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PWM-CONTROLLED HYDRAULIC SOLENOID VALVES FOR MOTOR VEHICLES

ELEKTROZAWORY HYDRAULICZNE STEROWANE SYGNAŁEM PWM STOSOWANE W POJAZDACH SAMOCHODOWYCH

JAROSŁAW GOSZCZAK[1], BARTOSZ RADZYMIŃSKI[2], ANDRZEJ WERNER[3], ZBIGNIEW PAWELSKI[4]
Lodz University of Technology

Summary

Paper presents the characteristics of two hydraulic electro-valves applied in automotive industry, produced by different manufacturers. Such electro-valves are controlled by PWM signal (Pulse With Modulation) and are used to control oil pressure in automatic gearboxes. Paper includes some basic information about PWM signal with its application. In the subsequent chapter, there will be given information about tested valves, acquired by an individual elaboration, including design and the fundamentals of operation.

In the followings sections, test bench is described and test results are presented. The temperature turned out as a very important factor which should be taken into account. In case of PWM controlling, for different temperatures some uncertainties of output pressure are possible. To avoid this undesirable phenomenon new control signal is proposed.

Different characteristics of electro-valves are included: output pressure as the function of steering signal, the value of force exerted by the slider, responsiveness to a step function of request, regulation possibilities and internal leakages. What is more, occurrence of hysteresis phenomenon is checked.

[1] Lodz University of Technology, Department of Vehicles and Fundamentals of Machine Design, ul. Żeromskiego 116, 90-924 Łódź, Poland; e-mail: jaroslaw.goszczak@p.lodz.pl

[2] Lodz University of Technology, Department of Vehicles and Fundamentals of Machine Design, ul. Żeromskiego 116, 90-924 Łódź, Poland; e-mail: bartosz.radzyminski@p.lodz.pl

[3] Lodz University of Technology, Department of Vehicles and Fundamentals of Machine Design, ul. Żeromskiego 116, 90-924 Łódź, Poland; e-mail: andrzej.werner@guest.p.lodz.pl

[4] Lodz University of Technology, Department of Vehicles and Fundamentals of Machine Design, ul. Żeromskiego 116, 90-924 Łódź, Poland; e-mail: zbigniew.pawelski@p.lodz.pl

Based on test results a number of conclusions are formulated with some practical pieces of information for the engineers of mechanical systems which contain elements controlled by PWM signal.

Keywords: PWM signal, electro-valve steering, temperature influence

Streszczenie

Artykuł niniejszy zawiera charakterystykę elektrozaworów hydraulicznych stosowanych w pojazdach samochodowych, pochodzących od dwóch producentów, których zmienną sterującą jest sygnał PWM (ang. Pulse With Modulation). Służą one do regulacji ciśnienia w obwodzie elektrohydraulicznym automatycznej skrzyni biegów pojazdów samochodowych. W artykule omówiono po krótce istotę sygnału PWM oraz jego zastosowanie. Scharakteryzowano badane elektrozawory, wraz z podaniem własnej analizy konstrukcyjnej oraz zasady ich działania. Porównano dwa różne rozwiązania zwracając uwagę na istotne, funkcjonalne różnice między nimi oraz zauważone niedoskonałości tychże rozwiązań.

W dalszej części artykułu omówiono stanowisko pomiarowe oraz wyniki badań, w których zwrócono uwagę na istotny wpływ temperatury na niejednoznaczność osiąganych ciśnień w przypadku sterowania przy pomocy sygnału PWM- zaproponowano inną zmienną sterującą, a następnie przedstawiono wyniki badań dla różnych wartości temperatury oleju.

Zawarto charakterystyki: wytwarzanego ciśnienia w funkcji sygnału sterującego, sprawdzając występowanie zjawiska histerezy, siły wywieranej przez trzpień elektrozaworu, czasu reakcji na skok jednostkowy o amplitudzie pełnego przesterowania, możliwości regulacyjnych oraz przecieków własnych elektrozaworu.

Sformułowano szereg wniosków, nasuwających się po przeprowadzeniu badań, będących praktycznymi i istotnymi wskazówkami dla konstruktorów układów mechanicznych w których zastosowanie znajdują elektrozawory sterowane sygnałem PWM lub inne elementy, których zmienną sterującą jest sygnał PWM.

Słowa kluczowe: sygnał PWM, elektrozawór sterowany sygnałem PWM, wpływ temperatury na pracę elektrozaworu

1. Introduction

Commonly used solenoid valves are split into two general types: bi-stable (fully open/fully closed) or continually opened/closed (capable to take any arbitrary position between the two extremes). To realize that latter type of control, the valve must be supplied with electric current of continually variable intensity. The Pulse Width Modulation (PWM) technique has become a common solution.

