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Research Paper

Different boost voltage effects on the dynamic response and energy losses of high-speed solenoid valves

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HIGHLIGHTS

- Analyze the distribution characteristics and changing law of eddy current energy loss.
- Reveal the main reason for limiting the dynamic response time of HSV.
- There is a maximum value of rate of effective energy utilization of solenoid valve.

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ABSTRACT

In the present investigation, a simulation of the dynamic characteristics of a high-speed solenoid valve (HSV) was performed using the finite-element method (FEM). The interrelation between power losses and the dynamic response of the HSV was investigated based on the FEM simulation model. The relationship between the boost voltage, dynamic response, and power losses was established according to the energy conversion at the HSV system. The simulation results indicated that as the boost voltage increases, the rising rate of the driving current at the solenoid valve increases sharply, which favors the quick opening of the solenoid, while the power losses caused by the eddy current at the iron core increase rapidly. The rapid increase in the energy loss of the eddy current was the main factor that limited the effectiveness of reducing the opening response time of the solenoid valve by increasing the boost voltage. Regarding the energy utilization, an optimal boost voltage existed, where the solenoid valve reached the highest energy utilization efficiency.

1. Introduction

The high-pressure common rail system has the advantages of being independent of the engine speed, injection timing, and adjustable flow rate of fuel injection, and is being widely used nowadays. Diesel engines with high-pressure common rail systems can achieve higher fuel economy and lower harmful emissions. The common rail injector of the high-speed solenoid valve (HSV) is the key component of the high-pressure common rail system. The control system of the common rail system, which is used to control the fuel injection quantity, injection timing, and fuel flow rate of the injection accurately, is the basis essence of the flexible control of the fuel injector of the HSV [1–3].

Since HSV is crucial for the precise control of the solenoid injector of high-pressure common rail injection systems, there are many reports on the working performance of the solenoid valve. Sun et al. [4] studied the influence of the structural parameters of the solenoid valve on the static electromagnetic force for the solenoid valve used in an electro-controlled unit pump. Cheng et al. [5] used a new soft magnetic material to design the structure of a magnetic circuit. Tao et al. [6] used different soft magnetic materials and changed the structure parameters to study the effects of the electromagnetic force. Miller et al. [7] investigated the effects of the coil parameters on the electromagnetic performance of a new solenoid valve for pneumatic emergency brake systems. Wang et al. [8] used the new soft magnetic material Al-Fe in the design process of a solenoid valve to obtain a faster opening response of valve. Al-Jaber et al. [9], Taghizadeh et al. [10], and Nitu et al. [11] analyzed the influence of the driving current/voltage on the maximum electromagnetic force of the solenoid valve

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and pointed out that with increasing driving voltage, the electromagnetic force increases proportionally.

The dynamic response of the solenoid valve is one of the most significant parameters that determine the accuracy of the flow rate fuel injection and multiple injection. The multiform energy transformation between the electromagnetic energy of the solenoid valve and the mechanical energy determines the dynamic response of the solenoid valve. Rejesh et al. [12] carried out experimental analyses of the dynamic response of two micro-valves and simulated the membrane dynamics. Ye and Chen [13] developed a model to study the dynamic characteristics of a two-stage solenoid valve. Cheng et al. [14] studied the relationship between the power loss and the dynamic response of the solenoid injector and revealed the effects of four different driven strategies on the power losses and dynamic response. Angadi et al. [15,16] applied the finite-element method (FEM) to investigate the coupled effects of electromagnetic and solid mechanics and found that the failure of the solenoid valve was due to the high temperature of the coil. Meng et al. [17] studied the electro-hydraulic valve of a heavy-duty transmission system and optimized the dynamic characteristics of the valve. Cvetkovic et al. [18] developed a theoretical model for the coupling of the electro-magneto-mechanical fields for the solenoid valve. Mutschler et al. [19] applied the simulation software SABER (Synopsys) to analyze the dynamic characteristics of a solenoid valve. Motoyuki et al. [20] performed multi-physics calculation and analysis of a micro-solenoid valve for automatic dispensing in chemistry applications.

Most of the existing relevant research has investigated the dynamic response characteristics of the solenoid valve. It is common to improve the opening response of the solenoid valve by raising the boost voltage, which ignores the energy distribution at the inner solenoid valve and reduces its electromagnetic energy utilization efficiency. The effect of the boost voltage on the opening response and the energy distribution at the inner solenoid valve and optimization of the boost voltage need further research. Therefore, the special viewpoint of an energy distribution with different boost voltage effects on the dynamic responses of the solenoid valve is utilized to reveal the interrelation of the boost voltage and energy conversion.

2. Description of models and methodology

2.1. Electromagnetic and mechanical model

The electromagnetic force, pre-load force of the spring, gravity of the moving components, and friction force jointly determine the dynamic response of the solenoid valve. In this work, the friction force in the motion of the moving parts of the solenoid valve is ignored. Therefore, the kinematics equation of the moving parts can be described by Newton's dynamic equilibrium equations:

$$F_{\mathrm{mag}} - F_{\mathrm{sp}} - m \cdot g = m\frac{d^2x}{dt^2} \tag{1}$$

where F_{mag} is the electromagnetic force, F_{sp} is the spring pre-load force, m is the gravity of the moving components, and x is the displacement of the armature.

The electrical behavior of the solenoid valve can be implemented by Kirchhoff's equilibrium equations [21]:

$$V - i \cdot R - N\frac{d\phi}{dt} = 0 \tag{2}$$

where V is the voltage source, i is the electrical current, R is the resistance of the solenoid valve, ϕ is the magnetic flux through each coil turn, and N is the coil turns.

