The design and development of an automatic transmission solenoid tester for wheeled vehicles

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Abstract
Solenoids are the most critical components in automatic transmissions. They are used to control the shift points, clutch locking, or pressure regulation of automatic transmissions. Since the number, type, and order of the solenoids all differ when they are used in different vendor’s automatic transmissions, making accurate normal/abnormal decisions for solenoids is very difficult, as it can lower the maintenance quality, to waste labor and material cost, and even reduce driving safety. This article proposes an “abnormal” inspecting method (i.e. for abnormality) for solenoids with high inspect ability and develops a learnable automatic transmission solenoid tester. This tester can perform solenoid testing on multiple channels at the same time. The test result statistics for all channel solenoids tested are generated automatically. It also provides visibility for users to view the difference comparisons of testing curves of temperature, pressure, voltage, current, and resistance on a graphical screen. The curve visibility function will be helpful for the solenoid diagnosis of abnormal or fault reasons.

Keywords
Solenoid valve, automatic transmission, fault inspection, mechatronics, hydraulic control system, learning function

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Introduction
In comparison with tracked vehicles, wheeled vehicles have such advantages as fast speed, high mobility, long running distance, low price, and convenient maintenance, but with low cross-country power and large turning radius as their weaknesses. Tracked vehicles are mostly military, for example, armored cars and tanks. Wheeled vehicles are the foremost type of civilian vehicle (e.g. cars and trucks). The automatic transmission (AT) is a key component of wheeled vehicles; it automatically changes the gear ratio while running, acting as the AT for the gearshift or pressure adjustment. At present, the AT vehicles with automatic shifting function use electronically controlled automatic transmissions (ECAT). This kind of AT can use different sensors to inform the driving computer of the working condition of engine; the driving computer then sends signals to actuate different solenoids in the hydraulic control system to change the oil duct in the AT to control the gears or adjust the pressure. In the ECAT, the solenoids can control the shift points and clutch locking or regulate the line pressure.

According to experience in practical repair and maintenance, the dysfunction of AT mostly results from the abnormalities or faults of the solenoids. When an AT solenoid is faulty or abnormal, the general repair
approach is to dismount all the solenoids from the vehicle one by one for inspection, so that the professional maintenance personnel can identify the faulty or abnormal solenoid according to experience for subsequent renewing and remedial operation.\textsuperscript{7,8} However, different numbers, types, and orders of solenoids are used in the AT of different brands. Therefore, it is difficult for maintenance personnel to judge whether or not a solenoid is faulty, resulting in severe difficulties in maintenance and repair, wasting manpower and material resources, and even compromising driving safety.

At present, a variety of solenoid testers have been developed for promoting inspection efficiency.\textsuperscript{9–15} However, the existing test systems mainly consider the difference between the test hydraulic pressure curve and normal hydraulic pressure curve as the basis of judging whether or not the solenoid is normal; the anomaly inspection capability is obviously insufficient as only one channel solenoid can be tested each time, and the inspection efficiency is confined. In fact, an AT solenoid can be divided into an electromagnetic structure and a mechanical valve body structure, and the failures include electric structure failure and mechanical structure failure.\textsuperscript{16,17} The following items can be inspected by measuring the current consumed by a solenoid: (1) impedance of coil, for checking the aging demagnetized state; (2) whether the action position of the magnetic core is fixed within the rated time; and (3) whether the coil is broken or the core is deactivated. The solenoid inlet/outlet pressure is measured to check (1) whether the valve seat closure is faulty or dirty, and (2) whether the spring of valve seat is too aged for full opening or complete closing.

According to the control mode of the driving computer, the solenoids of AT can be classified into ON/OFF type and duty cycle type:\textsuperscript{16,18,19}  

1. **ON/OFF type solenoid:** when the solenoid is ON, the needle valve is turned on and the line pressure is relieved directly. When the solenoid is OFF, the needle valve is locked tight, the line is closed, and the pressure cannot be relieved. Generally, the needle valve turn-on stroke is fixed; the voltage control signal is shown in Figure 1(a); this kind of solenoid is often used for shift control.

2. **Duty cycle solenoid:** the solenoid can change the needle valve turn-on stroke according to the time ratio of ON, so the amount of discharged oil is variable; the voltage control signal is shown in Figure 1(b). This type of control is known as pulse width modulation, and as PWM solenoid; its control mode generally uses fixed frequency. This kind of solenoid is often used for regulating the line pressure.

For the problems and limitations related to the present solenoid testers, this article proposes an innovative solenoid anomaly detection method by simultaneously considering both possible electric structure failure and mechanical structure failure of solenoids. Based on this method, we designed a multichannel solenoid inspection system with learning ability\textsuperscript{20,21} which can inspect an ON/OFF solenoid and PWM solenoid as the solution to the aforesaid problems and limitations. In terms of this solenoid anomaly detection method, the voltage can be supplied according to the voltage control curve, in order to measure the curve variation of the consumed current, in coordination with the oil pressure supply to measure the inlet and outlet pressures to work out the difference between the test hydraulic pressure curve and the standard hydraulic pressure curve, as well as the difference between the test current curve and standard current curve at the same time, greatly enhancing the anomaly recognition capability of the solenoid. In terms of the design of the solenoid inspection system, a universal inspection system with learning ability is proposed, which can establish the standard curves of a solenoid of unknown model by learning for the test operation of the solenoids of the model. In addition, this system constructs four solenoid testing channels; as four solenoids can be tested at the same time, the testing efficiency is greatly increased. The test result statistics for all channel solenoids tested are generated automatically. The user can perform combinatorial analysis of different test curves with the flexible...
display function of the system, to ascertain abnormal conditions and possible failure causes of the solenoid.