Referring to Fig.1, amplitude U1 and frequency (1/T) of the PWM control signal is constant, while its duty factor T_{on}/T is varied; see [2] for more basic facts about the PWM technique. The technique is commonly applied in automotive industry [3] and to control electric engines [1, 9, 10]. There are many variants in use [4] since search for better methods aimed to minimize energy losses and/or to better utilize microcontroller memory [5, 6] is still going on.

Signal frequencies are large enough to yield a practically infinitely variable control; the frequencies may reach even several MHz [8]. Figure 1 shows a single period in the PWM signal.

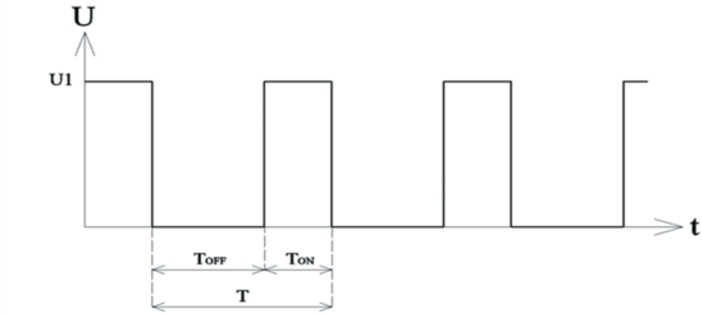

Fig.1. PWM control signal with period T, the period Ton when the signal is high (load is supplied), and the period T off when the signal is low [12]

Duty cycle is by definition the (percentage) fraction of time the signal remains high:

$$K_w = \frac{T_{ON}}{T} \cdot 100\% \tag{1}$$

Images of the two analysed solenoid valves of the smoothly adjusted types are shown in Figs. 2 and 3. Each solenoid encircles its stem. Magnetic field produced by PWM-signal currents flowing through the solenoid forces the stem out, pushing the valve hydraulic slider. Depending on its position, the slider connects various chambers of the valve hydraulic manifold.

Valve shown in Fig. 2 will be hereafter referred to as Solution (Device) I, while valve shown in Fig. 3 – as Solution (Device) II. The former is a general application device rated to operate at PWM frequency = 300 Hz. The latter valve was manufactured by a different manufacturer as a N/H device; that designation will be explained in a further part of this paper.

Both types are supplied from 12 VDC as devices commonly applied in motor vehicles.

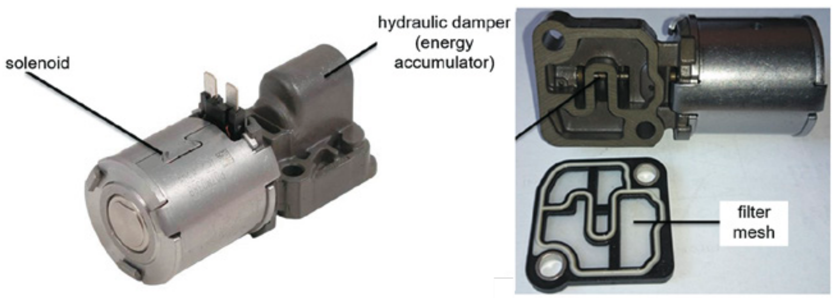

Fig. 2. Valve referred to as Device I [14]

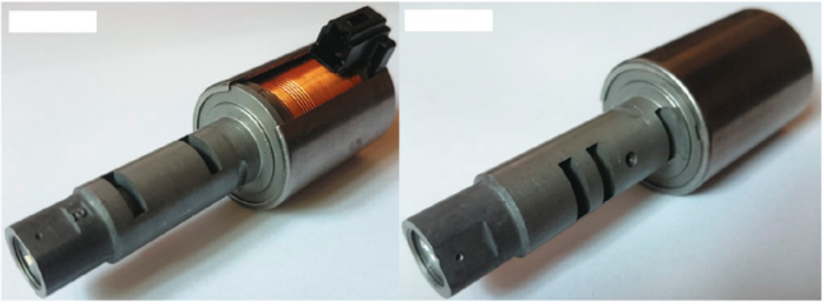

Fig. 3. Valve referred to as Device II. Top view (left), bottom view (right)

2. Principle of operation of solenoid valves

Solenoid valve function is to adjust pressure of oil at its output in line with instantaneous value of the PWM control signal applied to its solenoid. PWM signal current intensity translates directly into electromagnetic force that pushes the solenoid stem out.