According to the energy conversion equation, the energy equation of the magnetic circuit can be obtained:

$$V \cdot i \cdot dt = i^2 \cdot R \cdot dt + F_{mag} \cdot dx + dU_m \tag{3}$$

where Vi is the power input, $F_{\mathrm{mag}}dx$ is the mechanical work of the electromagnetic force, and dU_{m} is the variation of the magnetic energy in the system.

By combining Eqs. (2) and (3) with the expression of the magnetic energy Um, the mechanical work can be obtained as:

$$F_{mag} \cdot dx = \frac{1}{2}(N \cdot i \cdot d\phi - N \cdot \phi \cdot di) \tag{4}$$

According to Hopkinson's law, the following expression is derived for the magnetic force:

$$F_{mag} = \frac{1}{2} \cdot \phi^2 \cdot \frac{dR}{dx} \tag{5}$$

The derivative of ϕ with respect to x is a constant value and depends only on geometrical parameters, which can be determined. By recording both the current and voltage time histories, the magnetic flux as a function of time can be derived by integration from Eq. (2) to allow the computation of the electromagnetic force from Eq. (5).

2.2. Energy losses of the solenoid valve

In the energy conversion of the HSV, the control circuit loads transient field to the solenoid coil. Under the effect of the electric field, the magnetic material of the iron core is magnetized, thus forming a magnetic field and completing the conversion from electrical energy to magnetic energy. Under the action of the electromagnetic field, the solenoid valve produces electromagnetic suction that attracts the armature moving, thus completing the conversion from electromagnetic energy to mechanical energy. In the conversion process from electromagnetic energy to mechanical energy, there is a large part of energy without efficient usage, which is, however, consumed by the eddy current in the iron core and the coil resistance, forming the energy loss of the eddy current and the coil. This energy is not eventually used and most of it is converted to heat, which results in the rise of the temperature. According to the experimental analysis, only a small part of electronic energy is converted to kinetic energy, which drives the movement of the armature.

2.2.1. Mechanical energy of the HSV

When electricity is provided to the solenoid valve, under the action of electromagnetic suction, the armature of the solenoid valve overcomes the pre-tightening force of the spring and moves upwards. When the armature reaches the highest position, it will remain there under the action of the electromagnetic force. In that process, the electromagnetic energy is converted to mechanical energy. In the opening process of the solenoid valve, the electromagnetic force and the displacement of the armature are transient, so the effective mechanical energy of the solenoid valve is defined as:

$$P_{\mathrm{mechan}} = \int_0^t F_i \cdot S_i \tag{6}$$

where F_i is the transient electromagnetic force and S_i is the transient displacement of the moving solenoid valve.

2.2.2. Eddy current power loss

When a periodic change on the electromagnetic coil occurs, the magnetic field of the HSV core will change, and the inductive current core sections that are perpendicular to the direction of the magnetic field lines will close. This is called an eddy current and the energy loss generated by an eddy current is called eddy current loss. The eddy current loss in the form of heat emission causes the core temperature to rise and reduces the magnetic properties of solenoid valve. The eddy current power loss can be expressed as:

$$P_{\text{eddy}} = C_{\text{eddy}} f^2 B_{\text{m}}^2 d^2 / \rho \tag{7}$$

where C_{eddy} is the eddy current loss coefficient; f is the magnetic field frequency, B_{m} is the amplitude of the magnetic induction intensity, d is the wall thickness of the core, and ρ is the electrical resistivity of the material.

2.2.3. Solenoid copper power loss

The power loss of a solenoid coil is caused by driving current in the solenoid coil, which can be calculated by the following formula:

$$P_{\text{i}} = i^2 R \tag{8}$$

where i is the solenoid coil current and R is the resistance of the solenoid coil.

2.2.4. Ohmic power loss

Ohmic power loss is always associated with the conduction current distribution in conductors that are not perfect. Thus, the resistivity of conductors is responsible for the Ohmic power loss when current flows in such conductors. Ohmic loss always has a heating effect, which is often called Joule heating. The Ohmic loss is given by Ref. [21]:

$$P_{\text{Ohmic loss}} = i \int_{Vol} \frac{J \cdot J^*}{2\sigma} dVol \tag{9}$$

where J is the current density, J^* is the complex conjugate of the current density, and σ is the conductivity in siemens per meter.

According to Fig. 1, the total energy includes the mechanical energy, eddy current power loss, hysteresis loss energy, and solenoid copper power loss. Because the electromagnetic valve core and armature are made of soft magnetic materials with a narrow hysteresis loop, the hysteresis loss energy is small. Furthermore, the literature [22] has indicated that the eddy current power loss constitutes a larger proportion of the total energy under high frequency than the hysteresis loss energy. The solenoid valve in our study worked under high frequency. Therefore, the hysteresis loss energy was not considered in the calculation. The calculation of the total energy included the mechanical energy, eddy current power loss, and solenoid copper power loss.

