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Response characteristic of high-speed on/off valve with double voltage driving circuit

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Abstract. High-speed on/off valve, an important part of turbocharging system, its quick response has a direct impact on the turbocharger pressure cycle. The methods of improving the response characteristic of high speed on/off valve include increasing the magnetic force of armature and the voltage, decreasing the mass and current of coil. The less coil number of turns, the solenoid force is smaller. The special armature structure and the magnetic material will raise cost. In this paper a new scheme of double voltage driving circuit is investigated, in which the original driving circuit of high-speed on/off valve is replaced by double voltage driving circuit. The detailed theoretical analysis and simulations were carried out on the double voltage driving circuit, it showed that the switching time and delay time of the valve respectively are 3.3ms, 5.3ms, 1.9ms and 1.8ms. When it is driven by the double voltage driving circuit, the switching time and delay time of this valve are reduced, optimizing its response characteristic. By the comparison related factors (such as duty cycle or working frequency) about influences on response characteristic, the superior of double voltage driving circuit has been further confirmed.

1. Introduction

High-speed on/off valve, an important part of turbocharging system, Due to the high speed on/off valve could influence the pressure ratio of the turbocharger, the actuator links to the control port of valve. Times delay in response of the valve affect the leakage of the exhaust gas, and then affecting the stability of the pressure ratio. In order to improve the response characteristic, a number of studies have been done. In Ref.[1], the soft magnetic material of high specific resistance. Fe-Cr alloy, is used to replace original low carbon steel and a significant improvement on control response was achieved. In Ref.[2], presenting an optimal design method on the HSV's magnetic field by making a full consideration of the effects of various soft magnetic material's properties and geometries on the HSV's electronic performance. In Ref.[3], a method for investigating the armature mass importance on the EFI performance is proposed. It was found a range of values in which the response characteristic can be improved. In Refs.[4,5,6],the giant material is used to make the electromechanical converter and the switching time of the high-speed on/off valve is shortened. In Ref.[7], a parallel coil is presented to improve the dynamic performance of high-speed on/off valve. In Ref.[8], the influence of the mass of valve core, spring stiffness, spring preload and coil number of turns on solenoid valve responses are analyzed. In Ref.[9], simulation research on high-speed solenoid Valve, the authors found out that the factors that affect the closing and opening response characteristics of solenoid valve are drive current and the pretightening force of solenoid valve spring. These moves can improve the response characteristic but there are still many limitations. For instance, the less coil number of turns,



the solenoid force is smaller. The special armature structure and the magnetic material will raise cost. The pretightening force increasing, the closing time of solenoid valve becomes longer while the opening time is shortened.

In this paper, a new and effective method of shorting the times delay in response of high-speed on/off valve is proposed. The original driving circuit of this valve is replaced by double voltage driving circuit. To begin with, the mathematical model and simulation model of a high-speed on/off valve are established; next simulation and analysis between the different driving circuits are carried out to verify the improvements of response time by the double voltage driving circuit; finally, by studying the influences of related factors on response characteristic, the superior of the double voltage driving circuit is further confirmed.

2. Structure and working principle of the high-speed on/off valve

Fig 1 shows the structure of the high-speed on/off valve which is used in turbocharging system. In order to achieve the switch "on" and "off", by using PWM (Pulse-Width Modulation) controls the current of coil, the electromagnetic force is changed. The resultant of the electromagnetic force and the spring force then changes the position of the armature. Pushed by the armature, the motions of the valve core is then regulates the opening of this valve.

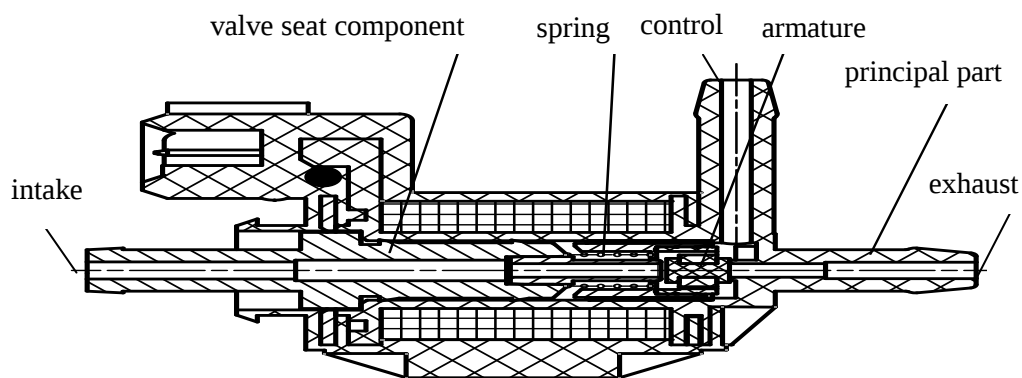


Figure 1. High-speed on/off valve in turbocharging system.