**Solenoid anomaly inspection method**

The procedure of the AT solenoid anomaly inspection method proposed in this article is shown in Figure 2. This inspection method comprises the following steps:

1. For a solenoid of model $A$, the standard outlet pressure $P_s$ and standard temperature $T_s$ of oil input for the solenoid are preset, the voltage control curve $V_i(t)$ of solenoid test is defined, and $t$ is the time; this is the test configuration of subsequent inspection operation;

2. A normal solenoid $a_0$ of model $A$ is used, the actuating environment of this solenoid is controlled according to the $P_s$, $T_s$, and $V_i(t)$ of the preset test configuration in Step 1; to test the solenoid $a_0$, a standard hydraulic pressure curve $P_i(t)$ and standard current curve $C_i(t)$ are generated. The range of allowable error of standard hydraulic pressure curve $E_{p}\Delta t_i(t) \sim E_{p\text{th}}(t)$ and the range of allowable error of standard current curve $E_{c}\Delta t_i(t) \sim E_{c\text{th}}(t)$ are defined, where $E_{p\text{th}}(t) = P_i(t) - \Delta E_p$, $E_{p\text{th}}(t) = P_i(t) + \Delta E_p$, $\Delta E_p = \alpha(P_{\text{max}} - P_{\text{min}})$, $E_{c\text{th}}(t) = C_i(t) - \Delta E_c$, $E_{c\text{th}}(t) = C_i(t) + \Delta E_c$, $\Delta E_c = \alpha(C_{\text{max}} - C_{\text{min}})$, $\alpha$ is the tolerable error percentage, $P_{\text{max}}$ and $P_{\text{min}}$ are the maximum and minimum values of pressure sensing, respectively, and $C_{\text{max}}$ and $C_{\text{min}}$ are the maximum and minimum values of current sensing, respectively.

3. According to the $P_s$, $T_s$, and $V_i(t)$ of the test configuration in Step 1, the oil is imported into the test solenoid $a_i$ of Model $A$, $i > 0$, and the actuating environment of this solenoid is regulated to test the solenoid $a_i$; a test hydraulic pressure curve $P_i(t)$ and a test current curve $C_i(t)$ are generated;

4. The $P_i(t)$ and $C_i(t)$ resulting from the test solenoid $a_i$ are compared with $P_i(t)$ and $C_i(t)$,
respectively, to obtain the difference \( \Delta P(t) = P_A(t) - P_B(t), \ \forall t \), and the difference \( \Delta C(t) = C_A(t) - C_B(t), \ \forall t \).

5. When \( P_A(t) \) and \( C_A(t) \) fall within the range of allowable error of \( P_B(t) \) and \( C_B(t) \), respectively (i.e. \( |\Delta P(t)| \leq \Delta P_{\text{th}} \) and \( |\Delta C(t)| \leq \Delta C_{\text{th}} , \ \forall t \)), the tested solenoid \( a_i \) is identified as “normal”; when \( P_A(t) \) or \( C_A(t) \) does not fall within the range of allowable error of \( P_B(t) \) and \( C_B(t) \) (i.e. \( \exists t, \ |\Delta P(t)| > \Delta P_{\text{th}} \) or \( |\Delta C(t)| > \Delta C_{\text{th}} \)), the tested solenoid is identified as “abnormal.”

6. If there are other tested solenoids \( a_i \) of model \( A \), return to Step 3.

The example of this inspection process is shown in Figure 3. Figure 3(a) shows the standard hydraulic pressure curve \( P_A(t) \) and standard current curve \( C_A(t) \) of normal solenoid \( a_0 \) established by performing Step 2, and the ranges of allowable error \( E_{\text{th}}(t) = \Delta P_{\text{th}}(t) \) and \( E_{\text{ch}}(t) \) thereof (gray regions). Figure 3(b) shows the test hydraulic pressure curve \( P_A(t) \) and test current curve \( C_A(t) \) of the tested solenoid \( a_i \) generated by performing Step 3. Figure 3(c) shows the comparison diagram of \( P_A(t) \) and \( C_A(t) \) in Step 4 and \( P_B(t) \) and \( C_B(t) \). It is observed that the curve \( P_A(t) \) and curve \( C_A(t) \) have exceeded the ranges of allowable error of curve \( P_B(t) \) and curve \( C_B(t) \), respectively, so this tested solenoid \( a_i \) is identified as “abnormal” in Step 5.

In addition, according to the anomaly inspection procedure shown in Figure 2, the solenoid test method proposed in this article will have learning function, because for the other unknown solenoids of model \( B \), as long as the procedures of Steps 1 and 2 are completed, the test configuration of solenoids of model \( B \) can be established in the system and the required \( P_A(t), C_A(t), E_{\text{th}}(t) \sim E_{\text{th}}(t) \) and \( E_{\text{ch}}(t) \sim E_{\text{ch}}(t) \) can be tested. Afterward, the anomaly inspection operation can be performed for the tested solenoid of model \( B \).

**System design**

**System architecture**

In this work, to design the solenoid inspection system, a test architecture which can inspect four solenoids simultaneously is established by simulating the solenoid operating environment in the AT. This test architecture can use one oil hydraulic storage tank to simultaneously actuate four solenoids of the hydraulic channel; the system can automatically monitor the temperature and pressure of the oil tank and the voltage signals delivered to various channel solenoids, and establish the required hydraulic pressure curve and current curve for inspection by detecting the channel pressure and consumed current of various solenoids. The architecture of this solenoid inspection system is shown in Figure 4. The functions of various constitutional units are described below:

1. Hydraulic tank: to store oil for actuation of solenoids.
2. Hydraulic driver: an oil hydraulic pump connected to the hydraulic tank. This hydraulic pump can pressurize the oil stored in the hydraulic tank and deliver it to various tested solenoids through the oil delivery pipe.
3. Hydraulic controller: it can receive the command signals from the monitoring host to control the hydraulic driver to deliver oil to actuate the tested solenoid.

4. Supply pressure detector: for detecting the supply pressure of oil pressurized and delivered by the hydraulic pump to the delivery pipe, the detected pressure signal can be transmitted by the signal transform unit to the monitoring host for processing.