2.3. Simulation model and basic settings

The electromagnetic energy conversion and power loss in the solenoid valve is complex because it is a process coupled with the electrical-magnetic-mechanical energy [18–21]. The three-dimensional FEM is suitable for the analysis of the complex electromagnetic energy conversion, and a detailed analysis and calculation can be conducted according to different structures of the solenoid valve. Based on the literature [22], the time harmonics generated by the driving current and the space harmonics of coil winding affect the eddy effect of the solenoid valve. The iron core of a high-speed solenoid valve is made of solid magnetic material and its eddy current effect is obvious. Therefore, it is necessary to determine the solenoid valve movement under a three dimensional (3D) transient field and an external excitation circuit in the analysis of the eddy effect. Fig. 2 shows the HSV model and its assembly location inside a high-pressure common rail injector. Some parts (i.e., the spring, sealing ring, and valve pin) have not been considered into the model because their materials are nonmagnetic, with magnetic permeability close to that of air. Thus, the dynamic solenoid valve model contains the iron core, armature, and coil winding. In the parameter settings, the specified pre-load force of the spring, the stiffness of the spring, the mass of the moving components, the number of coil turns, the initial resistance value, the initial inductance value, and the B-H magnetization curve (Fig. 3) of the iron core and armature are shown in Table 1.

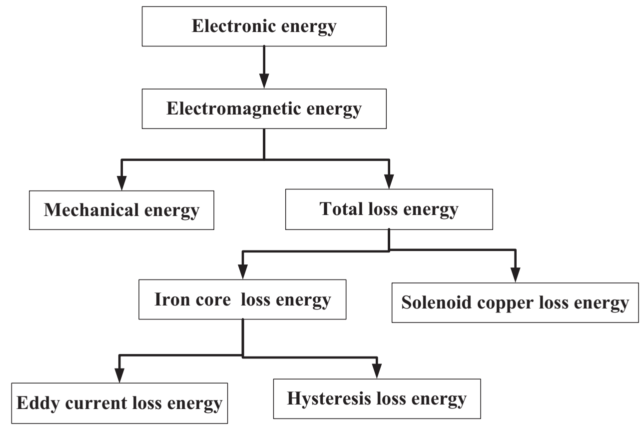


Fig. 1. The schematic of energy distribution at HSVS.

2.4. Simulation results and model validation

To validate the accuracy of the HSV simulation models, a comparison of the simulation and experimental results should be performed. In the present study, the precision of the simulation model was verified through experimental data of the armature lift curve. Fig. 4a shows the test bench used to measure the dynamic response of the HSV, which contains a power control unit, a driving current control unit, and the armature's displacement test unit. The boost voltage, hold current I, and hold current II could be set flexibly on the driving current control parameters, as shown in Fig. 4b. To open the solenoid valve faster, it is necessary to supply a high voltage, named boost voltage, to the solenoid valve. After the solenoid valve opens, it is used to supply the remaining low current. In this study, two orders of the hold current, hold current I and hold current II, were used in the drive circuit of the solenoid valve. Hold current I was used to ensure that the armature reaches the maximum lift reliably. Usually, hold current II was much lower than hold current I. Hold current II was used to maintain the armature at the maximum lift position.

Fig. 5 shows the comparison between the solenoid armature lift curves of the experimental data and simulation results. The results indicate that the simulation of the lift curve and the test data showed good consistency. Although in the closing process, a larger error existed between the calculated and experimental value, the maximum error between the simulation and the calculated values was not higher than 5%. The reason for analyzing the relatively large error in the shutting-down process of the solenoid valve is that the influence of the mechanical friction factors of moving parts, such as the solenoid valve armature, on their movement was ignored when conducting the dynamic 3D simulation of the solenoid valve. Therefore, when no friction was considered in the movement, the armature returning to its initial position was faster in the calculation.

3. Results and discussion

3.1. Influence of eddy current loss on the dynamic characteristics of the HSV

Under normal circumstances, the solenoid valve core and armature are made of soft magnetic materials with narrow hysteresis

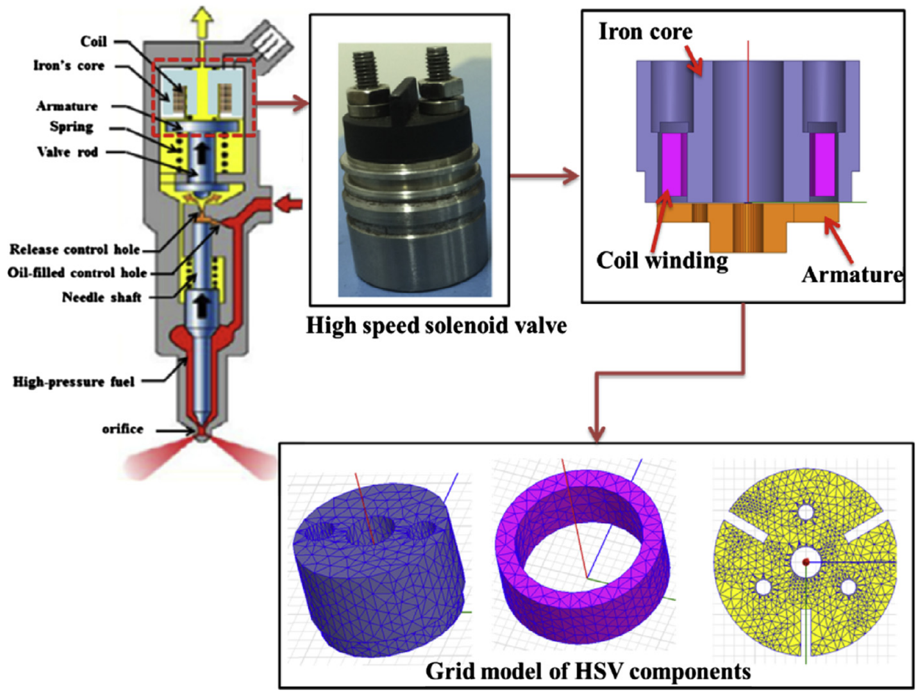


Fig. 2. The simplified 3D simulation model of solenoid valve of common rail injector.

