Study on the control of automatic transmission proportional solenoid valve at different temperatures

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Abstract. The automatic transmission control unit drives the proportional solenoid valve through PWM. The valve often appears the control fault at an oil higher temperature. Analyze the effect of the proportional solenoid valve on the coil current about the different ATF (Automatic Transmission Fluid) temperatures, PWM duty ratio and frequency. Test the oil output pressure under different parameters. The results show that under the high ATF temperature conditions, depending on different duty cycles to select the frequency that can reach the oil output pressure close to normal operating temperature. It maintains a low electromagnetic valve power loss and a certain flutter.

1. Introduction
The automatic transmission is a major part of the vehicle. The control of the solenoid valve determines the shifting time and shift quality of the vehicle, which has an important influence on the driving comfort and safety of the vehicle. The electronic control system takes the PWM to control the proportional solenoid valve. It converts the input current signal into electromagnetic force or displacement signal output, and control the oil output pressure [1-2].

The automatic transmission is required to transmit different speeds and torques during vehicle driving. Heavy load or frequent shifting will cause ATF to rapidly increase from the normal operating temperature to 150 °C. The PWM control of proportional solenoid valves for automatic transmission usually uses a fixed pulse frequency and a different duty cycle, to cope with the pressure changes during the clutch engagement [3]. Some researchers add the high frequency PWM signal to make the solenoid valve to self-oscillate and reduce oil hysteresis [4]. Excessively high oil temperature cause four results: the decrease of the lubrication effect, the overheating of the magnetic valve coil, the reduction of the current passing and the inaccurate control of the oil output pressure change [5]. This will reduce the quality of the shift, and even in serious cases the automatic transmission has a control malfunction. In this paper, the performance changes of the proportional solenoid valves with different ATF temperatures are studied. A method of adapting the adjusting the pulse frequency to different PWM duty ratios at high ATF temperatures was described. The hydraulic output value close to the normal operating temperature of the ATF was obtained.

2. Control performance analysis of proportional solenoid valve
Proportional solenoid valves can be divided into two types: normally closed and normally open. With the increase of the PWM duty cycle, the output pressure will also increase. If no current is input, the output of hydraulic pressure is zero, and the normally open type is in contrast.
2.1. Electromagnetic characteristic equation of proportional solenoid valve
Assuming that the magnetic circuit is unsaturated, and the displacement current and hysteresis effects are ignored. The electromagnetic force calculation model is derived from Maxwell's basic equation (1) [6-7]:

$$F = \frac{\partial W(x,i)}{\partial x}$$  \hspace{1cm} (1)

Where $F$ is the electromagnetic force, N; $W$ is the total energy in a magnetic field; $i$ is the coil current, A; $x$ is the spool travel, m.

By the equation (1) that, when the electromagnetic valve pole shoes are designed as a cone-shaped peripheral basin structure, the other mechanical structure parameters are consistent, the electromagnetic force is not related to the displacement of the valve spool, only depending on the coil current [7-8].

2.2. Electrical system equation.
The PWM-driven solenoid valve circuit controls the on-off of the high-power tube $G$, which is equivalent to the high frequency switching signal. The differential equation of proportional solenoid valve coil in electric control loop was calculated as follows equation (2) [9-10]:

$$U(t) = L \frac{di(t)}{dt} + (R + R_s)i(t)$$  \hspace{1cm} (2)

Where $U(t)$ is the driving voltage, V; $L$ is the coil inductor, H; $R$ is the coil DC resistance, $\Omega$; $R_s$ is the sampling resistance, $\Omega$; $i(t)$ is the coil real time current, A.

Solving the equation (2), it gets the change rule of solenoid valve coil current as follows equation (3):

$$i(t) = i_0\exp(-t/\tau) + \frac{U}{R + R_s}[1 - \exp(-t/\tau)]$$  \hspace{1cm} (3)

Where $\tau = L/(R + R_s)$ is the time constant of a circuit, ms; $i_0$ is the initial current value, A.

The PWM drive solenoid valve circuit was analyzed of RL transient as follows equation (4):

$$i(t) = \begin{cases} 
I - di - \frac{U}{R + R_s}\exp(-t/\tau) + \frac{U}{R + R_s} & 0 < t < DT \\
(I + di)\exp[-t/(\tau DT)] & DT < t < T
\end{cases}$$  \hspace{1cm} (4)

Where $T$ is the PWM drive control cycle, ms; $D$ is the duty cycle; $I$ is the steady current, A; $di$ is the wave current, A.

It can be seen that when other parameters of the solenoid valve are constant, the time constant, resistance, drive frequency, and duty ratio determine the steady-state current and current fluctuations. According to the instantaneous current, the steady current and its fluctuation were calculated as follows equation (5) [11]:

$$I = \frac{U}{2(R + R_s)} \left(1 - A\right) \left(1 + B\right)$$

$$di = I \frac{1 - B}{1 + B}$$  \hspace{1cm} (5)

Which $A = \exp(-DT/\tau)$, $B = \exp[(D-1)T/\tau]$.  

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In the control system, the electromagnetic force of the solenoid valve is directly determined by the current of the rising or falling proportional solenoid valve. And the fluctuating current makes the armature of solenoid valve to maintain a small amplitude vibration, and prevent the stagnation of the valve spool due to the static friction during restart [12]. The automatic transmission chooses an appropriate PWM duty cycle and frequency, which can change the average current driven, generate different electromagnetic forces, and obtain the oil pressure output that is consistent with the operating state.