5. Temperature driver: a preheating pump, for heating the oil in the hydraulic tank.

6. Temperature controller: a controller for controlling the heating action of the preheating pump; it can receive the command signals from the monitoring host, or the user operates the control action.

7. Temperature detector: for detecting the oil temperature in the hydraulic tank, the detected temperature signal can be transmitted by the signal transform unit to the monitoring host for processing.

8. Level detector: for detecting the oil height in the hydraulic tank; the detected level signal can be transmitted by the signal transformation unit to the monitoring host for processing.

9. Tested solenoid (sample): the tested solenoid to be inspected or the normal solenoid for establishing standard conditions.

10. Solenoid valve seat: molds of different specifications can be installed to provide the sockets of different models of tested solenoids, so that each tested solenoid is positioned and stably connected to the delivery line, and so the oil can be delivered smoothly to the solenoid. This valve seat can be provided with the solenoids of four channels, where the first channel is used to test the solenoid and to establish standard
conditions of solenoids; the other channels are used to test the solenoids.

11. **Voltage supplier**: a DC power supply supplying the voltage signals for actuating various tested solenoids.

12. **Voltage transform controller**: it can receive the command signals from the monitoring host, which are converted into output voltage signals of the voltage supplier to actuate the tested solenoid.

13. **Channel pressure detector**: for detecting the oil pressure of the channel solenoid; the detected pressure signal can be transmitted by the signal transformer to the monitoring host for processing; this system has four channel pressure detectors.

14. **Channel current detector**: for detecting the consumed current of the channel solenoid; the detected current signal can be transmitted by the signal transformer to the monitoring host for processing; this system has four channel current detectors.

15. **Signal transform unit**: NI USB-6341 multifunctional data acquisition control card\(^{22}\) is used as the signal transform unit; the signals detected by various detectors can be transformed into 0–10 V voltage to be processed by the monitoring host; meanwhile, the control commands from the monitoring host are transformed into control signal and sent to the controllers for controlling the oil temperature, hydraulic pump discharge pressure, and power supply outlet voltage to perform various control actions. The monitoring host can generate PWM voltage signals through this acquisition control card for the PWM solenoid test.

16. **Monitoring host**: the main control unit of the solenoid test bench; the signals detected by all the detectors can be imported through the signal transform unit, and processed by the automatic monitoring software to generate control signal output to perform the control tasks of various controllers. This automatic monitoring software is developed by LabVIEW graphical language\(^{23,24}\) for the user to establish the standard conditions of solenoids, performing tested solenoid inspection and solenoid grease removal.

**Hardware design**

To develop the hardware of the solenoid inspection system, the hardware system design for the solenoid test bench is completed first. Figure 5 shows the hardware system P&ID (Process & Instrument Diagram) of the solenoid test bench, including a heat insulating oil tank, a hydraulic control device, a solenoid valve seat, and a signal control device. The design structure is described below.

1. The hydraulic tank is connected to a hydraulic pump P-01; there is a filter F between the hydraulic tank and P-01 to filter the oil of hydraulic tank. The P-01 pressurizes the oil stored in the hydraulic tank and delivers it to the hydraulic control device through the oil delivery pipe. The outlet pressure transmitter PT-05 can detect the oil pressure in the delivery pipe; the detected pressure is displayed on the screen of monitoring host by pressure indicating controller PIC-05; it is fed back to control the pressure of P-01. In addition, the hydraulic tank is connected to a back pressure control valve BPV for reducing the input pressure of P-01 so that the oil can return to the hydraulic tank through the back pressure control valve BPV.

2. The hydraulic tank is connected to a preheating pump HT-01 for heating the oil in the hydraulic tank. There is a temperature transmitter TT-01 in the hydraulic tank for detecting the temperature of the oil; the detected temperature is displayed on the screen of the monitoring host by a temperature indicating controller TIC-01; it is fed back to control the temperature actuator TA-01 to actuate the heating action of HT-01.

3. The hydraulic control device comprises four electronically controlled switch valves (BV-1, BV-2, BV-3, and BV-4). These four switch valves are connected to the oil delivery pipe of P-01 through the line, and pivoted on the solenoids in the solenoid valve seat to control the actuation of the solenoids. The delivery channels of the hydraulic control device are connected to a pressure transmitter (PT-01, PT-02, PT-03, and PT-04) for detecting the pressure in various channels; the detected pressure is transmitted by the corresponding pressure indicators (PI-01, PI-02, PI-03, and PI-04) to the screen of the monitoring host. In addition, the lines are connected to the solenoid valve seat by a flow limiter (FC-01, FC-02, FC-03, and FC-04), respectively, to control the oil input flow to the solenoid valve seat to increase the accuracy of detection.

4. The solenoid valve seat can be provided with four molds simultaneously to test four solenoids: TV-1, TV-2, TV-3, and TV-4.

5. The signal control device contains a voltage signal transmitter VT-01 for detecting the voltage signals exported from DC power supply (DC Power) to various channel solenoids; the detected voltage signals can be displayed on the screen of...
monitoring host by a voltage indicating controller VIC-01. The VIC-01 controls the DC Power and SSR switching circuit simultaneously, providing the voltage signals for testing various channel solenoids. The signal control device has four current signal converters (AT-01, AT-02, AT-03, and AT-04) which are pivoted on the four tested solenoids on the solenoid valve seat, respectively, to detect the current signals of various channel solenoids. The detected current signals are transmitted by the corresponding current indicators (AI-01, AI-02, AI-03, and AI-04), respectively, to the screen of monitoring host.

In the P&ID diagram of Figure 5, the framed elements show that the signal can be transmitted through the signal transform unit to the monitoring host and displayed, or the monitoring host performs the feedback control action. For example, the pressure indicators PI-01~PI-04 and current indicators AI-01~AI-04 can transmit the hydraulic pressure signals and current signals of various channel solenoids to the monitoring host and display them. The indicating controllers PIC-05, TIC-01, and VIC-01 not only transmit the outlet pressure, oil tank temperature, and outlet voltage signal to the monitoring host, but also actuate feedback control for P-01, HT-01, and DC Power according to the obtained signal values, in order to automatically control the oil pressure, temperature, and voltage. Based on the system architecture in Figure 4 and the hardware design P&ID in Figure 5, the developed solenoid inspection system entity is shown in Figure 6.