3. Modelling of the high-speed on/off valve

3.1. Mathematical models

By Kirchhoff's voltage law, the voltage equation can be written as

$$U_s = (R_s + R_L)i + \varepsilon_L = Ri + N \frac{d\phi}{dt} \quad (1)$$

Where i is current of the coil; ϕ is total magnetic flux; N is the number of coil turns; R is the resistance in coil circuit.

By magnetic circuit Kirchhoff's law

$$iN = \phi R_m \quad (2)$$

Where R_m is the total magnetic resistance, it consists of the reluctance of ferromagnetic material in magnetic circuit, solenoid valve work air gap reluctance and non-working air gap reluctance. For solenoid electromagnet, due to the magnetic field strength is mainly focused on the solenoid inside, so the magnetic circuit of magnetic potential are mainly concentrated in the working air gap, the non-working air gap and magnetic resistance of the yoke can be ignored [10]. Air gap magnetic resistance of magnetic circuit is a very important parameter, due to the magnetic resistance rate of the air is far outweigh than the magnetic resistance rate of ferromagnetic materials, so the air gap

magnetic resistance calculation is accurate or not has highly affect to the accuracy of the calculation results of magnetic system.

The total magnetic resistance computation formula is as follows

$$R_m = \frac{\delta - x}{\mu_0 S} \quad (3)$$

Where δ is the air gap width of valve core and the core; x is the movement displacement of valve core. In particular, $\mu_0 = 4\pi \times 10^{-7} \text{ Vs / Am}$.

Substituting equation (3) into equation (2), It can be get

$$iN = \phi \frac{\delta - x}{\mu_0 S} \quad (4)$$

By Maxwell's electromagnetic suction formula, the electromagnetic force generated as a result of magnetic flux. And Tsinghua University's Jia-Li Qian, she obtained the expression of electromagnetic attraction by a large amount of calculation and analysis:

$$F_{mag} = \frac{1}{2} i \frac{d\phi}{d\delta} \quad (5)$$

She pointed out that this electromagnetic force equation (5) is applicable for any occasion of the electromagnet.

In general:

$$\phi = N\phi \quad (6)$$

ϕ is electromagnet flux.

Put the equation (4) into the equation (5), it can be get

$$F_{mag} = \frac{1}{2} i \frac{d\phi}{d\delta} = \frac{iN}{2} \frac{d\phi}{d\delta} = \frac{\mu_0 (iN)^2}{2 \delta^2} \quad (7)$$

Referring to Fig. 1 and applying Newton's second law of dynamic to the moving elements, the valve core equation can be written as

$$m_v \frac{d^2 x_v}{dt^2} + C_s \frac{dx_v}{dt} = F_{mag} - F_q - kx_v \quad (8)$$

Where F_{mag} is electromagnetic force, m_v is mass of the valve coil, including armature and pole; C_s is coefficient of viscous friction; F_q is aerodynamic force; k is spring coefficient; x_v is valve core displacement.

From the equation (7) and equation (8) can see the conclusion, when the structural parameter of the solenoid remain unchanged, if the current changes rapidly to a higher value, it can help to gain a larger force. The greater the changing rate of coil current is, the shorter the time for current value to reach a certain degree is, the shorter the time for electromagnet to provide a greater electromagnetic force is. Meanwhile, the higher the coil current increases, the greater the electromagnetic force is, the shorter the time for solenoid valve to close and the longer time for it to open.

In general, the factor of drive current affects the response characteristics of the high-speed on/off valve.

3.2. Dynamic model and simulation analysis

According to the structure and mathematical equations of the high-speed on/off valve, the dynamic model based on AMESim is built as showed in Fig 2 The electromagnetic force is changed by current of coil, and affects the responses of high-speed on/off valve. In the circuit system, the electric varies

directly with the voltage. Voltage may thus be said to produce an effect to the electromagnetic force, affecting the response characteristic of this valve. In order to get the principle of response, the voltage is set by 13.5V and 25V.