2.3. Calculation of solenoid valve coil current.

The PWM drive circuit was designed to drive the proportional solenoid valve, as shown in figure 1. The test used an oscilloscope to measure the voltage \( U_s \) at both ends of the series sampling resistance, and then obtained the change of coil current. A typical automatic transmission's ascending-proportional solenoid valve was used as the experimental target. The driving frequency of the automatic transmission manufacturers is 50 Hz. The indoor temperature was 25 °C, the sampling resistance was 0.5 \( \Omega \). The circuit used 12 V voltage when the resistance of high power valve G was ignored.

![Figure 1. PWM drive circuit.](image)

The inductor and DC resistance of the solenoid valve at ATF different operating temperatures were measured, and the time constants were calculated, as shown in table 1. When the temperature rises, both the DC resistance and the inductance increase, and the time constant decreases. The reduced value of time constant has little effect on the values of \( A \) and \( B \) in equation (5), the increase in DC resistance causes the steady-state current value to decrease.

| ATF temperatures | \( L(\text{mH}) \) | \( R(\Omega) \) | \( r(\text{ms}) \) |
|------------------|-----------------|----------------|----------------|
| 25 °C            | 11.107          | 5.5            | 1.851          |
| 85 °C            | 12.258          | 6.6            | 1.726          |
| 145 °C           | 13.47           | 7.47           | 1.690          |

From the time constant, the maximum cut-off frequency of the electrical system was about 550 Hz. According to the formula (5), the coil current fluctuation and current value change under different duty cycles conditions as shown in figure 2.

When the duty ratio is less than 50%, use a low frequency can quickly to establish the oil pressure in higher coil current. For the wave current, it is known from the Bode diagram of a second-order low-pass filter that the mechanical system of the solenoid valve is suppressed after the frequency is greater
than 50 HZ [4]. The higher the frequency is, the greater the suppression is. The maximum fluctuation value is the largest when the duty ratio is at 50%, and the fluctuation at both ends becomes smaller. The smaller the frequency is, the greater the fluctuation in the duty cycle that fluctuates by the greater value of the current fluctuations.

At different driving frequencies, the coil current at about ATF 85 °C is larger than that at 145 °C. The greater the duty cycle is, the larger the difference is. When the duty ratio is 100%, the current difference of the coil is about 0.2 A.

At the same driving frequency, the current fluctuation at ATF 85 °C is more 0.1 A than that at ATF 145 °C. The difference is the largest at a duty cycle of 50%, and the higher the driving frequency is, the smaller the difference is.

When calculating the coil current, the hysteresis loss, eddy current loss and magnetic circuit saturation of the solenoid valve were neglected. Therefore, when the actual PWM signal drove the proportional solenoid valve test, the coil current was less than the theoretical calculation. According to the above analysis and control system stability requirements, if the frequency PWM signal driving the proportional solenoid valve is too high, it will cause excessive power loss, increase the hysteresis loss and eddy current loss of solenoid valve [4]. So the relatively low frequencies should be selected under the same conditions.

![Figure 2. Coils current and wave current curve.](a)![Figure 2. Coils current and wave current curve.](b)

### 3. Test of output pressure of solenoid valve

The automatic transmission controls computer output different duty cycles according to the speed of the vehicle, which makes the proportional solenoid valve to output different oil pressures, control the shifting action and shift stability of the valve.

As shown in figure 3, an instruction was sent to a pulse generator by an upper computer. It was used to control the circuit of the solenoid valve line, read the voltage and current signals of the solenoid valve. As shown in figure 4, a hydraulic pump was used to connect the proportional solenoid valve, and the PWM drive circuit drove the solenoid valve to test the oil output pressure. On the test circuit, the input oil pressure $P_1$ was set to 520 KPa by the pressure regulating valve. When the ATF temperature was heated to 85 °C and 145 °C, the output pressure of the solenoid valve with different duty cycles or frequencies were recorded. During the test, the oil input pressure $P_1$ at the 85 °C setting dropped by about 20 KPa because the viscosity of the oil dropped after the temperature rise. In order to achieve the same test conditions, manually adjust the $P_1$ to achieve the same test oil input pressure (520 KPa).
According to the curves shown in figure 5, at the same ATF temperature, the higher the frequency is, the lower the duty cycle is, and the solenoid valve reached the upper limit of the oil output pressure. When the frequency exceeds 200 HZ, the required space ratio interval is not much different to reach the upper limit of oil output pressure. When the duty cycle and frequency were same, oil output pressure $P_2$ at ATF 85 °C was larger than the oil output pressure at 145 °C.

Excessively high PWM duty ratio will increase the power consumption of the solenoid valve and influence the closing response speed. Use too high PWM driving frequency will increase the iron loss of the electromagnetic coil, and cut down the wave current. It also will increase the static friction force when the solenoid valve is started again, affect the response performance and control accuracy of the solenoid valve [4, 13].

According to the above analysis and figure 5, when the vehicle speed or other conditions change, and the automatic transmission control computer adopts different PWM duty ratios. When the PWM duty cycle is 30% to 70%, the lower frequency should be selected to make the output oil pressure more smoothly. However, after 80% of the PWM duty ratio, the higher frequency should be used to quickly establish the oil pressure to meet the shift requirement [14]. When the temperature of ATF reaches 145 °C, and the PWM duty ratio is 30% to 70%, the PWM frequency can be set to 100 HZ. 200 HZ of The PWM frequency can be selected when the PWM duty ratio is greater than 80%. Other duty cycle intervals can be optimized by selecting the corresponding frequency to achieve the ideal solenoid valve oil output pressure.
4. Conclusions
The coil current of the proportional solenoid valve determines the electromagnetic force. The current curves of the solenoid valve coils at different ATF temperatures are in accordance with the theoretical values.

At a high temperature, the ATF can change the operating frequency of the solenoid valve to obtain an oil output pressure value close to the normal operating temperature of the ATF, and the operating frequency increases as the duty cycle increases.

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![Figure 5. Oil output pressure curve of solenoid valve.](image-url)
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