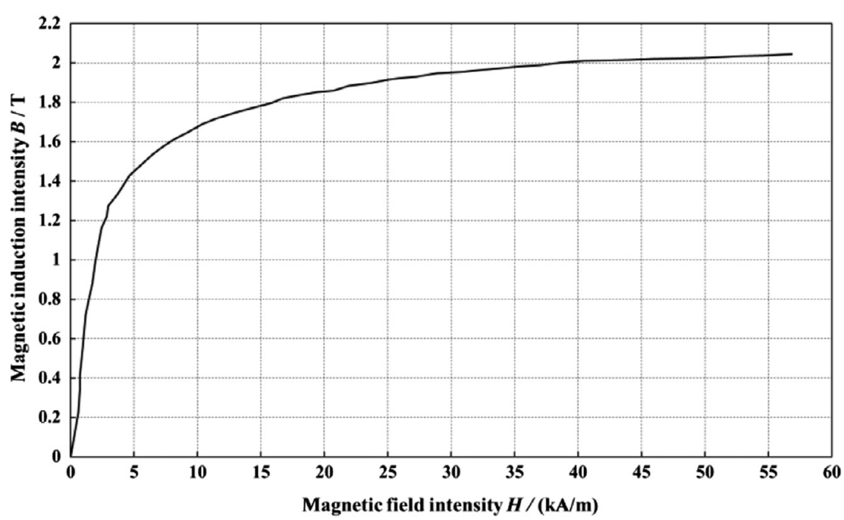
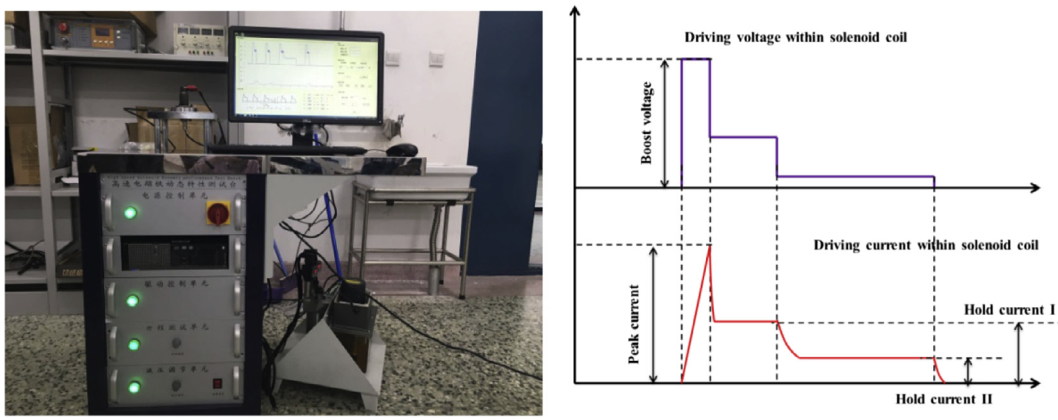


Fig. 3. The material and B-H curve.

Table 1
Detailed information of 3D simulation model.

Classification	Setting value
Pre-load force of spring/N	70
Stiffness of spring/(N/mm)	57
Mass of moving components/g	5.3
Number of coil turns	52
Maximum moving displacement of armature/μm	70
Total air gap between Iron core and armature/μm	120

loops, so the hysteresis loss energy is small. While the HSV is in a fast operation stage, especially in the opening phase, when the opening time is lower than 1 ms, the fast variation of the external magnetic field inevitably causes the generation of eddy current power loss in the iron core of the solenoid valve. The power loss will hinder the rapid increase of the solenoid valve driving current and then reduce the opening speed. In the closing phase, it is common to rapidly reduce the driving current to zero in order to make the solenoid valve armature fall back quickly. However, the rapid current change can lead to the generation of eddy current loss, which will also slow down the drop of the solenoid valve armature. Fig. 6 shows a comparison between the solenoid armature lift of the experimental data and the simulation results with or without eddy current power loss for the iron core. The results of Fig. 6 indicate that in the opening stage, the starting moment of the solenoid valve armature beginning to move lags compared to not considering the eddy current effect, and the rate of the armature lift is slower. In the closing phase of the solenoid valve, the armature falls back slower and returns to its initial position later when considering the eddy current effect than when this effect is not considered, although the armature starts to move downwards at the same time in both cases. The eddy current loss that occurs inside



(a) (b)

Fig. 4. (a) The test bench to measure the dynamic response characteristic of the solenoid valve; (b) The schematic of driving current control for HSV.

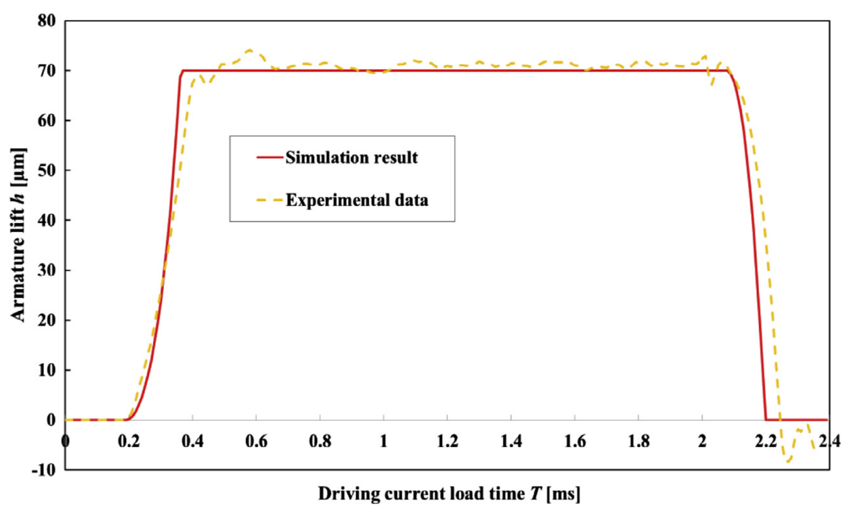


Fig. 5. Comparison of armature lift between simulation results and the experimental data (boost voltage = 70 V, 150 μs, hold current I = 14 A, hold current II = 5 A).

the core of the HSV in a common rail injector has an important influence on the opening and closing response characteristics of the solenoid valve. Additionally, its influence on the opening process of the solenoid valve is greater than its effect on the closing response.

