Characteristics of vacuum solenoid valves in case of various malfunctions

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Abstract. Vacuum solenoid valves are used to control actuators, in most cases connected with the emission system. In general, the diagnosis of modern cars is difficult due to the large number of elements and the fact that usually they gradually change their characteristics but remain operational. This is especially important for elements without feedback. The purpose of this research is to determine characteristics of faulty valves, which could be useful in diagnostics process. The results show change of valve characteristics at some of the most common problems during long term operation of the vehicle.

1. Introduction
Vacuum solenoid valves, also known as Electro-pneumatic pressure converters, Electric switch over valves or Boost control solenoids are used to control many systems of engines by controlling actuators - for example, variable geometry of the turbocharger, EGR valves, various bypass or throttle valves etc. [1-3].

![Diagram of actuators controlled by vacuum solenoid valves](image)

Figure 1. Most common examples of actuators, controlled by vacuum solenoid valves [3]
During the operation of the vehicle, these valves inevitably change their characteristics or are damaged, which leads to incorrect operation of the engine and ultimately to an increase in emissions of harmful components into the exhaust gases. Modern electronic engine control units (ECU) are equipped with a function for self-diagnosis and fault detection in the systems they operate. In the event of a fault in any of these systems, a trouble code is registered in ECU memory, which can be read by a diagnostic and test tools [4,5]. The car repair shops of the respective car brand have information systems and a database in which the technicians can find detailed information about the nature of the trouble code and the ways to repair the breakdown. Apart from that, there are many sites on the Internet with information about the meaning of these fault codes - for example https://www.obd-codes.com, and many others. When the nature of the fault is related to the control of an electrical circuit, a corresponding fault code is recorded in the ECU's memory which clearly directs the technician to the problem. For example, codes P0243, P0245 and P0246 which mean - “Turbo pressure regulation electro valve control - Open circuit, Short circuit to earth or Short circuit to positive “, indicates the corresponding problem in the electrical circuit of the turbocharger vacuum solenoid valve. Similar codes also exist for defective EGR vacuum solenoid valve and other engine systems [3]. There are also faults in which one or more elements of a system changes their characteristics in such a way that their electrical parameters remain within some normal limits, which prevents the registration of a fault, but the system still does not work properly. There are algorithms for detecting such faults based on the readings of the various sensors in the engine management system, but the detection of a particular element of the whole system is difficult due to the fact that the discrepancy may be due to each element of the system separately. As an example, OBD trouble code P0234 - „Turbocharger pressure signal: Pressure too high in relation to the reference value “ is stored in ECU memory when there is a difference between the turbocharging pressure reference value and the turbocharging pressure measured. Other possible trouble codes that are registered with the failure of the turbocharger vacuum solenoid valve are: P0238 - „Turbocharger pressure signal - Short circuit to positive, or open circuit“ which is recorded in case when measured value is too high and fault code P0100 - Flowmeter signal - Air flow not plausible, is recorded when there is a negative difference of 200 to 300 mg/stroke between the measured air flow and the air flow reference value. In all these cases, the ECU switches to an emergency engine control strategy and cutting of the EGR valve and EGR butterfly in all operating modes, cutting of the "exhaust heat recovery" function, limitation of engine torque and change to "Limp Home" mode [3,6,7]. The possible causes of these trouble codes according to the information systems of the authorized workshops for the given car brand can be turbocharging pressure sensor, variable geometry of the turbocharger jammed in the "maximum turbocharging" position, faulty turbocharger, vacuum problem, air flow sensor, EGR valve, electrical harness, any leak of air etc. Additional measurements and checks are required to detect the specific faulty element in the system according to the manufacturer's instructions and technical experience. Figure 2 shows a method for checking the condition of the valve provided by its manufacturer by which several of the possible faults are checked [3].

Figure 2. Test points according to the vacuum solenoid valve manufacturer [3]
There is a lot of research in the scientific literature related to the pneumatic control of various devices in automobile engines [1,2]. In most of these studies, it is either a matter of mathematical models and a detailed description of the operation of these valves or of the characteristics of new valves [8].

The purpose of this study is to determine the changes in the characteristics of vacuum solenoid valves after they have been replaced in car workshops due to a failure in the system they operate. For this purpose, several damaged valves were tested, and their characteristics were determined and compared with the characteristics of a new valve.