Table1 shows that the main definitions and values of notations used in the model.

Based on the emulate analysis, the response characteristics of high-speed on/off valve in different driving voltages are obtained. In the parameter mode of the AMESim software, parameter settings are provided with reference to table 1. In simulation mode, the related graph curves are shown as shown in Fig 3, it shows the influences of different voltages on the valve response.

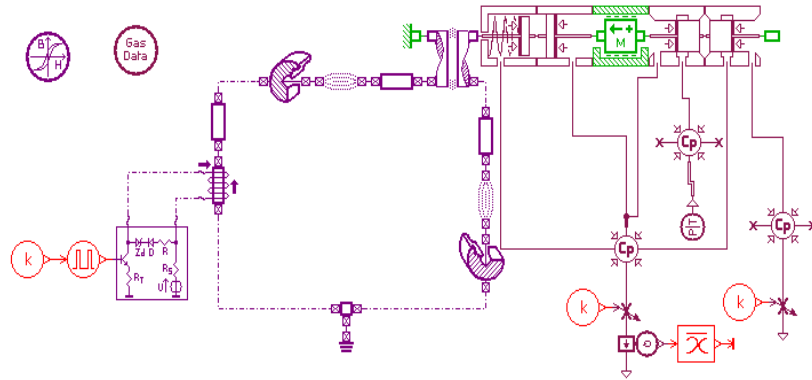


Figure 2. The simulation model of high-speed on/off valve.

Table 1. Simulation parameters

Parameter	number
voltage driving[V]	13.5 (25)
gas pressure [kPa]	1.813
gas constant [J•kg/K]	287.1
gas temperature[K]	293.15
mass of valve coil[kg]	0.00175
coil turns[tr]	1460
frequency[Hz]	30
initial air gap[mm]	1.16
pole diameter[mm]	8
Spring preload [N]	0.34
spring coefficient[N/mm]	0.1446
chamber length at zero[mm]	2.35
electrical resistance[Ω]	23
duty ration	0.5

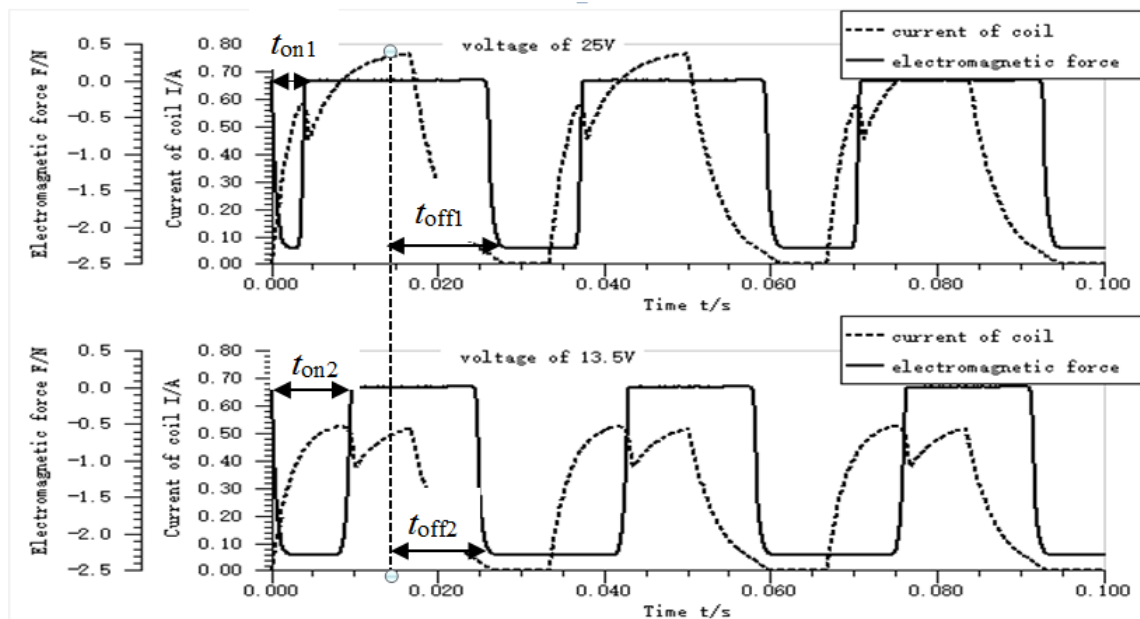


Figure 3. The influences of different voltages on the valve response.

