A study on characteristics of vacuum solenoid valves

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Abstract. Vacuum solenoid valves have been widely used in internal combustion engine engines. They are used to regulate various processes in the car's systems by controlling actuators – for example, variable geometry of the turbocharger, exhaust gas recirculation (EGR) valves, various bypass or throttle valves. The vacuum solenoid valves are controlled by the electronic control unit (ECU) by means of a constant frequency and pulse width modulation of the controlling signal. In operation, these valves change their characteristics over time, which leads to a change in the control of the actuators, and hence to the overall operation of the engine and systems related to the environmental performance of the vehicle. Often there is no feedback on the actual value compared to the demand and their correct diagnosis is difficult. In this work an experimental study was performed, which shows dependence of pressure characteristics from possible deviations of some parameters (vacuum system, power supply) in operation of the vehicle.

1. Introduction

Internal combustion engines are one of the main air pollutants in big cities [1]. Today, strict standards have been introduced for harmful components in exhaust gases, and significant progress has been made in reducing them [2]. The emission control technologies developed in recent years are very effective in reducing the emissions of most cars, but if all elements of the engine management system work according to the characteristics set by the manufacturer [3-8]. In modern internal combustion engines additional control systems are used, such as exhaust gas recirculation (EGR), variable geometry turbine control, wastegate valves, throttle valves, charge geometry control etc. In many cases, these systems are controlled by the electronic control unit (ECU) through PWM solenoid valves, connected to pneumatic actuators using vacuum from the vehicle’s vacuum circuit, figure 1.

![Figure 1. Schematics of pneumatic actuator system for control of various engine systems (adapted from source [10]).](image)

The pneumatic actuator is connected to the controlled device by a mechanical connection and its chamber is divided into two chambers by an elastic membrane. The vacuum solenoid valve maintains
the pressure in one of the actuator chambers, which generates a force on diaphragm due to pressure difference. A spring action is used to bring the diaphragm to its initial position. The pressure in the actuator results in a force on the membrane that transfers to the connecting rod that is attached to the controlled system. The pressure in the actuator chamber $p_{\text{act}}$ is maintained by a vacuum solenoid valve between atmospheric pressure $p_2$ and the vacuum $p_1$ in the car installation and the operation of the controlled system depends on its characteristics [9].

Number of studies related to the pneumatic control of various devices in automobile engines can be found in scientific literature. In his study Mehmood [9] examined various sources that describe physical modelling of the solenoid valves. He found that in most cases its magnetic and pneumatic models are discussed separately. In his work, he presented both the magnetic and pneumatic model of the vacuum solenoid valve, defining detailed mathematical model for a variable geometry turbocharger pneumatic actuator controlled by a vacuum solenoid valve. In his work, he does not present the dependences between the fill factor of PWM and the pressure supplied by the valve, as well as the dependence of the pressure on the supply voltage. In [10] the author examined many works in which the modelling and control of pneumatic actuators are considered and found that very few authors have treated the modelling of vacuum solenoid valves. In his work, the solenoid valves were studied by conducting an experiment in which he used a frequency of 300 Hz for the control signal and the supply voltage from 10.3 to 11.9 volts.

The purpose of this study is to determine dependence of pressure characteristics from possible deviations of some parameters (vacuum system, power supply) during normal usage of the vehicle, which can be useful in diagnosis. For this purpose, a stand was made for testing the parameters of valves. To determine the operating conditions of the solenoid valves, measurements were made on some vehicles at typical driving conditions. It has been found that for this type of solenoid valves, made by Pierburg, control signal with constant frequency of 250 Hz and variable fill factor of 10 to 99% is used. The pressure maintained in the vehicle system provided by the vacuum pump of the brake system is around 50 mbar(a), and in the case of intensive frequent use of the brakes can reach up to 400 mbar(a) for a brief period of time.

2. Construction and principle of operation

The principle of operation is based on the balance of forces acting on the armature of the electromagnet – figure 2 and figure 3. The pressure supplied by the electro valve is included between the atmospheric pressure and the vacuum from the vehicle’s vacuum circuit. The force which acts under the plunger is proportional to the atmospheric pressure. Two forces act in the opposite direction – the magnetic force created by the electromagnet and the force proportional to the pressure in the actuator chamber. If the coil is not energized (figure 3a), the pressure on both sides of the diaphragm is equal to atmospheric pressure and plunger is in equilibrium. Valves 1 and 2 are closed. If there is little leakage from valve 1 or if it is not completely closed, the pressure in the actuator chamber decreases slowly. This causes the piston to move in the direction of the actuator chamber and valve 1 closes. When the coil is supplied with PWM (Pulse Width Modulation), it causes a force to be applied to the armature, proportional to the fill factor of PWM. This force causes the plunger to move in the direction of the coil and the valve 1 to open (figure 3b). At this time, the valve 2 is still closed. The air from actuator chamber passes through the open valve 1 into vacuum chamber and the pressure decreases to a new equilibrium (green line). When the PWM fill factor decreases or completely shuts off, the electromagnetic force decreases or disappears causing the piston to move in the direction of the actuator chamber and the valve 2 to open (figure 3c). The pressure in the actuator chamber increases in proportion to the fill factor of the PWM [10].
Figure 2. Construction of vacuum solenoid valve:
1 – body with electromagnet; 2 – electrical connector; 3 – connection to the atmosphere; 4 – armature; 5 – spring; 6 – valve plate; 7 – membrane; 8 – to actuator; 9 – to vacuum source.