Figure 5. Hardware design P&ID.
Automatic monitoring software development

In this work, LabVIEW graphical language\textsuperscript{23,24} is used as the development tool for the automatic monitoring software of the solenoid inspection system. The modular layer structure of the developed software system is shown in Figure 7. This software system architecture comprises such main constitutional modules as a voltage control curve editing unit, a standard condition multiple tests unit, a solenoid grease cleaning unit, a solenoid test setting unit, a repeated solenoid testing unit, a test result statistics unit, and a flexible curves display unit.

This software system can provide a solenoid testing procedure with learning function, so that it can build the standard curves of unknown models’ solenoids by learning, and then be used for the test operation of the solenoids of the model. The complete testing process is shown in Figure 8.

The execution steps of this testing process are described below:

1. Identify the model of solenoid: for the solenoid to be inspected, the first step is to identify the solenoid as a solenoid of a known or unknown model.
2. Edit voltage control curve: for a solenoid of an unknown model, the first step is to edit its voltage control curve. The voltage control curves are divided into ON/OFF type and PWM type. Figure 9(a) shows the voltage control curve of an ON/OFF type, where the voltage signal of interval $[a, b]$ can activate the solenoid ON, so $V_{ON}$ is the activating voltage. Different solenoid activating voltages will result in differences in the interval $[a, b]$. Figure 9(b) shows the voltage control curve of PWM solenoid, where $t_1$ represents the ON time of solenoid, and $t_1/t_0$ is the ratio of duty cycle (or duty ratio, $r_d$); this ratio will influence the line pressure controlled by the solenoid.
3. Build standard conditions of the solenoid: for a normal solenoid of an unknown model, the edited voltage control curve is loaded, and then performs multiple tests for the normal solenoid; the obtained average standard pressure curve and average standard current curve are used to establish the standard conditions of the solenoids for this model. When the procedure

![Figure 6. Solenoid inspection system entity.](image)

![Figure 7. Hierarchy chart of software system modules.](image)
of building standard conditions is completed, the model of the solenoid is known.

4. Load standard conditions of solenoid: for a solenoid of a known model, the standard conditions of the model can be loaded as the criteria of inspection.

5. Repeated tests for solenoid: for a tested solenoid of a known model, 1~4 channels can be specified for the solenoid testing, and the system can perform the synchronous test repeatedly and automatically; after multiple tests, the fail rate of each tested solenoid can be calculated as the basis of identifying normal or abnormal.

6. Flexible curve display: after the repeated solenoid tests, the differences between the pressure, current, voltage, temperature, and impedance test curves of various channel solenoids and the standard curves are checked to diagnose the normal or abnormal state of the solenoid.

7. Judge inspection result: the normal or abnormal solenoid is judged according to the frequency of the inspection results of various test solenoids.

8. Normal result output: if the solenoid inspection result is identified as normal, the solenoid normal output is performed.

9. Judge grease clear: if the solenoid inspection result is identified as abnormal, whether the anomaly detection result is induced by grease of the solenoid should be considered before the fault is determined. Therefore, the first step is to judge whether the solenoid has performed the grease cleaning procedure; if not, the solenoid grease removal operation is performed first; if yes, but the inspection result is still identified as abnormal, it can be identified as a faulty solenoid.

10. Solenoid grease cleaning: the grease cleaning operation is performed for the selected channel solenoids according to the working voltage, working temperature, pulse frequency, and working time set by the user.

11. Fault result output: if the solenoid inspection result is identified as a fault, the solenoid fault output is performed.

12. Test a solenoid of the same model: if there is another solenoid of the same model to be tested, return to Step 5 to perform the solenoid inspection operation again.

Figure 8. Flowchart of solenoid testing process.

Figure 9. Voltage control curves: (a) voltage control curve of ON/OFF solenoid; (b) voltage control curve of PWM solenoid.
13. Test a solenoid of other models: if there are tested solenoids of other models, return to Step 1 to perform the solenoid model identification and related inspection operation again.

Solenoid inspection operation

Install tested solenoid

Adequate hydraulic oil shall be put in the oil tank of the solenoid test bench before the solenoid inspection; the solenoid to be inspected is then loaded in the corresponding mold, and the mold is installed on the solenoid test bench. For example, the 2-3 shift solenoid of GMC THM 4L80-E automatic transmission (Figure 10(a)) is used as tested object. Figure 10(b) shows the mold. Figure 10(c) shows this solenoid has been loaded in mold and installed on the test bench. Afterward, the heater of test system is actuated till the oil is heated to standard temperature $T_s$; the automatic monitoring software of this solenoid inspection system can be started to perform the aforesaid solenoid inspection procedure.

Edit voltage control curve

Figure 11(a) shows the voltage control curve edit screen of ON/OFF solenoids; the user can enter the starting voltage, ending voltage, and working time for each segment of the control curve in the voltage control table on the left of this screen; the system can perform a validation check of the complete control curve; the valid control curve is automatically displayed in the curve diagram on the right side of the screen. The edited ON/OFF voltage control table can be saved for ON/OFF solenoid test.

