system that converts electromagnetic energy into mechanical energy. When the solenoid valve operates, it directly controls the fuel injection process, which has an impact on fuel quantity and the timing of the fuel injection system. This means the solenoid valve must have a strong electromagnetic force and quick response characteristics to make sure that the control accuracy and response speed are high enough to operate. Many factors can influence the solenoid valve’s characteristics, such as structural parameters, control parameters, working temperature, liquid pressure, etc. Therefore, to evaluate the effect of the main structural and control parameters regarding its static attractive torque and dynamic response characteristics, in theory, a mathematical model of a solenoid valve is built. This enables the theoretical basis of structural design and the control method of the solenoid valve to be defined. Meanwhile, simulation models of the solenoid valve are built to provide relevant parameters and an analytical basis for the electronic control fuel injection system simulation.

2. Mathematic model of solenoid valve
In practice, the working process of a solenoid valve is a typical progression of: electricity produces magnetism, magnetism produces force, and force produces motion. During this process, different systems interact to convert electrical energy from the drive current into mechanical energy for the valve to move. According to the function and principle of a high-speed solenoid valve, the mathematic model of a solenoid valve is expressed by three equations: the circuit equation, the magnetic equation, and the motion equation. These three equations produce interactions by their relevant physical quantities. [1-3]
2.1 Circuit equation
Regardless of the coil circuit’s additional resistance and additional induction, the equivalent circuit of the circuit module can be obtained after simplifying the drive circuit of the magnetic coil of the solenoid valve.

The driven circuit is powered only when the solenoid valve is in the opening and hold processes, because according to the circuit principle, voltage \( U \) of the coil circuit is equal to the voltage of the equivalent resistance of coil circuit plus the induced voltage of total flux linkage in the circuit, that is,

\[
U = iR + \frac{d\psi}{dt} = iR + L \frac{d(i)}{dt}
\]  

(1)

where \( U \) is the driven voltage, \( i \) is the circuit current, \( R \) is the coil equivalent resistance, \( \psi \) is the total flux linkage, and \( L \) is the coil equivalent inductance. [4]

2.2 Magnetic equation
The electromagnetic force of the solenoid valve can be obtained by the Maxwell equation,

\[
F = \frac{B^2S}{2\mu_0}
\]  

(2)

where \( B \) is the magnetic induction intensity, \( S \) is the effect area, and \( \mu_0 \) is the air permeability. [5]

Hypothesizing that the magnet is not saturated, and ignoring the induction current, flux leakage, and the resistance of the ferromagnet,

\[
B = \frac{iN}{SR_\delta}
\]  

(3)

where \( i \) is the circuit current, \( N \) is the number of coil turns, \( R_\delta = \delta / \mu_0S \) is the air gap reluctance, and \( \delta \) is the air gap distance.

Using the three equations above, we obtain,

\[
F = \frac{\mu_0S}{2} \frac{i^2N^2}{\delta^2}
\]  

(4)

2.3 Motion equation
The solenoid valve is moved by magnetic force, spring force, and fuel force. However, the fuel force is complicated. It comprises the diameter of the armature, the distance between armature and the valve seat, etc., and the pressure change in the control cavity of the solenoid valve (during the injection process). Simplified, the fuel force is a combination of the force of fuel to the armature \( F_1 \), and the fuel resistance \( F_2 \), so the motion equation of the solenoid valve is,

\[
m \frac{d^2x}{dt^2} = F + F_1 - F_2 - F_s = F + F_1 - f \frac{dx}{dt} - k(x + x_0)
\]  

(5)

where \( d^2x / dt^2 \) is the acceleration of the armature, \( F_s \) is the force of the spring, \( f \) is the viscous damping coefficient of fuel, \( dx / dt \) is the speed of armature, \( k \) is the stiffness of the spring, \( x \) is the displacement of armature, and \( x_0 \) is the preloaded distance.

3. Simulation model of solenoid valve
A solenoid valve is a typical dynamic nonlinear system. When functioning, the circuit module, magnetic module, and motion module are all in various states of change, and the energy is shifts among the different systems. According to the solenoid valve mathematical model, the simulation models of the circuit module, magnetic module, and motion module can be analyzed using Matlab/Simulink software.
3.1 Simulation model of circuit module
According to the circuit equation, the simulation of the circuit module can be represented as shown in figure 1. In this model, the input parameter is driven voltage $U$, and the output parameter is coil current $i$, which is also the driven current of the solenoid valve.

![Figure 1. Simulation model of circuit module](image1)

3.2 Simulation model of magnetic module
According to the magnetic equation, the simulation of the magnetic module can be represented as shown in figure 2. In this model, the input parameter $i$ is the output parameter of the circuit model (see figure 1), and the output parameter is the magnetic force $F$.

![Figure 2. Simulation model of magnetic module](image2)

3.3 Simulation model of motion module
According to the motion equation, the simulation of the motion module can be represented as shown in figure 3. In this model, the input parameter is the magnetic force $F$, and the output parameter is the velocity $V$ and the displacement $x$ of the armature.

![Figure 3. Simulation model of motion module](image3)

Where the “double integrator” module sets the boundary condition of the solenoid valve motion. When the solenoid valve is added to the driven voltage, the force acting on the armature is less than
the resistance, and therefore it does not move, with a resultant displacement of zero. Conversely, when
the force is greater than the resistance, the armature starts to move, reaching the maximum
displacement; thereafter, the armature is in a balanced state, and stays at the maximum displacement,
until the power is turned off.