Nomenclature:

t_{on} —opening time;

t_{off} —closing time.

From Fig 3, it is understood that the opening time of the high-speed on/off valve is reduced but the closing time is increased when the voltage is increased. This phenomenon occurs because of the variation of electromagnetic force and the maximum current. The facts as follow: during the process of power, when the voltage is set to 25V, the maximum electromagnetic force accomplished in shorter time than the voltage is 13.5V, then load force is overcome and the valve core is opened. But in the process of power failure, when the voltage is set to 25V, the current is greater than the voltage is 13.5V, and high current comes down to zero in more time. In order to improve the response characteristic, the voltage cannot simply be increased or reduced.

4. Driving circuit optimize

On the one hand, a high driving voltage is used in high-speed on/off valve which makes the acceleration of the high-speed on/off valve closing time and the reduced of opening time. On the other hand, using a low voltage has the opposite effect. In order to improve the response times, the driving circuit needs to be designed to have a characteristic of variable voltage output.

4.1. Double voltage driving circuit

Double voltage driving circuit is respectively using two constant working voltage of different sizes in different stages of the working process, in order to provide large driving current and small maintaining current to adjust the voltage modulation current.

In this paper, the scheme of double voltage driving circuit is applied to this high-speed on/off valve. Fig 4 shows the principle of double voltage driving circuit.

In this circuit diagram, the driving circuit consists of two switches, two diodes and a DWZ regulator. Two switches are identical IRFP150, two diodes are D1 and D2 respectively. PWM₁ and PWM₂ are control signals, respectively controlling two electronic switches 1 and 2; this measure is aimed to control the high voltage source and the on/off valve. When the PWM₁ signal is high, the PWM₂ signal is low, the switch 1 is closed, the switch 2 is disconnected, and the PWM driving voltage is driving voltage is U_1 with U_2 , after through R_1 , R_2 , and then getting the voltage of the is higher. But

when the PWM_1 signal is low, the PWM_2 signal is high, the switch 1 is disconnected, the switch 2 is closed, and only the low voltage is operated at this time, so the driving voltage is only U_2 . D2, DWZ and RZ constitute the high speed switch valve release circuit.

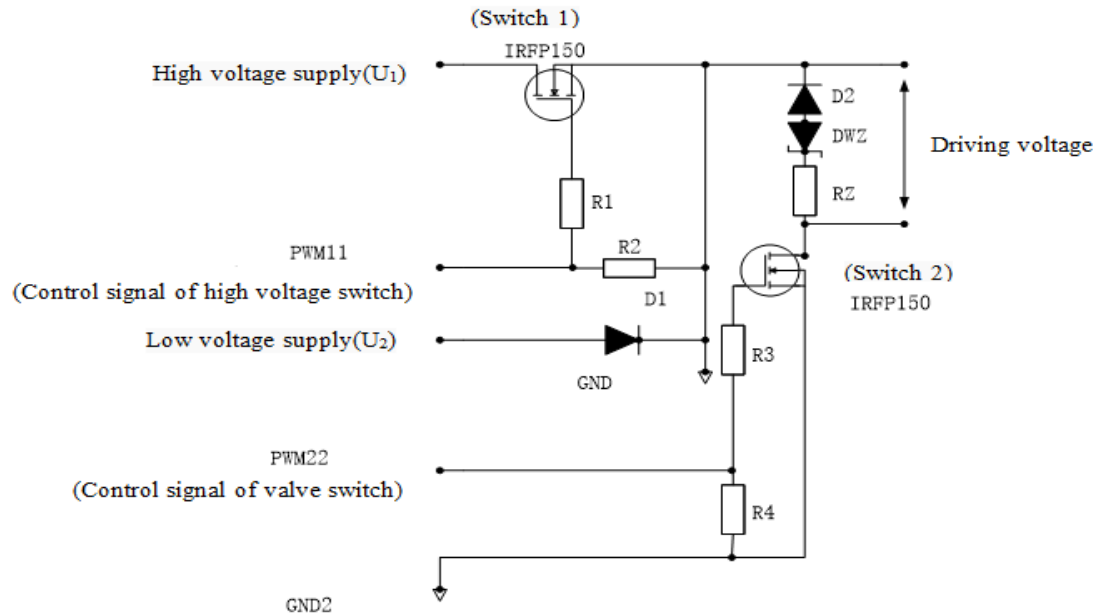


Figure 4. Principle of double voltage driving circuit.