The stem moves the slider of the hydraulic manifold, as shown in Fig. 4. The figure shows a very simple design sketched by authors of this paper to make solenoid valve principle of operation as clear as possible. The figure helps also to identify differences introduced in a more complicated design of the device referred to in this paper as Device II (Fig. 5) and in a much more sophisticated construction of the device referred to as Device I (Fig. 6).

In design depicted in Fig. 4, the moving valve slider can connect output pressure p_c chamber either with oil supplied at a high supply pressure p_s (to increase p_c) or with pressure bleed X to the atmosphere (to drop p_c). That way the valve may smoothly adjust p_c all the way from the atmospheric pressure to the supply pressure. The stem moving force comes from any unbalance between magnetic forces exerted by the solenoid and feedback forces proportional to the p_c value and the difference of the slider active areas at both sides of the p_c chamber.

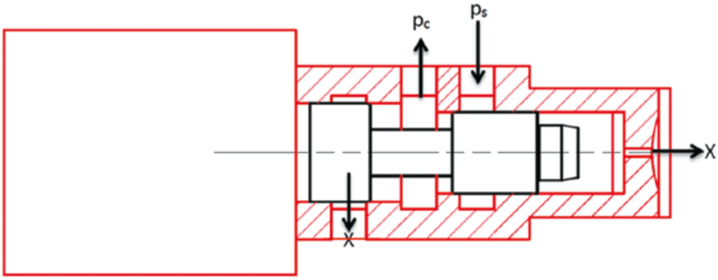

Fig. 4. Diagram showing the structure of solenoid valve, which is sufficient to perform the required functions

Slider in Fig. 4 is shown in the neutral position: output pressure p_c neither increases nor drops. Forces exerted by the electromagnet (transmitted by the stem on the slider), and the resultant force, which is the result of the pressure p_c on these two surfaces of the piston, are balanced.

If there is an increase in the force from the electromagnet, the channel to pressure p_s opens. Lesser force exerted on the solenoid opens the channel to oil bleed, until the forces return to balance, which causes the channel to cut off. On the other hand, Figure 5 shows a diagram of the solenoid valve specified as the Device II.

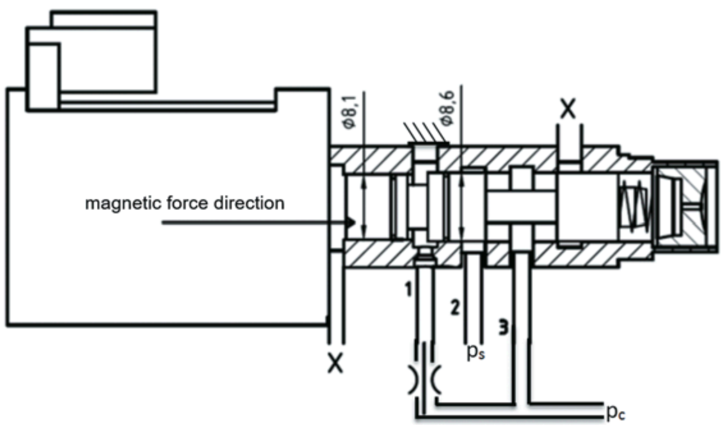

Fig.5. A diagram of the solenoid valve referred to as Device II

Spring load acting on the valve slider in this construction to the left is balanced with two forces pushing to the right: magnetic force and feedback exerted by output pressure p_c acting on two opposite circular surfaces of the slider, Ø8.6 mm and Ø8.1 mm. Slider in Fig. 5 is shown in the neutral position.

Since movements of the Device II slider are very small, spring load is practically constant. The increase in the force exerted by the electromagnet, which is a function of the desired PWM signal (specifically, the current passing through the solenoid) and in temperature, pushes the slider right and opens the vent and thus reduces the pressure p_c. A new equilibrium point is established at the increased desired value of PWM signal and reduced pressure. It means that output pressure is normally high (without applying PWM signal and therefore, the current to the solenoid), which is shown by N/H (Normal High) designation on the case. This solenoid valve is rated for supply pressure up to 20 bar, therefore the output pressures p_c may be take any value from atmospheric pressure up to 20 bar (at PWM signal equal to 0%) minus losses in internal channels of the valve itself. That particular valve type is offered also in the N/L (Normal Low) version [13].

Construction of the device referred to as Device I shown in Fig. 6 is much more sophisticated, although the slider is like above driven by a combination of the stem-transmitted magnetic force and output pressure p_c feedback net force. Areas on which the pc pressure develops respective forces are given by maximum slider diameter (Ø7 mm) in chamber F, and slider diameter reduced to Ø4.68 mm in chamber A (0.172 cm^2). Solenoid stem is not mechanically connected with the valve slider; synchronized movement of both these parts is guaranteed by a spring inside the solenoid that keeps the stem sticking to the slider. The output pc pressure is worked out in chamber C, while chambers A, E and F provide feedback force.