2. Experimental set-up
To determine the static characteristics of faulty valves, the following test stand has been used. The stand enables to be explored the set pressure at different duty cycle of PWM signal. The stand is shown on figure 3. Constant adjustable pressure can be maintained at the inlet of the tested valve by means of the vacuum pump, the pressure regulator and the tank. The valve outlet is connected to an actuator chamber. For monitoring and recording of pressures, the inlet and outlet are connected to a 2-channel MAP sensor. The control signal with variable pulse width (PWM) is supplied by a DAC device. The control signal is fed to the tested valve through an amplifier designed to control electromagnetic devices with a built-in flyback diode. The values from the pressure sensors and the control signal are recorded by a digital oscilloscope [8].

3. Results and discussions
For current study were used electro pneumatic valves, made by Pierburg (figure 3, pos.4). The tested valves have been replaced in car repair shops due to a malfunction in the system of which they are a part. The valve is controlled by signal with constant frequency of 250 Hz and varying duty cycle. The characteristics pressure vs duty are determined by increasing the duty cycle from 0% to 100 % and back in steps of 10 %. In addition to electrical and other mechanical malfunctions that are possible, the study identified the following faults in the vacuum solenoid valves (figure 4): - clogging of the air filter (pos.1), micro deformations of the valve plate (pos.2), partial rupture of the membrane (pos.3).
Figure 4. Vacuum solenoid valve construction and elements prone to cause malfunction
1 – air filter; 2 – valve plate; 3 – rubber membrane.

Figure 5. Regulated pressure vs duty cycle of new valve and used valve with clogged filter

One of the most common problems of these valves is clogging of the filter which is venting the valve to the atmosphere. On figure 5 with green colour is shown a new valve and with red a faulty valve (on this and the following graphs). The characteristic of regulated pressure vs duty cycle differs considerably from the reference one and the faulty valve is providing more vacuum in the whole range, with difference reaching up to 50 %.

Figure 6. Regulated pressure vs duty cycle of new valve and used valve after prolonged operation
On figure 6 and figure 7 are shown examples of gradual change of characteristic of the valve during prolonged operation, where the problem is micro deformations of the rubber valve plate and this leading to the valve plate (figure 4, pos. 2) not sealing well. Usually the valve is supplying more vacuum to the actuator. In one of the cases the vacuum valve has wider hysteresis than usual at high duty ratios (figure 6).

Figure 7. Regulated pressure vs duty cycle of new valve and used valve after prolonged operation (another example)

Figure 8. Regulated pressure vs duty cycle of new valve and used valve after prolonged operation with partial rupture of the rubber membrane

Figure 8 illustrates the behaviour of a pneumatic valve with a small partial rupture of the rubber membrane. Here the problems occur at upper medium and high duty ratios. It should be noted that these valves can deteriorate very fast from some point on.

Figure 9 shows the effect of a faulty power stage of the part of ECU, which is controlling the Vacuum solenoid valve. There is a flyback diode, which is allowing the current to decrease slowly when the power transistor is switched off during PWM. When this flyback diode is burned out, the tendency is to supply much less vacuum at the whole practical working range (10-90 %).
Figure 9. Regulated pressure vs duty cycle of new valve, with faulty ECU power stage (burned out diode)

Figure 10. Regulated pressure vs duty cycle of new valve and used totally inoperative valve

On the last figure is shown a valve which resistance is in the recommended tolerances by the service documentation, but mechanically is totally inoperative.

4. Conclusion
Experimental research has been done and characteristics of several faulty electromagnetic pneumatic valves are determined. These characteristics can help in the diagnostics process of valves, due to the lack of feedback signal.

From this experimental research can be concluded that:
1. As the valve ages, as well as when the venting to the atmosphere is clogged, the tendency of change is to increase the regulated vacuum.
2. Damage (puncture) to the rubber membrane leads to decrease of regulated vacuum.
3. A flyback diode is essential for correct operation of the valve. In case of malfunction in it the deviation from demand value can reach up to 80%.
4. For accurate diagnostics of this type of valves it is advised to use specialized equipment and additional testing than that proposed by OEM service recommendations.
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