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ACCURACY AND DURABILITY INCREASING OF THE BODY LEVEL CONTROL SYSTEMS IN THE IMMOBILE STATE OF THE VEHICLE

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Abstract

Pneumatic suspension is increasingly used in many cars. Control of a car body level is the main function of the pneumatic suspension. The experimental determination of the pneumatic spring characteristics suitable for the design and modeling of the car level control system is presented. The characteristics of the pneumatic spring are determined, that determine the quality of the control system. The effect of temperature changes inside the pneumatic spring is experimentally determined due to heat exchange on air pressure and vertical force during alignment of the car body. In addition, through modeling is evaluated by changing the level of the car body due to the impact of heat transfer. An original method of controlling the lifting and lowering of the vehicle body is proposed. The method is based on the energy balance and is the basis for reducing the number of strokes of the electropneumatic valve. The change in the level of the body due to the temperature effect is leveled due to the indirect consideration of this effect using the pressure sensor in the cylinder.

Keywords: pneumatic spring, vehicle body level control, influence of compressed air temperature.

List of Symbols/Acronyms

PI, PD and PID – proportional-integral, proportional-differential and proportional-integral-differential regulators, respectively;
H – the current position of the body [m];
h – target position of the body [m];
δn – half the width of the dead zone [m];
EK1 and EK2 – inlet and outlet solenoid control valves, respectively;
$S_a(H)$ – effective area of the pneumatic spring [m^2];
$[V(H)]$ – the volume of the pneumatic spring shell [m^3];
m – the weight of the body falling on the pneumatic spring [kg];
g – free fall acceleration [m/s^2];
$p_s(H)$ – pressure dependence on the position of the body in the open volume of the shell under static load [Pa];
$p_b(p_{st})$ – dependence of the pressure in the closed volume of the shell on the pressure under static load [Pa];
n – polytropy index;
b – damping coefficient of the shock absorber [N·s/m];
T_0 – air temperature in the pneumatic spring at the time of opening of the electromagnetic valve [K];
P_0 – air pressure in the pneumatic spring before opening the solenoid valve [Pa];
k – adiabatic exponent.

1. INTRODUCTION

Controlling the suspension of a motor vehicle allows you to solve many problems [1-3]. The basic functions for trucks and buses are considered to be tilting or lowering the bus body during boarding of passengers [4-5], changing the height of the body to overcome difficult sections of route [6], axle load control with undesirable load weight distribution [6], maintaining a constant level of the body when moving and unloading the vehicle [6], managing shock absorber characteristics to increase stability [6]. Controlling the suspension is a multifaceted task that involves different goals and approaches to control in the appropriate movement mode of the motor vehicle. The purpose of the work is to improve the process of changing the height of the vehicle body when it is stopped for boarding passengers or unloading cargo. The challenge of this fairly simple process is to ensure the accuracy of the positioning of the vehicle body [7] and maintaining a sense of comfort for passengers. The use of a classic three-position regulator with a small dead zone causes the electro-pneumatic valves [7] to operate excessively, which causes discomfort to passengers and shortens the service life of the electro-pneumatic valves. Using PI, PD, or PID regulators requires storing information about their coefficients in a

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manufacturer's database for each vehicle [7], which is inconvenient and expensive for the manufacturer and the consumer as well. The creation of a control system that would not have the indicated shortcomings requires taking into account the parameters of the pneumatic circuit of the suspension, the parameters of the motor vehicle, and the mechanical and thermodynamic properties of the pneumatic elastic element. Among the characteristics of pneumatic elements, two types can be distinguished [8 – 10]:

- characteristics of an elastic element as a closed volume;
- characterization of the elastic element as a volume connected through an open control valve to the receiver.

Such characteristics can be found in the manufacturers of pneumatic cylinders, but unfortunately, the manufacturers cite a single characteristic without taking into account its change due to hysteresis phenomena in the elastic shell of the pneumatic element. An additional source of disturbance during body leveling is the change in air temperature inside the elastic pneumatic element [11]. As a result of temperature changes, the pressure and level of the vehicle body [12] changes.