4.2. Simulation analysis

Two sets of simulations were carried out for the original driving circuit scheme and the double voltage driving circuit scheme. Fig 5 shows the simulation model of high-speed on/off valve on the double voltage driving, the driving voltage is set to 25V and 5V, high voltage is a driving in short time, set the duty ration of PWM_1 to 10% and the duty ration of PWM_2 to 50%(adjustable). Fig7 shows the voltage and current of coil in the double voltage driving circuit. It can be learned from Fig 6 that high-voltage load, current of coil is increased rapidly to 0.636A within 2.6ms; next, when the high-voltage closed but low-voltage load, the current of coil is reduced to 0.22A and keeps a steady; finally, when the low-voltage closed, the current is rapidly reduced to zero.

The original circuit is set to 25V or 13.5V. The simulation results of the influences of different driver circuits on the valve response are shows in Fig 7 Table 2 shows the comparison of the different response times under different driver circuits of high-speed on/off valve.

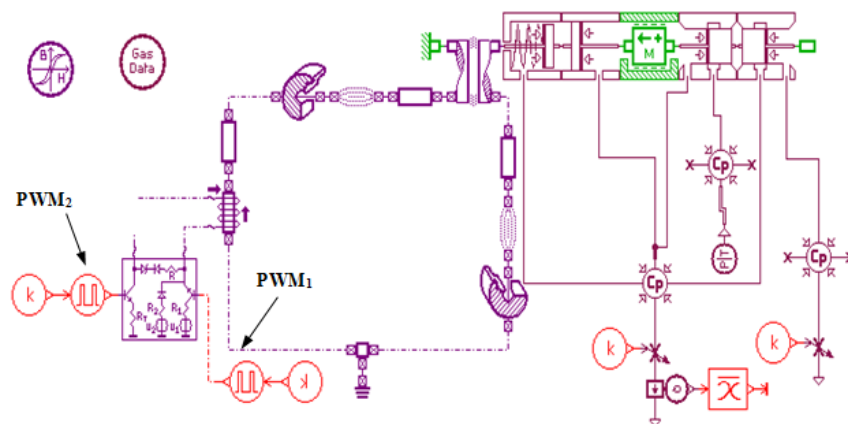


Figure 5. The simulation model of high-speed on/off valve on the double voltage driving.

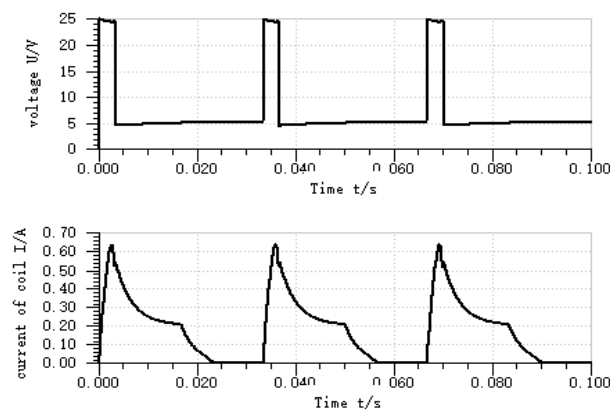


Figure 6. Double voltage driving circuit.