Figure 11(b) shows the voltage control curve edit screen of PWM solenoids; the user can enter the PWM signal frequency $F$, start the duty ratio ($r_{sd}$), end duty ratio ($r_{ed}$), duty ratio variation value ($\Delta r_{sd}$), and the number of signals of each $r_{sd}$ in the voltage control table on the left of this screen. As shown in the control table, the PWM signal frequency $F$ defined in Line 1 is 100 Hz (10 ms per signal), the $r_{sd}$ changes from 10% to 90%, $\Delta r_{sd}$ is 1%, and the number of signals of each $r_{sd}$ is 10, meaning each $r_{sd}$ takes 100 ms (0.1 s). The $F$ defined in Line 2 is also 100 Hz, the $r_{sd}$ changes from 90% to 10%, $\Delta r_{sd}$ is −1%, and the number of signals of each $r_{sd}$
is also 10. Therefore, the PWM control voltage of the two lines will use signal frequency \( F = 100 \text{ Hz} \); the \( r_d \) increases from 10% to 90%, and then decreases from 90% to 10%, and each \( r_d \) takes 10 signals, 0.1 s. In the same way, the system can perform a validation check of the PWM voltage signal; the valid voltage control curve can be automatically displayed in the curve diagram on the right of the screen according to the selected drawing object. The edited PWM voltage control table can also be saved for PWM solenoid test.

**Building standard conditions of a solenoid**

To build the standard conditions of a solenoid, the user can set up the model parameters as in the screen shown in Figure 12. For example, the model of solenoid entered in this screen is “4L80E-23Shift,” and file “D:\Solenoid Test Data\4L80E OnOff.vct” is selected to define the voltage control curve \( V_c(t) \); the test parameters are then entered, including voltage type (ON/OFF), standard temperature \( T_s \) (90°C), standard pressure \( P_s \) (16 kg/cm²), sampling rate \( \Delta t \) (0.2 s), tolerable error percentage \( \alpha \) (8%), tolerable error of standard pressure \( e_p \) (0.2 kg/cm²), PID parameter P-Value (3), I-Value (120), D-Value (120), and number of repeated tests \( N_s \) (4); the bracketed values are set values.

The “Edit control curve” button in Figure 12 can be clicked to display the voltage control curve edit screen shown in Figure 11 for the user to define the required voltage control table.

When the user has completed the test parameters setting, the “Standard condition test” button can be clicked to enter the solenoid test screen, as shown in Figure 13. When the user clicks the “Start pressure control and standard condition test” button in this screen, the system first controls the outlet pressure of the hydraulic pump according to the PID parameters and \( e_p \), so that the pressure reaches and remains at standard pressure \( P_{s\text{st}} \), then the tests for standard conditions of solenoid model are repeated; the number of tests is \( N_s \) (4) to generate \( N_s \) hydraulic pressure curves \( P_s(t) \) and \( N_s \) current curves \( C_s(t) \), \( i = 1 \) to \( N_s \). Figure 13 shows the screen after 4 repeated tests for standard conditions of the model.

Figure 14 shows the test scene of a normal solenoid; the oil is ejected when the solenoid is turned on and the oil is locked when solenoid is turned off.

After \( N_s \) tests for standard solenoid conditions, the system will calculate the average value of the \( N_s \) hydraulic pressure curves \( P_s(t) \) and \( N_s \) current curves \( C_s(t) \), respectively, as the standard pressure curve \( P_s(t) \) and standard current curve \( C_s(t) \) of the solenoid of this model, expressed as equations (1) and (2), respectively.

\[
P_s(t) = \frac{\sum_{i=1}^{N_s} P_s(t)}{N_s}, \forall t
\]

\[
C_s(t) = \frac{\sum_{i=1}^{N_s} C_s(t)}{N_s}, \forall t
\]

Finally, the system uses the solenoid model, voltage type, \( \Delta t, T_s, P_s, \alpha, e_p, P\text{-value}, I\text{-value and D-value}, as
well as the generated $P_s(t)$ and $C_s(t)$ curves, as the standard test conditions of this solenoid model, and this model (4L80E-23Shift) is automatically taken as the file name and saved in a standard condition file (e.g. D:\Solenoid Test Data\4L80E-23Shift.sdc) for testing the solenoids of this model.

**Repeated tests for solenoids**

To perform the test operation of tested solenoids, the user can set up the standard conditions of solenoids in the solenoid test setting screen, as shown in Figure 15. First of all, the user must load the standard conditions of the model of tested solenoids, for example, when the [D:\Solenoid Test Data\4L80E-23Shift.sdc] standard condition file is selected and read, the system loads the standard conditions of the model “4L80E-23Shift” from this file, and displays the standard condition parameters (solenoid model, voltage type, $\Delta t$, $T_s$, $P_s$, $\alpha$, $e_p$, $P$-value, $I$-value and $D$-value) on the screen.

Afterward, the number of repeated tests $N_t$ for the tested solenoids is set up and the channels to be tested are selected in this screen; herein, the $N_t$ is set as 5, meaning the solenoids will be tested five times in the

**Figure 13.** Menu after 3 repeated tests for standard conditions of solenoid.

**Figure 14.** ON/OFF test for normal solenoid: (a) oil is ejected when solenoid is turned on; (b) oil is locked when solenoid is turned off.
future, and the results of each test are counted in order to judge the success or failure of the solenoid test. This system can provide at most four test channels for the user to perform solenoids test operation; the user can set up the channel to perform a solenoid test by clicking the “Channel 1,” “Channel 2,” “Channel 3” or “Channel 4” button on the screen; the Test or Cancel state can be switched by clicking any button. All four channel buttons are set as Test state in this screen, so the system will repeatedly test the solenoids in these four channels.

After the user sets up the test channels and the times of repetitive work, the “Start solenoid test process” button can be clicked to enter the solenoid repeated testing screen, as shown in Figure 16. In this system, the repeated test process for tested solenoids is similar to the repeated test procedure of building standard solenoid conditions; both of them must adjust the
hydraulic pump outlet pressure to standard pressure value \( P_{in} \); the error is lower than \( e_p \) (0.2 kg/cm\(^2\)), and the repeated test operation of solenoids is then performed. There are four working charts for Channels 1 - 4; each chart displays the standard pressure curve \( P_i(t) \) and standard current curve \( C_i(t) \) (white curves). The white dotted lines above and below the two curves represent the range of tolerable error. The test pressure curve \( P_i(t) \) (yellow curve) and test current curve \( C_i(t) \) (blue curve) of the channel solenoid advance with the test process till the round of testing ends, and then the next round of test is started; \( N_i \) rounds of test will be performed.