3.2. Distribution of eddy current power loss of the HSV

During the operation of a solenoid valve, electromagnetic energy is converted to mechanical energy. However, owing to power loss, only a small part of the electromagnetic energy can be converted to mechanical energy. A large proportion of the electromagnetic energy is converted to heat energy by raising the temperature of the HSV body. The rising temperature leads to a shorter working lifetime of the solenoid valve and reduces its reliability. Therefore, reducing the power loss and improving the dynamic performance of the solenoid valve are always the main goals in the industry. The simulation results of the eddy current power loss of the solenoid valve shown in Fig. 6 were obtained by using the software ANSYS Maxwell. Fig. 7 displays that in the transient working process of solenoid valves, the energy loss of the eddy current is mainly generated in three stages of the transient current: in the first stage, the driving current increases rapidly from zero to the peak current range (point 1–point 2); in the second stage, the driving current is reduced from hold current I to hold current II (point 3–point 4); in the third stage, the driving current quickly decreases from hold current II to zero (points 6–7). In the above three stages, the driving current inside the solenoid coil exhibits strong transients, that is, current surges or drops, which cause transient changes of the external magnetic field of the solenoid valve, resulting in the generation of energy loss in the eddy current of the solenoid valve core. Meanwhile, it can be observed that the energy loss of the eddy current is closely related to the changing rate of the driving current of the solenoid valve. The greater the changing rate of the solenoid valve driving current is, the greater the eddy current loss generated inside the core. According to the above explanations, it is not hard to understand why the energy loss of the eddy current is the largest in the opening phase of the HSV, where the largest increasing rate of the driving current was at least 600 A/ms.

Fig. 8 shows the calculation results of the power loss distribution of the eddy current inside the iron core of the HSV in the opening phase. From Fig. 8, it can be seen that at different times, the energy loss of the eddy current in the solenoid valve core is different and its corresponding distribution is not uniform. When t = 0.06 ms, the driving current of the solenoid valve increases from

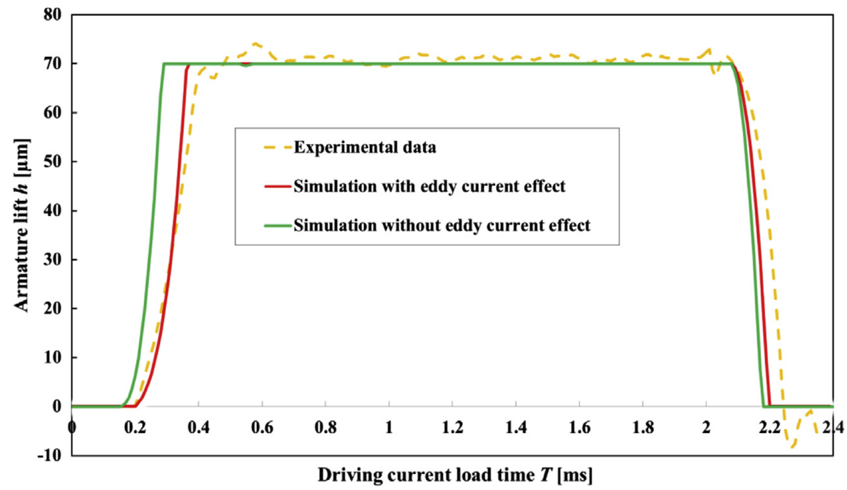


Fig. 6. Comparison on armature lift between simulation results with consider of eddy current effect and without.

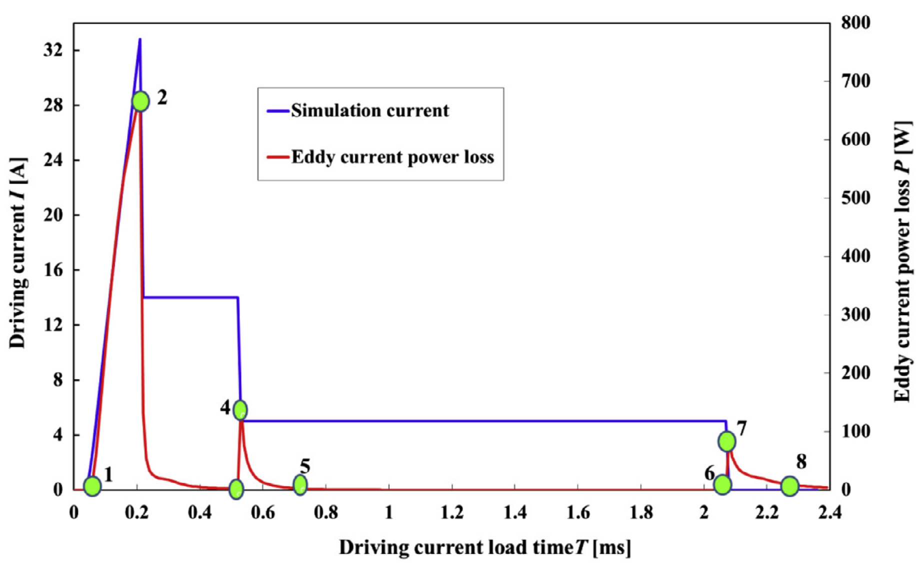


Fig. 7. The schematic of defining opening and closing response time of HSV (boost voltage = 90 V, 150 μs, hold current I = 14 A, hold current II = 5 A).