Figure 3. Principle of operation: a) idle; b) decrease of absolute pressure; c) increase of absolute pressure.

3. Experimental set-up
To determine the static and dynamic characteristics, the following test stand has been built and used. The stand enables to be explored the set pressure at different duty cycle of PWM signal, at different voltages and at various system pressures. The stand is shown in figure 4.

Constant adjustable pressure can be maintained at the inlet of the tested valve by means of the pressure regulator, the tank and the vacuum pump. If a mechanical pressure regulator is not available, another vacuum solenoid valve can be used for this purpose. The valve outlet is connected to an actuator chamber, in our case an EGR valve. For monitoring and recording of pressures, the inlet and outlet are connected to a 2-channel absolute pressure sensor (MAP sensor). The rate at which the pressure in the actuator chamber changes depends also on its characteristics and is not investigated in this study. A stabilized power source with the possibility of changing the output voltage is used to supply the valve. The control signal with variable pulse width (PWM) can be supplied by a commercial PWM generator for manually controlling the duty cycle. Another option is with a DAC device which is capable of PWM generation. The second choice is more complicated in case of programming but provides more flexibility in case some automation or dynamic characteristics – time for reaching the set value, are needed. The control signal is fed to the tested valve through an amplifier designed to control electromagnetic devices with a built-in freewheeling diode. The values from the pressure sensors and the control signal are recorded by a digital oscilloscope.
Figure 4. Experimental test stand:
1 – vacuum pump; 2 – pressure regulator; 3 – vacuum tank; 4 – vacuum solenoid valve;
5 – actuator; 6 – laptops; 7 – DAC for control signal generation; 8 – power supply; 9 – amplifier; 10 – 2-channel absolute pressure sensor; 11 – DAQ device.

4. Results and discussions
For current study were used electro pneumatic valves, made by Pierburg (figure 4, pos.4), which are commonly used by Europeans car manufacturers. The valve is controlled by signal with constant frequency of 250 Hz and varying duty cycle. The valve starts opening at 12÷13% duty. At idle (closed) state the system is feeding the valve with 10% duty. The usable range of duty cycle is 10 to 90%.

The characteristics pressure vs duty are determined by increasing the duty cycle to 100 % and back at steps of 10%. Figure 5 and figure 6 show the change of regulated pressure $p_{act}$ at different values of the system pressure $p_i$, that's the pressure of the cars vacuum system (in the article “mbar(a)” stands for unit of absolute pressure). This change can happen in case of malfunction of the car’s vacuum system – worn vacuum pump or leak in the system. For comparison between system pressure $p_i=50$ mbar(a) and $p_i=250$ mbar(a) there is very little change in the characteristics – less than 1.8%. In the case of $p_i=450$ mbar(a) there is the same small change in the characteristics until 70% duty ($p_{act}=500$ mbar(a)), that’s 50 mbar above the system pressure. After that point the regulated pressure $p_{act}$ reaches the system pressure, value beyond which it cannot fall.
Figure 5. Regulated pressure vs duty cycle at two different system pressures: 50 mbar(a) and 250 mbar(a).

Figure 6. Regulated pressure vs duty cycle at two different system pressures: 50 mbar(a) and 450 mbar(a).

Figure 7. Regulated pressure vs duty cycle at two different supply voltages: 14 V and 12 V at system pressure 50 mbar(a).

The dependence of regulated pressure $p_{act}$ from the supply voltage to the valve is shown on figure 7 and figure 8. It can be seen a gradual, but significant decrease of actual value of pressure against demand one, the error is around –33% at 90% duty for both cases.
Figure 8. Regulated pressure vs duty cycle at two different supply voltages: 14 V and 12 V at system pressure 250 mbar(a).

Figure 9. Current through the valve vs duty cycle.

Figure 10. Current through the valve for one cycle of the control signal.

Difference of current through the coil at different system pressures is negligible. On figure 9 is shown current (rms value) for the case with system pressure $p_s = 50$ mbar(a) and supply voltage $U=14$ V. There is linear trend of the current at the range $10\%$-$100\%$ duty cycle. More detailed picture of the
current for one cycle of the control signal is shown on figure 10. The current in all cases is not falling to zero, instead is gradually decreasing.

5. Conclusion
Experimental research has been done and multi-parameter characteristics of a type of electromagnetic pneumatic valves are determined. These characteristics can help greatly in the diagnostics process of valves, due to the lack of feedback signal. It can be concluded that the system pressure doesn’t pay an important role on the regulated pressure. In case the demand value is 50 mbar(a) or more above the vacuum pump pressure, the valve will be capable to maintain the regulated pressure with error less than 2 percent. The valve is much more sensitive to the supply voltage. A difference of 2V at the valve will lead to significant error in maintaining the set value, which can reach up to –32% at 90% duty cycle of the control signal.

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