On this screen, the pressure curve in the working chart of Channel 3 has turned red, meaning the pressure test for Channel 3 solenoid has failed because the test pressure curve has exceeded the tolerable range of pressure. In fact, in the overall solenoid test process, as long as any test curve exceeds the tolerable range, the curve immediately turns red.

When the repeated test procedure for solenoids is completed, the system will automatically store the test records of all the test channels. In this kind of test record, \( N_i \) test pressure curves, \( N_i \) test current curves, \( N_i \) outlet pressure curves and \( N_i \) temperature curves are stored for the solenoid of each channel for subsequent test result statistics and analysis.

**Test result statistics and curve analysis**

In order to perform the statistics and analysis of each channel solenoid test result, the pressure curve of \( i \)-th test is represented by \( P_i(t) \), and the current curve of \( i \)-th test is represented by \( C_i(t) \). The pressure failure rate, current failure rate, and total failure rate of each test can be calculated. The pressure failure rate of \( i \)-th test is represented by \( F_{pi} \); the current failure rate is represented by \( d_{ci}(t) \); \( d_{ci}(t) \) represents the decision on whether the \( t \)-th measured current falls within the range of allowable error in the \( i \)-th test. Various failure rates are defined as follows

\[
d_{pi}(t) = \begin{cases} 1, & E_{pi}(t) \leq C_{i}(t) \leq E_{ph}(t) \\ 0, & P_{i}(t) < E_{pi}(t) \text{ or } P_{i}(t) > E_{pi}(t) \end{cases} \tag{3}
\]

\[
d_{ci}(t) = \begin{cases} 1, & E_{ci}(t) \leq C_{i}(t) \leq E_{ch}(t) \\ 0, & C_{i}(t) < E_{ci}(t) \text{ or } C_{i}(t) > E_{ci}(t) \end{cases} \tag{4}
\]

\[
F_{pi} = \frac{1}{n} \sum_{i=1}^{n} d_{pi}(t), \quad i = 1, \ldots, N_i \tag{5}
\]

The success or failure of the test result can be determined by judging whether or not the total failure rate of each test is zero, that is, if \( F_{pi} = 0 \), the \( i \)-th test result \( R_{ti} \) is “Success,” on the contrary, if \( F_{pi} > 0 \), \( R_{ti} \) is “Fail.” Therefore, the overall test result \( R_t \) of the solenoid can be defined as “Success” only if total failure rate of all the \( N_t \) tests is zero; otherwise, “Fail.” \( R_{ti} \) and \( R_t \) are defined as equations (8) and (9), respectively

\[
R_{ti} = \begin{cases} \text{Success}, & F_{pi} = 0, \quad i = 1, \ldots, N_i \\ \text{Fail}, & F_{pi} > 0 \end{cases} \tag{8}
\]

\[
R_t = \begin{cases} \text{Success}, & \sum_{i=1}^{N_t} F_{pi} = 0 \\ \text{Fail}, & \sum_{i=1}^{N_t} F_{pi} > 0 \end{cases} \tag{9}
\]

For example, after the repeated test procedure for solenoids in Figure 16 is completed, the system displays the complete test result on the solenoid test result statistics screen in Figure 17. This screen contains the four statistical tables of solenoid test results of Channels 1-4. According to these statistical tables, the test results of Channel 1, Channel 2, and Channel 4 are “Success,” and the test result of Channel 3 is “Fail.” Each statistical table contains the statistics of five tests (each test has a record), and each record contains four fields: pressure failure rate, current failure rate, total failure rate, and test result. The pressure failure rate of the first test for Channel 3 solenoid is 43/151, meaning 151 pressure values are extracted from the test pressure curve, 43 pressure values are identified as fail values as they exceed the tolerable range of error of standard pressure curve. As long as any test fails, the solenoid test is identified as “Fail.”

In order to assist the user in further reviewing the solenoid test failure condition and discussing the possible failure cause, this system provides a flexible display function of test curves, allowing the user to perform combinatory analysis of different test curves. For example, when the “Display test curve” button is clicked in the lower part of the screen in Figure 17, the system will enter the testing curves display screen shown in Figure 18. The right part of this screen is a tab switched page display area; there are four labels of channels, and the corresponding page can be displayed by clicking any tab; each page contains a channel test chart and a voltage graph. The left part of the screen provides the control buttons for the user to select the display object; the topmost button is used for selecting \( i \)-th test to display, \( i = 1, \ldots, N_i \), while the lower part provides the switching
button for 10 curves, including channel pressure, pressure range (upper and lower bounds of pressure), set pressure, channel current, current range, set current, impedance, outlet pressure, standard pressure and oil temperature, which can be clicked to switch “Display” or “Hide.” If the button is switched to the “Display” state, the corresponding curve is immediately displayed in the channel test chart. On the contrary, if the “Hide” state is switched to, the corresponding curve will disappear from the channel test chart.

As shown in Figure 18(a), the Channel 3 test chart and voltage graph page of the 3-th test are selected in the screen, and the five control buttons for channel pressure, pressure range, set pressure, channel current, and current range are set as “Display” status, so the test pressure curve (yellow curve) and test current curve (blue curve) obtained by the 3rd test for Channel 3 solenoid will be displayed. The curves of the pressure range (dotted gray curves) are on both sides of the curve of set pressure (gray curve). The lower voltage
The graph displays the set voltage curve (gray curve) and actual voltage curve (red curve). According to the comparison and analysis of the aforesaid curves, the channel pressure curve has exceeded the upper bound of set pressure, so the solenoid test fails. According to the comparison of outlet voltage curve, the normal activated voltage is 10 V (red vertical dash line), and the activated voltage of test solenoid is about 11 V (green vertical dash line), higher than normal activated voltage.