In neutral position oil does not flow between the p_s supply chamber D and chamber E (p_c), nor between bleed B and chamber C (p_c). That way the p_c pressure does not change. However, any movement of the slider to the right (larger that the dead zone) will open a passage between chambers D and E and will increase the p_c pressure. The same is true of the opposite movement direction: any movement of the slider to the left will open a passage between chamber C and bleed B and will decrease the pc pressure. The slider moves in reaction to a changed PWM control signal.

The stem extension capabilities are mechanically limited and in the tested copy of the valve it was observed that the slider/stem combination did not move strictly together. As a result, slider position was not clear-cut defined at all times. A residue pc pressure of about 0.5 bar was observed for that reason, in absence of any PWM control signal.

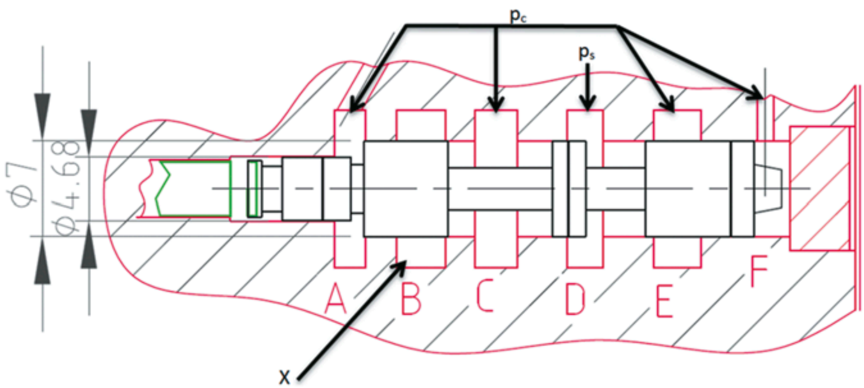

Fig. 6. Relative position of slider and the cylinder of the valve referred to as the Device I

Other shortcomings of the discussed solution were also identified during the tests: the valve is prone to oscillations. Most probably the manufacturer was aware of that tendency and that's why energy accumulator visible in Fig. 2 (comprising a cylinder, a piston, and a spring) was introduced. The output pressure p_c acting on the bottom surface of the piston compresses the spring. The accumulator task is to slow down pc pressure changes, that way to stabilize operation of the valve.

Diameter of the piston inside energy accumulator and rigidity of its spring was measured. Knowing the degree to which the spring was compressed in its extreme positions (mechanical constraints) we were able to characterise the accumulator, see Fig. 7. Accumulator does not influence any valve dynamic properties if pressure is outside the accumulator operating range of 0.36 – 4.95 bar.

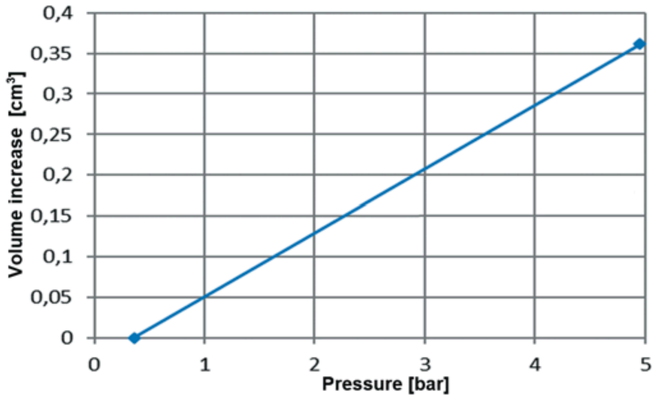

Fig. 7. Characteristic of the energy accumulator integrated into Device I

The accumulator did not fully prevent the valve against generation of oscillations in some conditions. Time dependency of signals from pressure transducers installed at the valve supply port p_s (red line) and at the valve output port p_c (yellow line) is shown in Fig. 8. The PWM signal was constant.