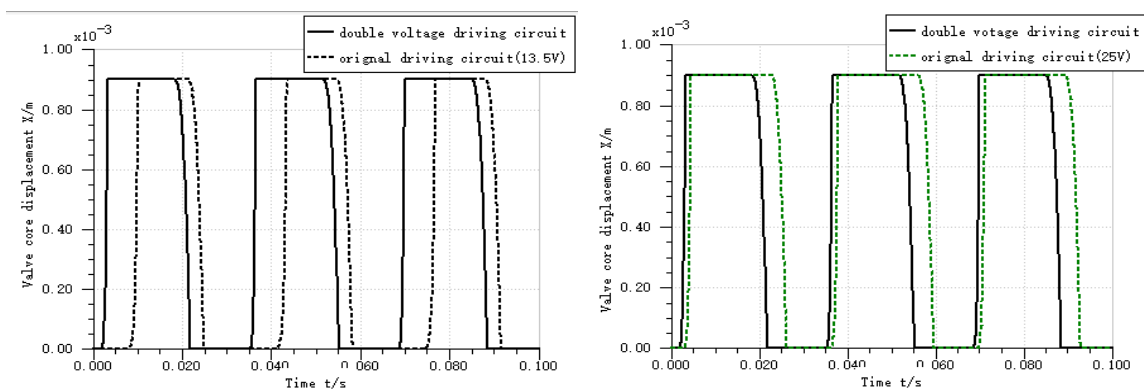


Figure 7. The influences of different driver circuits on the valve response.

Table 2. Comparison of the response times

parameter	Switching time(ms)		Delay time(ms)	
	Opening	Closing	Opening	Closing
Double voltage driving circuit	3.3	5.3	1.9	1.8
Original driving circuit(13.5 V)	10	8.2	7.7	4.6
Original driving circuit(25 V)	4.6	9.5	3	5.9

From Table 2, it can be seen that the delay times and switching times of the high-speed on/off valve is reduced by using the double voltage driving circuit. This is mainly due to the high voltage can make the current to rise faster at the beginning, the better initial condition of the closing of valve core will be get by using a low maintaining voltage after the valve totally opened. It can avoid the drawbacks of only using the high voltage or the low voltage driving.

5. Influences of related factors on response characteristic

In order to further study the superior of double voltage driving circuit, under the existing condition of the high-speed on/off valve, by the comparison related factors (such as duty cycle or working frequency) about influences on response characteristic.

5.1. Influence of duty ratio on response characteristic

The variation of duty cycle restricts the movement of valve core in some extent, Fig 8 shows the influence of different driver circuits on the valve response characteristic when changes the duty cycle.

Both of them are driven by a working frequency of 30HZ. Different driving circuits are the original driving circuit of 13.5V and the double voltage driving circuit, duty cycles respectively are 100%, 80%, 60%, 50%, 30% and 10%.