zero to 1.36 A. The overall loss of the eddy current inside the core is smaller and is mainly distributed near the coil. When t = 0.12 ms, the driving current increases from 1.36 A to 15.16 A. The eddy current loss increases rapidly inside the core and near the coil and the impact range of the highest eddy current loss increases. The farther from the coil, the lower the increase of the eddy current loss in the iron core is. When t = 0.18 ms, the driving current inside the coil increases to 27 A and the increase rate of the driving current reaches150 A/ms. The energy losses of the eddy current in the iron core further increase, resulting in a further expanding area that produces the largest eddy current loss, which expands to almost all areas of the solenoid valve pole. When t = 0.2 ms, the driving current in the coil increases to 32.8 A, the range of the highest eddy current loss continues to increase and fills almost two-thirds of the solenoid valve core area. Then, the current loss of the core eddy reaches the maximum, and its distribution range is also the widest. After t > 0.2 ms, the driving current of the solenoid valve is in the phase of hold current I highest. The changing rate of the driving current is not altered, and the energy loss of the eddy current generated inside the core begins to quickly decrease with increasing drive time, as shown in Fig. 8(e) and (f).

3.3. Dynamic response time and power loss inside the iron core in the opening process of the HSV

The response to the closing stage depends on the hold current value, working stroke of the solenoid valve, pre-load force of the spring, and mass of the moving parts. These parameters remained unchanged when studying the boost voltage effects. Therefore, this study investigated the effects of the boost voltage on the opening response of the solenoid valve, but not on the closing response. As seen in Fig. 9, when the boost voltage increases from 50 V to 130 V, the opening response time of the solenoid valve armature decreases gradually, but its decrease rate is gradually reduced. When the boost voltage is greater than 70 V, it continues to increase, and its positive effects on the improvement of the opening response time of the solenoid valve continue to be smaller. Numerous research reports have pointed out that an excessive increase in the boost voltage does not significantly improve the opening response characteristics of the solenoid valve. However, there is no literature indicating that the improving effect of the continuously increasing boost voltage on the opening response characteristics of the starting stage of the solenoid valve. The fol-