According to the circuit model, magnetic and motion model shown above, and the relationship
among the parameters, the full dynamic simulation model is established in figure 4.

4. Analysis of dynamic response characteristic of solenoid valve

The dynamic response characteristic of solenoid valves primarily means the time characteristic of the
armature pull-in and reset processes, which (open time and close time) determines the dynamic
response characteristic of the solenoid valve. Herein, we have only analyzed the dynamic
characteristics of the pull-in process.

4.1 Dynamic response analysis

Setting the driven voltage to 24V, and the input structural parameters and the control parameters of the
solenoid valve, the analysis of the dynamic response can then be conducted. Figure 5 and figure 6 are
result charts, in which figure 5 is the driven current changing with time, figure 6 is the magnetic force
changing with time.

It can be seen from figure 5 and figure 6, that under a driven voltage of 24V, the solenoid valve can
reach the maximum current of 14A, which is in accordance with the solenoid valve’s technique
parameter; the maximum force can reach 90N.

4.2 Influence of solenoid valve parameters on dynamic characteristic

The performance of the solenoid valve is related to its structural and control parameters. The study of
the influence of related parameters on its dynamic characteristic is of direct relevance to the
formulation of the solenoid valve control method. The parameters that are most important are: number
of coil turns, air gap distance, spring preload, mass of the armature in the structure, the driven voltage, the pulse width, and keeping voltage constant.

4.2.1 Driven voltage. As per the solenoid valve math equation: as the driven voltage increases, so does the current in the coils. The rate of change of force increases and the pull-in time decreases. Meanwhile, when the armature is pulling, the acceleration is increasing. If the air gap distance is constant, the motion time decreases. Figure 7 is the relationship between driven voltage and displacement response time.

As shown in the figure 7, when the driven voltage increases, the time taken for the armature to reach the maximum displacement decreases. Nevertheless when the driven voltage reaches a certain level, the reduction quantity of response time decreases as the voltage increases. The temperature also increases, resulting in a decrease in the saturation flux density in the valve element. In addition to this, a current level that is too high will cause damage to other equipment and the coil. Thus, when the solenoid valve opens, the driven voltage should be decided by the structural parameters such as number of coil turns, resistance, and induction. In this paper, 24V is the set driven voltage of the solenoid valve.

4.2.2 Air gap distance. It is widely known that the magnetic force is inversely proportional to the square of air gap width $\delta$. As the gap distance increases, the magnetic force decreases rapidly. Meanwhile, leakage magnetic flux increases with the air gap distance, making the magnetic force decrease. As this force decreases, the time taken for the armature to reach the maximum displacement increases, compromising the dynamic characteristic. Figure 8 is the response time of the armature with respect to various air gap distances. As air gap distance increases, the response time of the armature increases.

When $\delta$ reaches a critical level, as the leakage flux increases and the magnetic induction intensity in the air gap decreases, the magnetic force will drop until it cannot overcome the spring preload, thus the solenoid valve will not close. Therefore, the Air gap distance should choice a smaller value when designing a solenoid valve.

4.2.3 Spring preload. Spring preload has the effect of both open and closed response characters of the solenoid valve. When pulling-in, it is in resistance, and when reset, it is in motion. The greater the force is, the longer the time it will take to pull-in, but the reset time will be less. Figure 9 shows the effect of the preload to displacement response time.

Preload is set at 10N, 30N, and 50N respectively. It can be seen from the figure that as the preload increases, the displacement response time also increases. When the preload reaches a certain level, the magnetic force cannot overcome the preload, and the solenoid valve cannot open. When the supply pressure and driven voltage is confirmed, the preload has an optimum data range, which should ensure that a low enough preload should be chosen under the condition of rated voltage with the solenoid valve closed. [6]
4.2.4 Number of coil turns. Figure 10 shows the relationship between magnetic force and the number of coil turns. Under the condition where the driven voltage and the air gap distance remain unchanged, the magnetic force increases with the number of coil turns. This decreases the time taken for the armature to pull-in, and improves the dynamic response characteristic of the solenoid valve. But in actual progress of design, if there are too many turns, the resistance and inductance will also increase, which will become an obstacle to the current increase when pull-in occurs, and the current will also decrease slower when reset. If the number of turns is too few, the magnetic force will be too small to pull-in. Therefore, the number of coil turns must ensure the solenoid valve has good dynamic characteristic and enough magnetic force. There are many factors in real design, and an optimum number of coil turns should be chosen to meet the requirement.

5. Conclusions
Through the simulation research of solenoid valves, the influence of driven voltage, initial air gap distance, and reset spring preload on the dynamic response characteristic of a solenoid valve was evaluated. Charts of displacement with respect to time were also investigated with the following conclusions made.

(1) Under 24V driven voltage, the driven current can reach 14A, and the response time and speed can meet requirements.

(2) When the driven voltage increases, the displacement response time decreases, when air gap distance increases, the displacement response time increases, when the preload increases, the time for the armature to pull-in increases, but the reset time decreases.

(3) When the driven voltage and air gap distance are constant, the greater the number of coil turns, the greater the magnetic force is.

(4) The parameters of solenoid valve cannot simply be increased or decreased. A value should be chosen in accordance with practical applications.

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