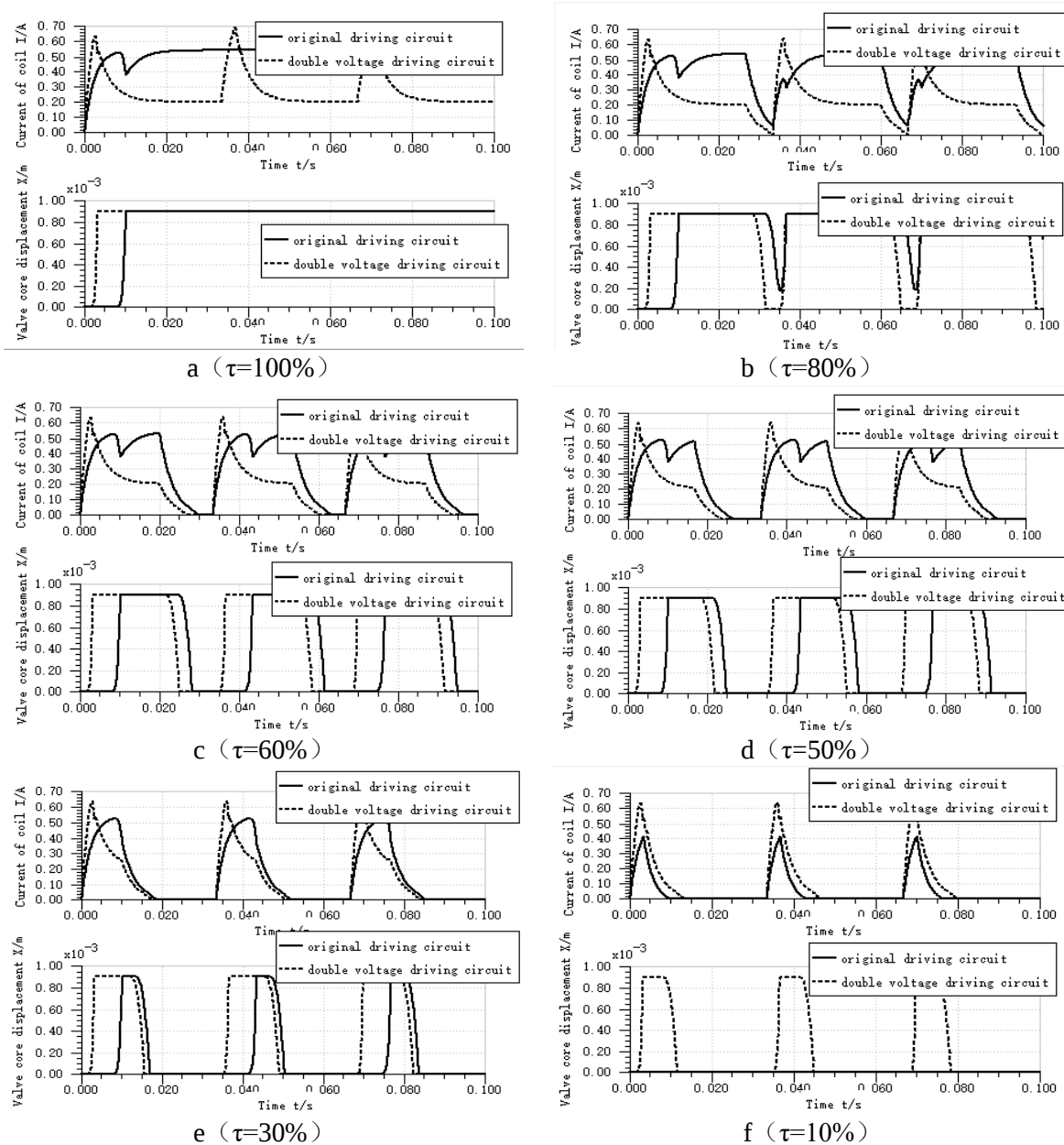


Figure 8. The influences of different driving circuits on the valve response when changes the duty cycle.

From Fig 8, the switching times and the movement process of the high-speed on/off valve are changed by the duty ratio. The following results are obtained: (1) At the same duty ratio, the high-speed on/off valve closing time and opening time are reduced when the valve is driven by the double voltage driving circuit, the response performance of the high-speed on-off valve is more superior. (2) At the small duty ratio (such as $\tau=10\%$), when the valve is driven by the original circuit, the electromagnetic force cannot overcome the load force, and the spool cannot be turned on. But the valve has the normal process of opening and closing because the valve is driven by the high voltage

during the double voltage driving circuit. (3) At the big duty ratio (such as $\tau=80\%$), when the valve is driven by the original circuit, the valve has not the process of completely closing because the PWM pulse rising edge has come but the current of coil has not dropped to zero. But the valve has the normal process of opening and closing because the valve is driven by the low maintaining voltage during the double voltage driving circuit.

5.2. Influence of frequency on response characteristic

The PWM signal of the high-speed on/off valve has better function of reproduction. Due to a delay of response time of high-speed on/off valve, the working frequency of PWM signal cannot be selected very high. Using a double voltage driving circuit can affect the response time to a certain extent, Fig 9 shows the influences of different driver circuits on the valve response characteristic when changes the working frequency. Both of them are driven by the 50%’s PWM₂ duty cycle and the 10%’s PWM₁ duty cycle. Different driver circuits are the original driving circuit of 13.5V and the double voltage driving circuit, they are driven by a working frequency of 20HZ, 30HZ, 50HZ and 70Hz, respectively.