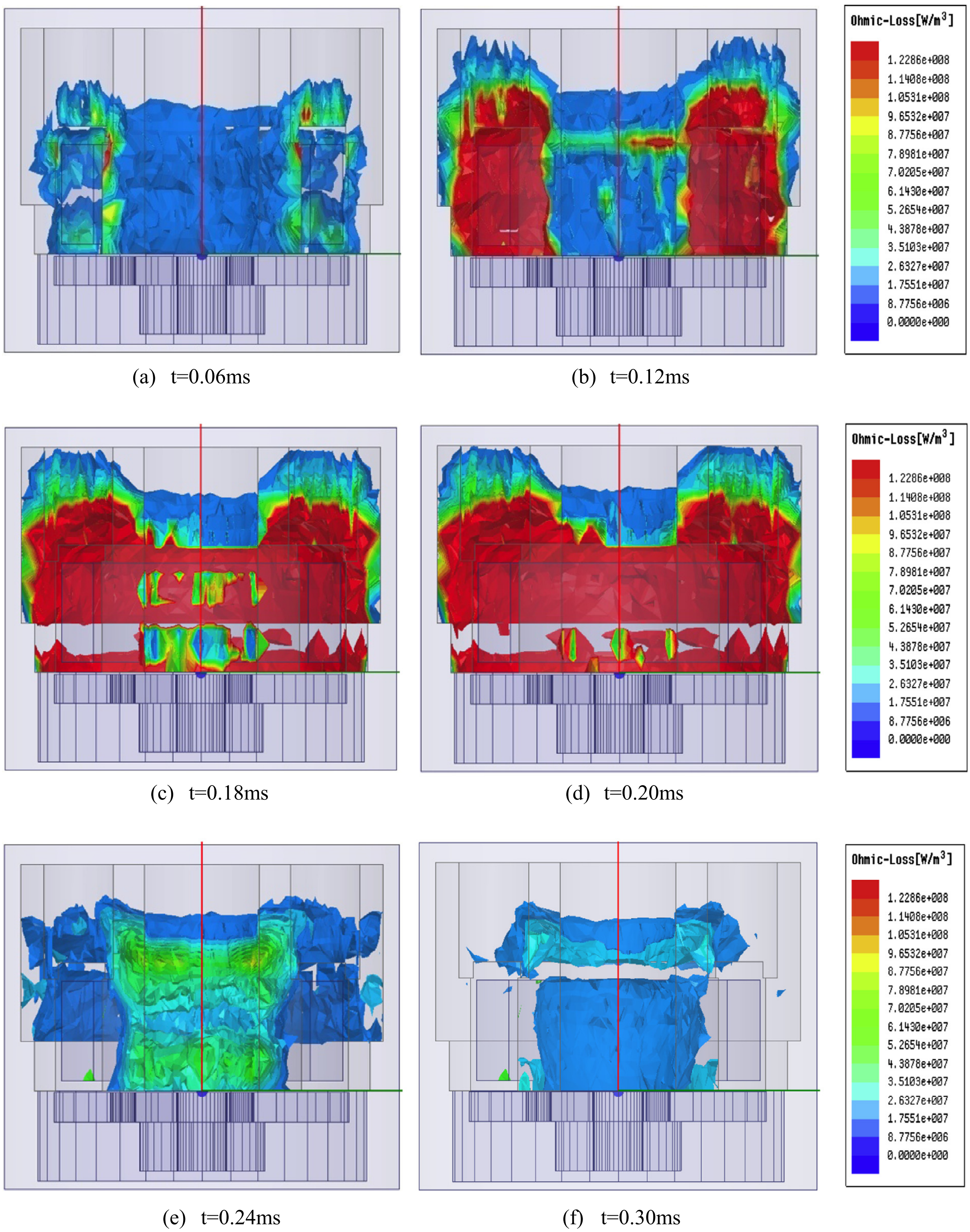


Fig. 8. The eddy current power loss distribution within iron core of HSV.

lowing in-depth analysis was carried out on the relationship between the boost voltage and the opening response time of the solenoid valve from the viewpoint of the solenoid valve energy distribution.

Under the condition of keeping other parameters constant, increasing the boost voltage of the solenoid valve means the increase of the total energy of the solenoid valve. If the efficiency of converting the electromagnetic energy of the solenoid valve into mechanical energy is a fixed value, this means that the mechanical energy obtained by the solenoid valve increases. As a result, the solenoid valve has faster opening movement and shorter opening response time. However, as seen in Fig. 9, when the boost voltage increases from 50 V to 130 V, the opening response time of HSV decreases gradually, but its decreasing degree is gradually reduced

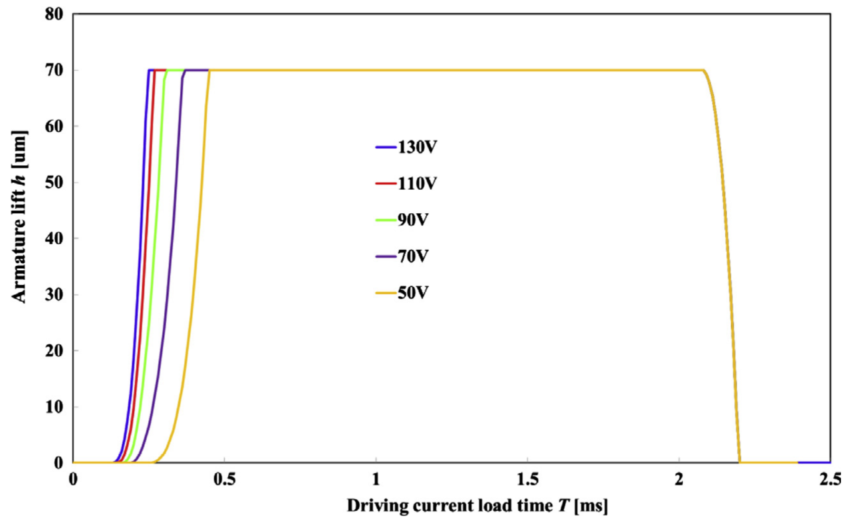


Fig. 9. Influence of different boost voltage on working process of solenoid valve.

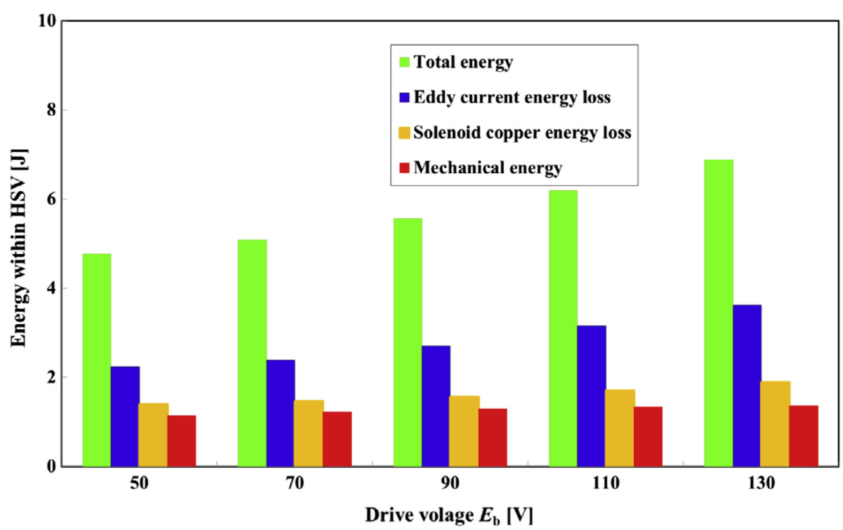


Fig. 10. The energy distribution of solenoid valve.

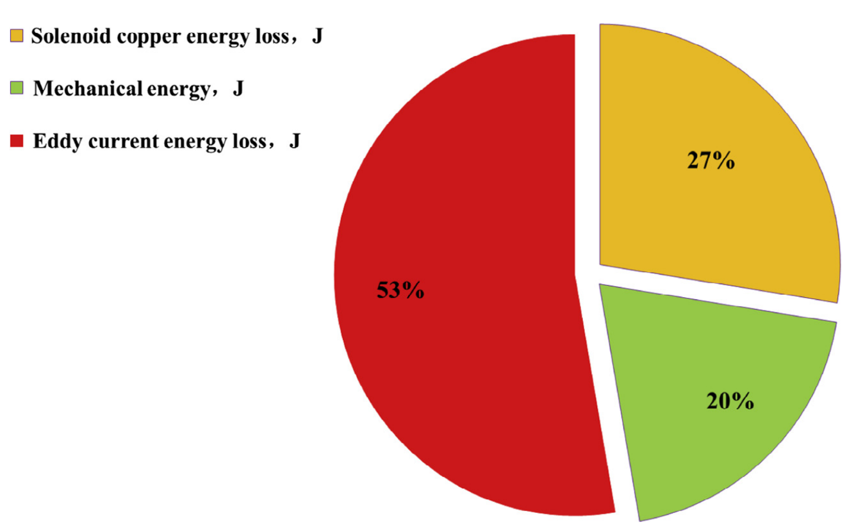


Fig. 11. The energy distribution fraction within HSV.