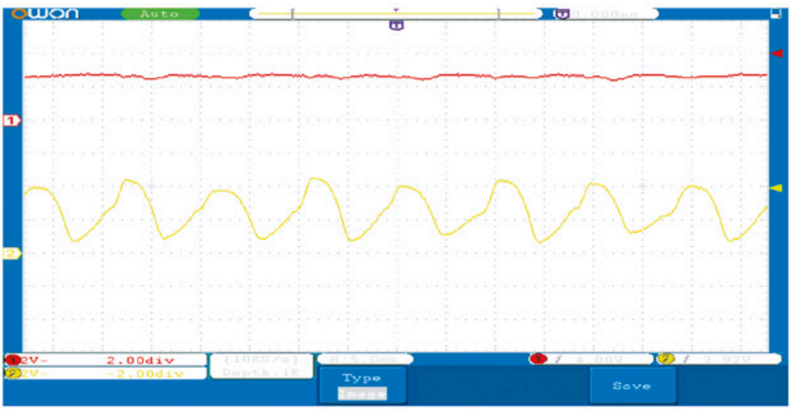

Fig. 8. Oscilloscope screen revealing Device I tendency to generate oscillations

3. Test bench

Fig. 9 shows a schematic diagram of the test bench. Displacement pump of a constant unit volume supplied the tested solenoid valves, via a feeder block, with oil at delivery rate Q_s, temperature t, and pressure p_s. The valve produced output pressure p_c depending on the PWM control signal.

Internal leakages from the tested valve – i.e. amount of oil that was coming outside the valve in its neutral position when no oil delivery was intended – were measured. The leakages are caused mainly by play between the valve slider and cylindrical surfaces. They depend mainly on oil temperature and output oil pressure.

Adjustment valve at the p_c pressure port simulates consumption of oil by loads supplied by the valve. Output oil delivery rate may be measured by supply line delivery rate Q_s meter if internal leakages are taken into account. Main oil tank was equipped with an integrated oil heating system.

Intensity of the current in PWM signal supplied from the generator to the tested valve was measured. Signals produced by delivery rate meter, pressure transducer and temperature transducer were logged.

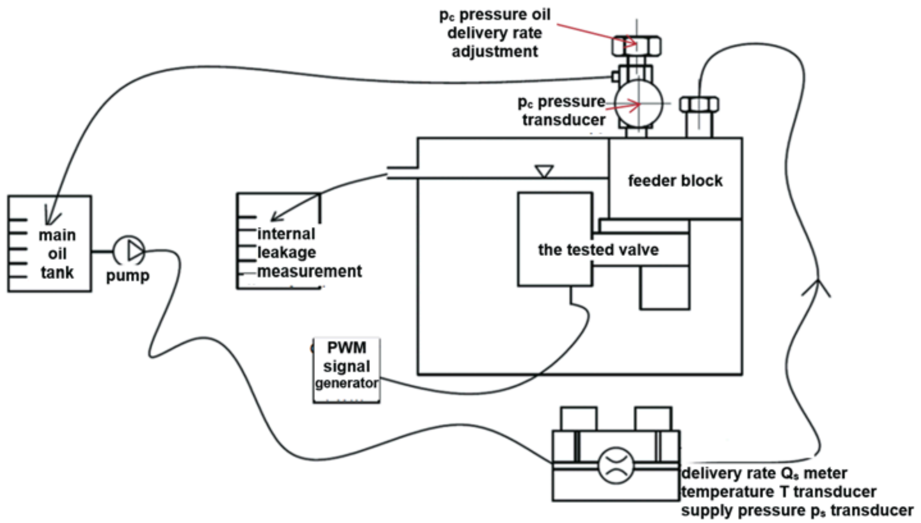

Fig. 9. Test bench schematic diagram

4. Measurement results

4.1. Output pressure p_c vs. PWM control signal

Output pressure p_c produced by Device I for two temperatures is charted vs. PWM control signal in Fig. 10. Device supply pressure p_s was 15 bar. The points measured when the signal was increased did not precisely agree with points measured when the signal was decreased, however, the differences were quite small. Generally, it can be said that no hysteresis was observed. Similar results were obtained for Device II.

However, the differences observed at various temperatures were significant. Magnetic force exerted by the solenoid is proportional to mean intensity of the current flowing through it, rather than directly to the PWM signal value. The current depends on solenoid coil resistance, which varies with coil temperature. 4.7 Ω coil resistance was measured at 18ºC, while 6.3 Ω at 90ºC. It is worth mentioning that the coil temperature is not identical to the oil temperature, since the current flowing through the coil may heat it up even up to 90ºC.

Results of similar measurements made on Device II are shown in Fig. 11. Here also the temperature makes a clear difference. 5.2 Ω coil resistance was measured at 20ºC, while 7.2 Ω at 110ºC, i.e. at the temperature to which the coil heats up at PWM signal equal to 100%, when no cooling oil was flowing through the valve.