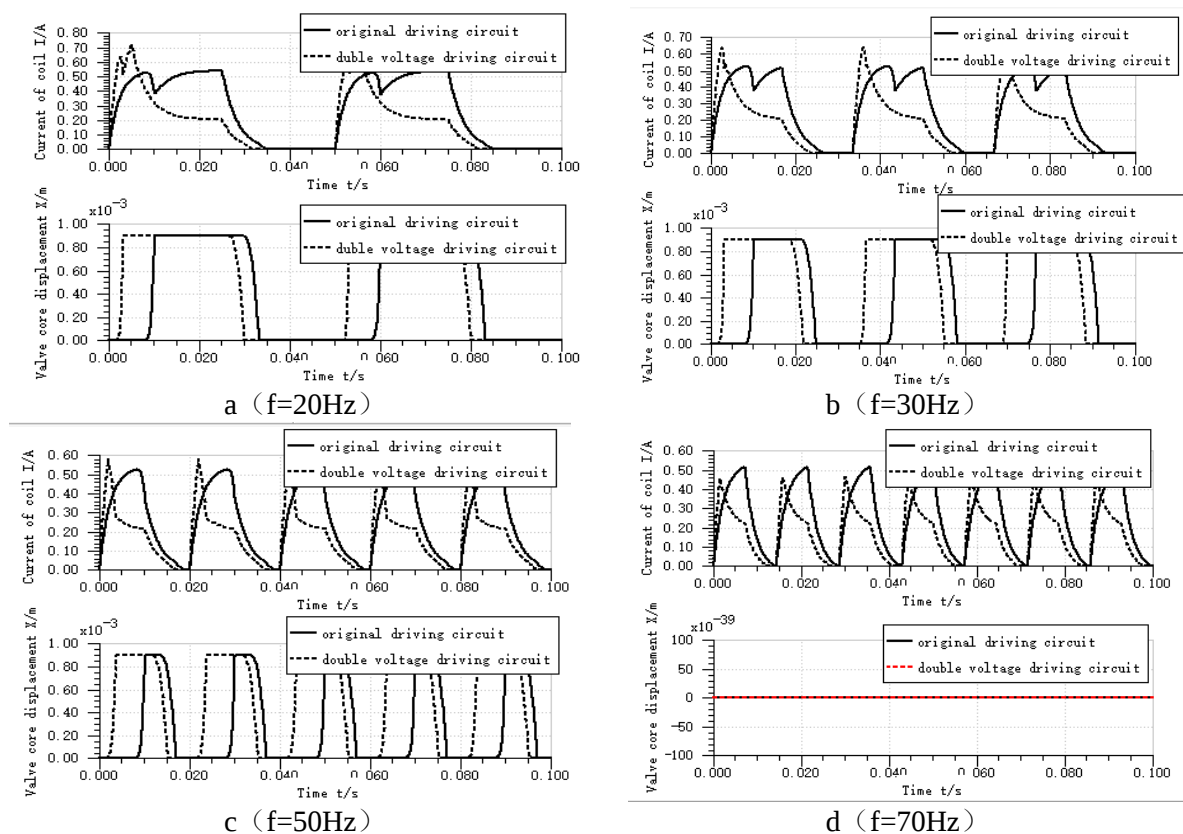


Figure 9. The influences of different driving circuits on the valve response when changes the working frequency.

From Fig 9, the switching times, delay times and the movement process of the high-speed on/off valve are changed by the different working frequency. The following results are obtained: (1) when the working frequency is increased, the dynamic characteristics of the electromagnetic force need to be improved, that makes the response characteristics of the high-speed on/off valve become poor. The main reason is that the working frequency is too much, that causing the current rise cannot make the magnetic field into the saturated state. Controlling the working frequency in a certain range is necessary. (2) At the same working frequency, the high-speed on/off valve closing time and opening time are reduced when the valve is driven by the double voltage driving circuit, and the response

performance of the high-speed on-off valve is more superior. (3) Double voltage driving circuit improves the response characteristics of this valve, the higher the working frequency, the greater the effect (such as $f=50\text{Hz}$). (4) When the high-speed on/off valve is driven by working frequency of 30 Hz, it has a better response characteristic. Therefore, 30HZ is always taken as working frequency in this valve.

6. Summary

In this paper, based on the analysis of limitations for the response characteristic of high-speed on/off valve, the double voltage driving circuit scheme is put forward and investigated by theoretical analysis and simulation. The comparison of the simulating results confirms the superior of the scheme. The following conclusions were reached.

- (1) When the high speed on/off valve is driven by the double voltage driving circuit, the switching times and delay times of this valve are reduced, optimizing its response characteristics.
- (2) The current of coil and the valve core displacement of the high-speed on/off valve are changed by the duty ration.
- (3) At the same duty ratio, the high-speed on/off valve is driven by double voltage driving circuit that has advantage in the movement process than original driving circuit.
- (4) When the working frequency is increased, the dynamic characteristics of the electromagnetic force need to be improved, that make the response characteristics of the high-speed on/off valve become poor.
- (5) Double voltage driving circuit improves the response characteristics of the valve, the higher the working frequency, the greater the effect.

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