In order to know whether the simultaneous test for multiple channel solenoids results in insufficient hydraulic pump outlet pressure, the outlet pressure curve can be added to the test chart to observe whether the curve descends obviously when multiple solenoids are actuated simultaneously, to relieve pressure. Figure 18(b) shows the screen with an additional orange outlet pressure curve, as this curve keeps fixed pressure value, with no obvious descent. Therefore, this system can stably control the outlet pressure of the hydraulic pump, which is not influenced by simultaneous actuation of multiple channel solenoids.

**Solenoid grease clean procedure**

To perform the solenoid grease cleaning operation, the control parameters can be set up on the screen, as shown in Figure 19, such as the working voltage of the power supply, working pressure of the hydraulic pump, frequency of pulse voltage, PID parameters, and working time. In addition, the user can select the channels for grease cleaning; for example, the user only sets “Channel 1” and “Channel 3” as Clean status in this screen, so the system will shake the oil sludge out of the two channel solenoids by vibration on 1000 Hz working pulse frequency; the cleaning operation time is 3 min, and the system will control the outlet pressure in the preset 16 V.

**Analysis and discussion**

**Experimental result analysis**

This study uses the solenoids of THM 4L80-E automatic transmission for an actual inspection experiment. The solenoids of THM 4L80-E automatic transmission include four models, which are 1-2 shift solenoid, 2-3 shift solenoid, pressure control solenoid (PCS) and torque converter clutch (TCC) solenoid. The first two are ON/OFF solenoids, and the last two are PWM solenoids. The solenoid test of each model follows the inspection process in Figure 8; the standard conditions are built before the repeated tests are implemented, and the repeated tests can be divided into two stages, that is, when the preliminary test (Stage 1 test) result is Fail, the solenoid grease cleaning operation must be performed before the Stage 2 test.

In order to analyze the solenoid test result, a solenoid test result classification table is defined according to whether the test pressure curve and test current curve are higher than, within, or lower than the tolerable range of error, as shown in Figure 20. The PH, PN and PL represent the test pressure curve is higher, within and lower, respectively, than its tolerable range of error. The CH, CN and CL represent the test current curve is higher, within and lower, respectively, than its tolerable range of error. The CH, CN and CL represent the test current curve is higher, within and lower, respectively, than its tolerable range of error. The CH, CN and CL represent the test current curve is higher, within and lower, respectively, than its tolerable range of error. This solenoid test uses four solenoids of each of the four models used in THM 4L80-E automatic transmission, which are installed in Channels 1~4 for the synchronous test. The test is repeated 20 times ($N_t = 20$) for each model. In terms of statistics of test results, the numbers of failures of Stage 1 and Stage 2 tests will be represented by $N_{1f}$ and $N_{2f}$, respectively; $R_{1f}$ and $R_{2f}$ represent the results of Stage 1 and Stage 2 tests, respectively ($S =$ success, $F =$ fail). Finally, $RC_1$ and $RC_2$ classify and represent the results of Stage 1 and Stage 2 tests, respectively (e.g. classification table of Figure 20).
For the ON/OFF solenoid test, $P_s = 16$ kg/cm$^2$, $T_s = 90$°C, $e_p = 0.2$ kg/cm$^2$, $\Delta t = 0.2$ s and $\alpha = 8\%$; the test result analysis tables of 1-2 shift solenoid and 2-3 shift solenoid are shown in Tables 1 and 2, respectively. According to Table 1, the 1-2 shift solenoid of Channel 1 is a normal solenoid; the solenoid of Channel 2 fails in the Stage 1 test (PH), but after the grease cleaning operation, the Stage 2 test result has become Success perhaps because the grease of the solenoid or valve seat induces poor closure and normal status is recovered after the grease removal. The solenoid of Channel 3 fails in all 20 tests of two stages (PL, CH), identified as faulty solenoid. The solenoid of Channel 4 has normal pressure test result in the two-stage test (PN), but the current test result is Fail (CL), so it is identified as a solenoid with electromagnetic structure failure. 

According to Table 2, the 2-3 shift solenoids of Channels 1 and 2 can be improved to normal solenoids by the grease cleaning operation. The solenoids of Channels 3 and 4 have electromagnetic structure failure problem (CH), and fail to be improved by grease removal operation.

For PWM solenoid test, $P_s = 16$ kg/cm$^2$, $T_s = 90$°C, $e_p = 0.2$ kg/cm$^2$, $\Delta t = 0.2$ s, $\alpha = 10\%$. In addition, the operating frequency of PWM voltage signal is defined as $F = 614$ Hz; the duty ratio $r_d$ increases from 1% to 99%, and then decreases from 99% to 1%, and each $r_d$ takes 10 signals, 10/614 s, the variation of test pressure curve $P_{ti}(t)$ and test current curve $C_{ti}(t)$ resulting from the ascending and descending of $r_d$ is reviewed.

Table 3 shows the PCS solenoid test result analysis sheet. It is observed that the solenoids of Channels 1 and 2 have an electromagnetic structure failure problem; the Channel 3 fails in Stage 1 test (PL), but the Stage 2 test result has changed into Success after grease removal operation. The Channel 4 solenoid test result is a normal solenoid. Table 4 shows the TCC solenoid test result analysis sheet; it is observed that the solenoids of Channels 1 and 3 have an electromagnetic structure failure problem (CH); the solenoids of Channels 2 and 4 fail in the Stage 1 test (PH), but succeed in Stage 2 test after the grease cleaning operation.

Discussion on the characteristics

The solenoid inspection method proposed in this article and the developed test system have the following characteristics:

1. Learning function: for an AT solenoid of unknown model, as long as the standard conditions of the solenoid model are built, the

### Table 1. 1-2 shift solenoid test result analysis sheet ($V_{so} = 9.5$ V).

| Part no. | Channel no. | $N_{f1}/N_{t}$ | $R_{1t}$ | $RC_{1}$ | $N_{f2}/N_{t}$ | $R_{2t}$ | $RC_{2}$ |
|----------|-------------|----------------|----------|----------|----------------|----------|----------|
| 5231462  | 1           | 0/20           | S        | PN, CN   |                |          |          |
| 5231463  | 2           | 4/20           | F        | PL, CN   | 0/20           | S        | PN, CN   |
| 5231476  | 3           | 20/20          | F        | PH, CH   | 20/20          | F        | PH, CH   |
| 5231478  | 4           | 8/20           | F        | PN, CL   | 3/20           | F        | PN, CL   |

S: success; F: fail.