The above results show that the mean current flowing through the solenoid coil is by all means a better control signal than the PWM voltage signal. Control based on mean coil current would be temperature-independent. Output pressure pc produced by Device I is charted vs. mean current (arithmetic mean of current values throughout the averaging period) in Fig. 12.

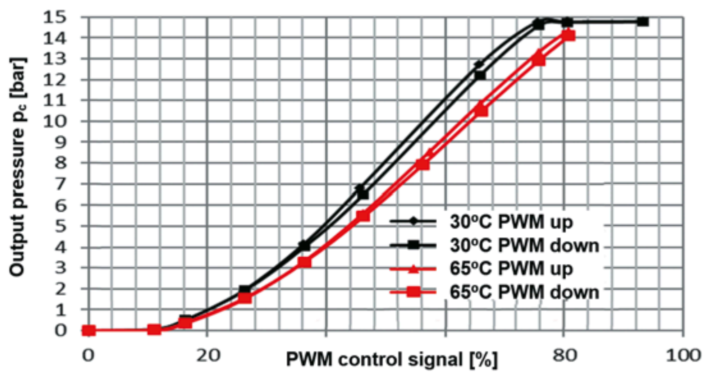

Fig. 10. Output pressure p_c produced by Device I vs. PWM control signal for various temperatures

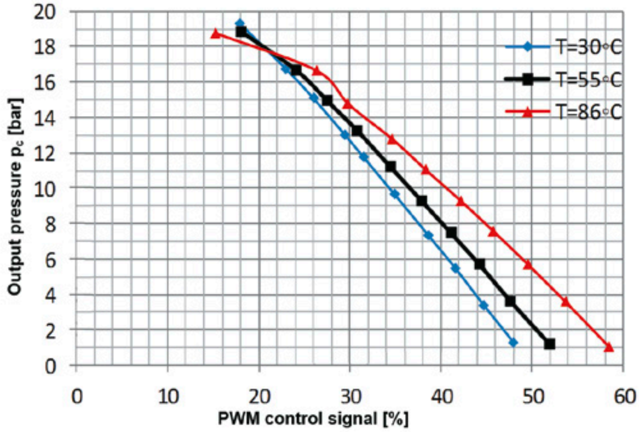

Fig. 11. Output pressure pc produced by Device II vs. PWM control signal measured for various temperatures

4.2. Output pressure p_c vs. mean coil current

As can be seen in Fig. 12, if plotted vs. mean coil current on the abscissa, data for various temperatures overlap. Selection of the mean coil current rather than the PWM control signal as the independent variable takes care of not only temperature deviations, but also of any possible changes resulting from possible variations in valve solenoid power supply voltage.

This can also be confirmed by data shown in Fig. 13: solenoid magnetic force does not depend on temperature, but in the first place on the coil mean current.

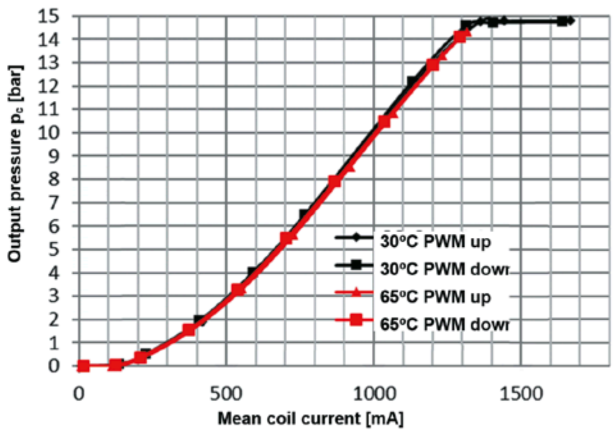

Fig. 12. Data from Fig. 10 plotted vs. mean coil current for various temperatures

4.3. Magnetic forces

Tests were conducted to find magnetic force exerted by Device I solenoid. They were carried out at two temperatures, about 25°C and 65°C. Results are plotted in Fig. 13. An interesting observation is the fact that temperature has no effect on the force generated by the coil, when the mean current is operated, instead of PWM signal – there is no perceivable change of inductivity of the coil.

It is worth to point out that the dependency is far from linear, particularly for low current values (duty). It should be remembered that solenoids not only have resistance, but also reactance. This parameter is responsible for a large fraction of transients in relation to low duty factor signals at low mean currents (PWM signal) and the deviations from linearity. However, solenoid valve driven actuator or coupling is often equipped with some return spring; to move the actuator/coupling from rest, the pc pressure must exceed a threshold substantially higher than zero. In such circumstances the shape of the dependency for near-zero values is irrelevant.

Exactly for that reason – a spring built into the valve – no similar dependency from linearity was observed for low values of the PWM control signal for Device II, see Fig. 11.