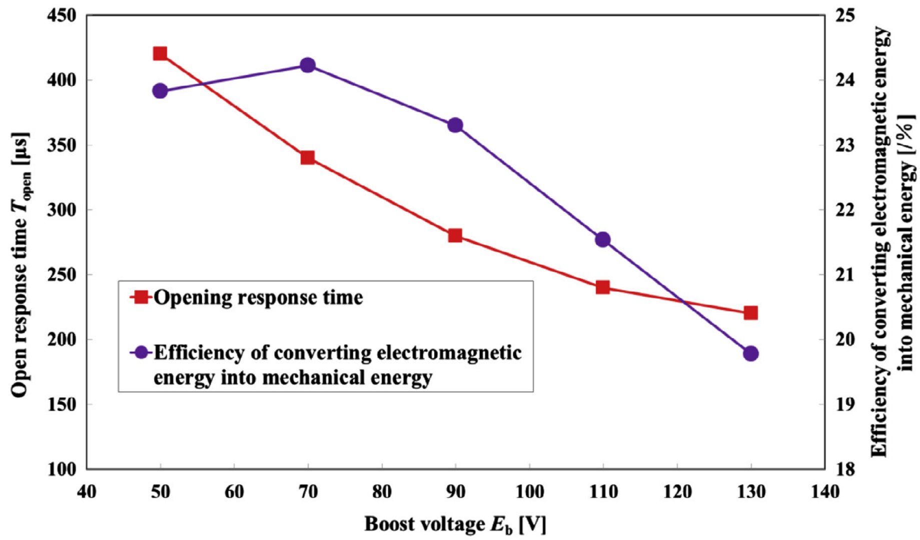


Fig. 12. Influence of boost voltage on the opening time and mechanical energy converting efficiency of HSV.

because in the increasing process of the boost voltage, the energy loss of the eddy current in the solenoid valve and the coil rapidly rises, resulting in a reduction of the efficiency of transforming the electromagnetic energy of the solenoid valve into mechanical energy. Fig. 10 presents the energy distribution in the internal solenoid valve, calculated using a 3D simulation. As seen in Fig. 10, in a working cycle of the solenoid valve, when the boost voltage increases from 50 V to 130 V, the increase rate of the total energy of the solenoid valve is 44.1%,that of the energy loss on the coil is 35.4%,that of the eddy current energy is 62%, and that of the mechanical energy is only 19.6%. As seen in Fig. 11 from the energy distribution of the solenoid valve, the largest proportion of energy loss is that of the eddy current. The second largest is the, solenoid copper loss, whereas the smallest is that of the mechanical energy, which determines the dynamic response of the solenoid valve. The results indicate that is not used and formed energy loss

As seen in Fig. 12, when the boost voltage increases from 50 V to 130 V, the efficiency of converting the total energy of the solenoid valve into mechanical energy increases first. Then, when the boost voltage reaches the maximum of 70 V, the conversion efficiency falls rapidly. When the boost voltage is lower than 70 V, the opening response time of the solenoid valve rapidly decreases and the conversion efficiency of the effective energy of the solenoid valve increases with the increase of the boost voltage. While the boost voltage is greater than 70 V, the conversion efficiency of the effective energy of the solenoid valve is quickly reduced, which causes the increasing amount of effective mechanical energy used to improve the opening response time of the solenoid valve to become smaller and smaller. Consequently, under the condition of a continuously increasing boost voltage, the reduction of the opening response time of the solenoid valve becomes gradually lower, although the opening response time keeps decreasing. Therefore, within a certain range, a higher boost voltage is beneficial to improve the opening dynamic responses of the solenoid valve. However, when the boost voltage is too large, the opening response time of the solenoid valve is not significantly affected by the increase of the boost voltage. At this point, unused energy consumed for the internal heating of the solenoid valve is generated in great quantities, which lowers the efficiency of converting the electromagnetic energy of the solenoid valve into mechanical energy. This increase in unused energy leads to the rise of the temperature of the solenoid valve, which reduces its service life and working reliability.

4. Conclusions

In this study, FEM was used to investigate the electromagnetic field and power loss distribution of the HSV. The main conclusions are listed below:

(1) During the opening process of the HSV, a rising boost voltage reduces the opening response time. However, with increasing boost voltage, its improving effect on the opening response time of the HSV is gradually reduced.
(2) As the boost voltage increases, the eddy current loss of the solenoid valve core increases rapidly. The efficiency of the conversion of the electromagnetic energy into mechanical energy is reduced. The increase of the eddy current loss becomes important for limiting the reduction of opening response time.
(3) During the opening process of the solenoid valve, the effective energy utilization of the solenoid valve has a maximum value. Before the peak, the opening response of the solenoid valve becomes faster and its effective energy utilization improves with increasing boost voltage. After the peak, a rapid increase in the eddy current loss results in the fast drop of the effective energy utilization of the solenoid valve, which lowers the impact of the boost voltage on reducing the opening response time.

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