### Table 2. 2-3 shift solenoid test result analysis sheet ($V_{so} = 10$ V).

| Part no. | Ch. # | $N_{f1}/N_{t}$ | $R_{1t}$ | $RC_{1}$ | $N_{f2}/N_{t}$ | $R_{2t}$ | $RC_{2}$ |
|----------|-------|----------------|----------|----------|----------------|----------|----------|
| 526243   | 1     | 13/20          | F        | PL, CN   | 0/20           | S        | PN, CN   |
| 526245   | 2     | 14/20          | F        | PL, CN   | 0/20           | S        | PN, CN   |
| 526252   | 3     | 10/20          | F        | PN, CH   | 10/20          | F        | PN, CH   |
| 526256   | 4     | 6/20           | F        | PH, CH   | 3/20           | F        | PL, CH   |

S: success; F: fail.

### Table 3. PCS solenoid test result analysis sheet.

| Part no. | Channel no. | $N_{f1}/N_{t}$ | $R_{1t}$ | $RC_{1}$ | $N_{f2}/N_{t}$ | $R_{2t}$ | $RC_{2}$ |
|----------|-------------|----------------|----------|----------|----------------|----------|----------|
| 521365   | 1           | 20/20          | F        | PH, CL   | 20/20          | F        | PH, CL   |
| 521368   | 2           | 20/20          | F        | PN, CH   | 20/20          | F        | PN, CH   |
| 521377   | 3           | 14/20          | F        | PL, CN   | 0/20           | S        | PN, CN   |
| 521378   | 4           | 0/20           | S        | PN, CN   |                |          |          |

PCS: pressure control solenoid; S: success; F: fail.
solenoid of the model can be tested to check whether or not its performance is normal.

2. Applicable to different voltage control types: for ON/OFF solenoid and PWM solenoid, the required voltage control curve can be defined for inspection operation.

3. Considering the potential mechanical structure failure or electromagnetic structure failure of solenoids, according to experimental results, the pressure curve abnormal (PH or PL) or current curve abnormal (CH or CL) conditions may occur. This system simultaneously performs measurement and comparison of hydraulic pressure curve and current curve; the solenoid anomaly detection capability can be greatly enhanced.

4. Cleaning function: the solenoid grease removal operation can be performed by vibration of high frequency impulse voltage to eliminate the abnormal condition of poor closure of the valve seat resulting from sediment incrustation of the solenoid oil column. According to the experimental results, many solenoids with too high pressure curve (PH) can be improved and recovered to normal solenoids after the oil sludge removal operation.

5. Multiple test channels are provided: this system can stably control the outlet pressure of hydraulic pump for performance testing and the grease cleaning operation for multiple (1 to 4) test solenoids; the inspection efficiency is increased.

6. Automatic repeated tests: as a part of AT solenoids is not completely continuously faulty, sometimes there is only one fault after several actuations; this system can automatically perform multiple rounds of repeated tests for solenoids according to the $N_f$, setting value, to detect the failure frequency in multiple tasks.

7. Test curve display function: for the test curves recorded in the repeated test process of multiple channel solenoids, the user can perform combinatory analysis of different curves with the flexible display function of system to ascertain the abnormal condition of the solenoid and diagnose the possible failure causes.

### Table 4. TCC solenoid test result analysis sheet.

| Part no. | Channel no. | $N_f/N_t$ | $R_{11}$ | $RC_1$ | $N_{f2}/N_t$ | $R_{21}$ | $RC_2$ |
|----------|-------------|-----------|----------|--------|-------------|----------|--------|
| 524163   | 1           | 6/20      | F        | PH, CH  | 3/20        | F        | PH, CH |
| 524164   | 2           | 14/20     | F        | PL, CN  | 0/20        | S        | PN, CN |
| 524168   | 3           | 20/20     | F        | PL, CH  | 20/20       | F        | PL, CH |
| 524172   | 4           | 14/20     | F        | PH, CN  | 0/20        | S        | PN, CN |

TCC: torque converter clutch; S: success; F: fail.

### Conclusion

For the problems and limitations of the present AT solenoid testers, an innovative solenoid anomaly inspection method is proposed by simultaneously considering both the possible electric structure failure and mechanical structure failure of solenoids. This method can measure the curve variation of consumed current and outlet pressure of the solenoid according to the voltage control curve to compare the test pressure curve with the standard pressure curve, and to compare the test current curve with the standard current curve; the solenoid anomaly detection capability can be greatly enhanced.

According to this solenoid anomaly inspection method, a multichannel solenoid inspection system with learning ability is developed herein. This system allows the user to test a normal solenoid of an unknown model to establish the standard conditions of the solenoid model; multiple solenoids of the same model can then be tested repeatedly. In this study, according to the proposed solenoid inspection procedure, the multichannel synchronous inspection experiment is performed for the four kinds of solenoids (two ON/OFF solenoids and two PWM solenoids) used in the GMC THM 4L80-E automatic transmission. According to the experimental results, the normal hydraulic pressure curve (PN) and abnormal current curve (CH or CL) may occur in the test. Therefore, this system is provided with measurement and comparison of the current curve; the solenoid anomaly detection capability can be greatly enhanced. In addition, the solenoids with poor valve seat closure resulting from oil column sediment incrustation (failure types are PH, CN) can be improved and recovered to normal solenoids effectively by the grease cleaning operation.

The solenoid inspection system developed in this article may be applied in solenoid fault inspection in the maintenance aspect, and applied in quality control in the manufacture aspect, which will enhance the performance of the fault maintenance and the part manufacturing of the AT.

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