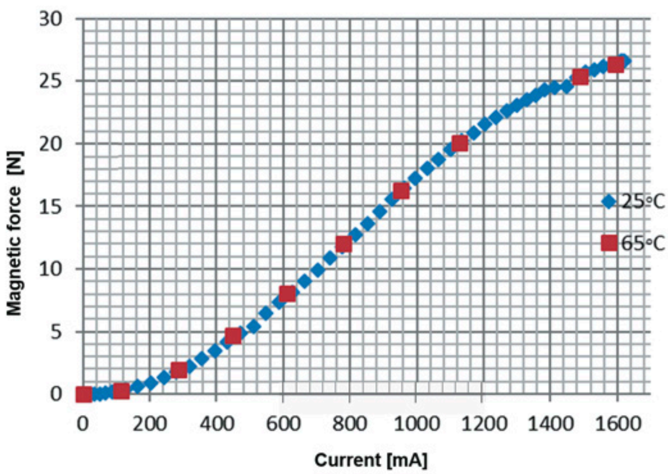

Fig. 13. Device I solenoid magnetic force measured for various temperatures and plotted vs. mean coil current

4.4. Solenoid valve reaction time

The study included valve dynamic properties tests. Response to a step-like function applied to Device I is shown in Fig.14; a zoomed fragment of the response is shown at the bottom. PWM signal [%] and pressure p_c [bar] are shown on the left vertical axis, coil mean current [A] is shown on the right vertical (auxiliary) axis. Time in seconds is shown on the horizontal axis.

The used PWM generator allowed step-like change of the control signal as soon as by the next PWM signal period, i.e. after 0.003(3) s, when the PWM signal frequency was 300 Hz. The first break in the PWM(t) curve corresponds to start of the step. In its later portion, the PWM curve resembled an exponential curve because the applied analogue transducer, by necessity integrated the step-like signal. As can be seen in the diagram, the solenoid valve response (p_c pressure) occurred faster than changes in the PWM control signal, which is not a real effect. Similar lag may be observed in the coil mean current, a signal also integrated with a time constant of about 1s.

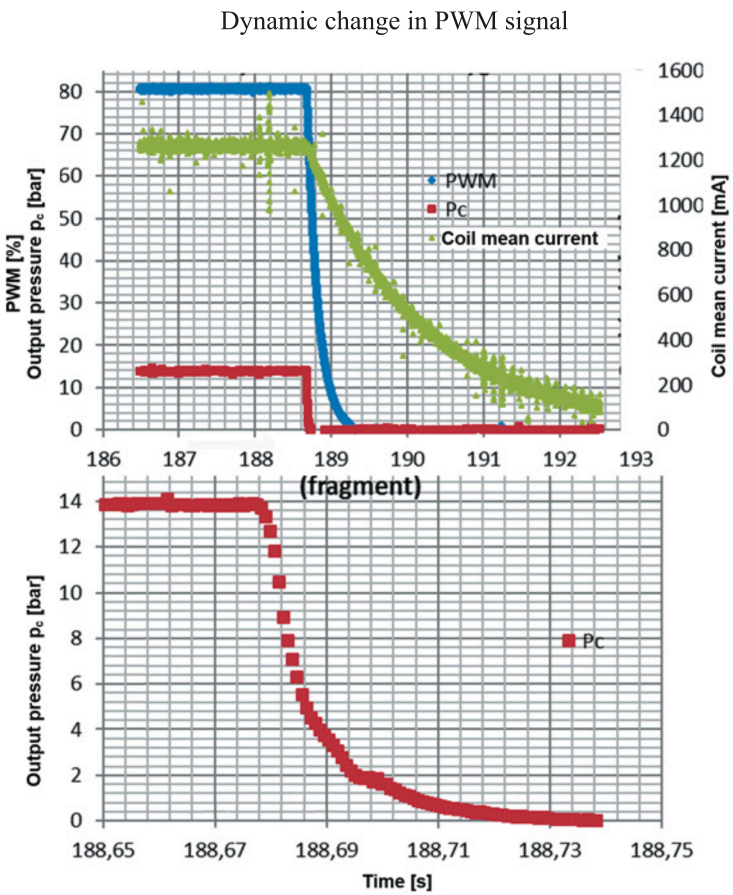

Fig. 14. Diagrams presenting dramatic changes of control signal in solenoid valve, referred to as Device I

4.5. Leaks in the valve

Fig. 15 shows results of measurements of leakage in Device I supplied with pressure p_s=15 bar and producing output pressure p_c=0. Each plotted point represents an average of a few measurement results. As was expected, leakages strongly grow with increasing oil temperature because of declining oil viscosity.

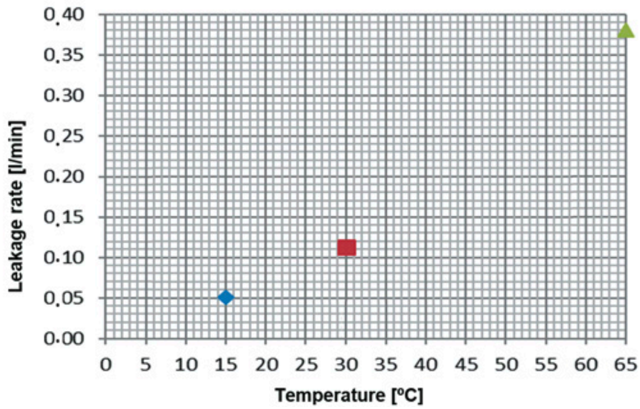

Fig. 15. Device I leakage rate vs. temperature

4.6. Linearity range of the solenoid valve

Valve output pressure p_c vs. oil delivery rate measured for Device I supplied by pressure p_s=15 bar is plotted in Fig. 16. Output pressure p_c was set for 8 bar, then oil delivery rate was gradually increased and p_c was measured. Another measurement run was made for initial p_c=12 bar. All points measured in the 8 bar run are located along a straight line. Slope of that line is given by solenoid valve spring coefficient: to open more the oil supply channel, the spring must be more loaded at the expense of the output pressure. The last point measured in the 12 bar run deviates from the straight line, which reflects a limited valve linearity range at that output pressure: when oil supply channel is entirely open, valve is not able to supply more oil. From that moment on, oil delivery rate depends on resistance of flow throughout the valve.

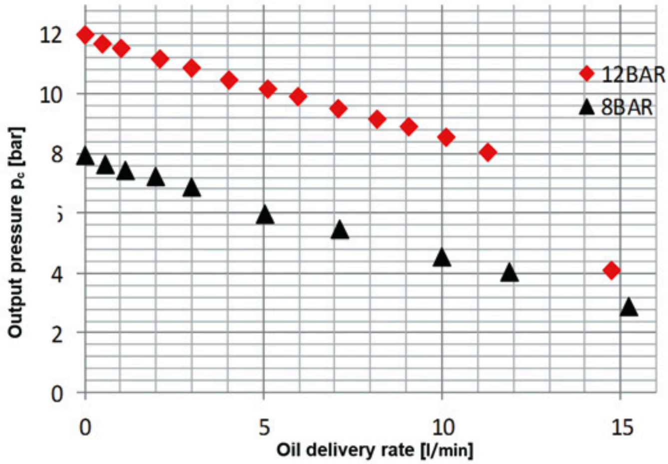

Fig. 16. Device I output pressure p_c vs. oil delivery rate for two initial output pressures, p_c=8 bar and p_c=12 bar. Supply pressure p_s = 15 bar

4.7. Other observations and comments

The performed tests/analyses of solenoid valves produced by two different manufacturers have given rise to some doubts in respect to the construction of the valve referred to as Device I. It seems that the spring in that valve should be transferred from the solenoid stem at the left of the slider to the right of the slider. Such spring would guarantee a permanent stem/slider contact. If no such spring is present, a situation in which the stem is withdrawn, while the slider is not, becomes possible. Stem/slider contact may be broken, since the only reason for it to move left is the feedback pressure force in chamber F (see Fig. 6). When PWM signal (and the output pressure p_c) was decreased very slowly, at some point the residue pressure was not sufficient to move the slider further. A spring placed to the right of the slider would push it all the way to the left, that way guaranteeing a permanent contact of the slider with the solenoid stem.

5. Conclusions

The performed tests/analyses of solenoid valves produced by two different manufacturers allowed to propose a modification of construction of the valve referred to as Device I. The modification consists in introducing a spring that would guarantee a permanent contact of the slider with the solenoid stem, and thus guarantee an unambiguous position of the slider in each case.

Universal physical laws allow to formulate the following recommendations concerning operation of all solenoid valves of the type referred to as Device I:

- Precision of the control at different temperatures would benefit if mean coil current was the control signal rather than the PWM signal. Even if oil temperature is kept constant, coil heats up under the influence of the current flowing through it, and coil resistance changes.
- An insignificantly short reset time (from the point of view of automotive industry typical applications) may be ignored for valves of the tested type.
- Solenoid valve internal leakages significantly depend on oil temperature, and their level can by no means be disregarded.

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