2. STUDY OF THE PNEUMATIC SPRING CHARACTERISTICS

The study of the characteristics of the pneumatic spring was carried out on the load stand (Fig. 1a). The given stand allows you to maintain the given position of the height of the pneumatic spring and to change the height with the help of an electromechanical drive located on top of the stand. A pneumatic spring [13] is installed on a scale with a load sensor ZEMIC H2F-C3-3t-3T6 [13] (Fig. 1.b, c). Inside the pneumatic spring, the pressure was measured using a tube that prevents the influence of dynamic factors on the measurement results (Fig. 1c). Pressure sensor based on Freescale Semiconductor MPX5999D [15] sensor. To simulate the operation of a motor vehicle suspension, the characteristic of the pneumatic spring as a closed cylinder is usually used. It represents a set of curves given at different pressures in the cylinder or active load at a static position of the body. The curves forming the characteristic are polytropes [10]. Such a characteristic is suitable for modeling the smoothness of the movement of a motor vehicle or determining the active dynamic loads on the suspension elements during movement. The process of lifting and lowering the body occurs with a different configuration of the pneumatic circuit of the suspension. In this mode, the electromagnetic pressure control valve in the pneumatic cylinder is open and the volume of the cylinder is connected through pipelines to the receivers. Thus, during the adjustment of the body height and after the adjustment process, the pneumatic circuit acquires a different configuration. It is the characteristic of the pneumatic spring as a volume connected through the open control valve to the receiver that is necessary to simulate the process of controlling the level of the vehicle body.

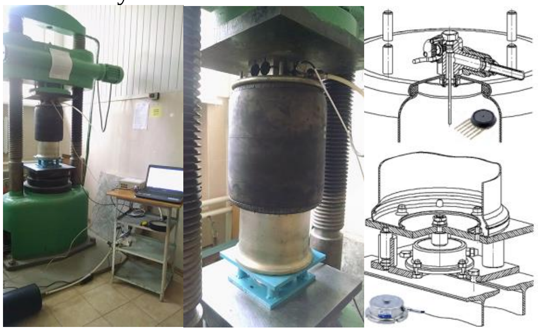
a b c

Fig. 1. Stand and components for determining the characteristics of a pneumatic spring

Usually, manufacturers of pneumatic springs cite characteristic of the cylinder as a closed volume [9]. Another characteristic is also sometimes given in the technical documentation [8], but it is averaged and does not take into account changes in the parameters of the pneumatic spring due to hysteresis phenomena in its shell.

To use classical methods of research of pneumatic devices [16-21], it is necessary to know the dependence of the effective area of the pneumatic spring on its height $S_e = f(H_{ps})$ and the volume on the height $V_{ps} = f(H_{ps})$. These functions make it possible to determine the pressure inside the pneumatic spring and the vertical force acting on the vehicle body. Both functions must take into account the hysteresis of the pneumatic spring shell. Obtaining the corresponding function was carried out by gradually filling and emptying the shell of the pneumatic spring at a fixed height of the pneumatic spring. Also, during the process of filling and emptying, video recording was carried out to digitize the shape of the shell and determine the volume of the pneumatic spring as the pressure changes. On the basis of the process of monotonous increase and decrease of pressure in the pneumatic spring (Fig. 2), the surface of the load dependence on the pneumatic spring on the pressure and its height was obtained (Fig. 3). A similar surface was constructed for both the intake process and the pneumatic spring release process. On the basis of these surfaces, surfaces reflecting the change in the effective area of the pneumatic spring when it is filled and emptied are built, according to each process (Fig. 4).

Another characteristic of the pneumatic spring is the heat exchange with the surrounding environment during the processes of air intake and air release due to fluctuations in the temperature of the air inside the shell. When it works with a closed volume, during the movement of the motor vehicle, fluctuations of both the pressure and the temperature of the air inside the shell occur due to the vibrations of the body. When the car stops, the oscillations stop and

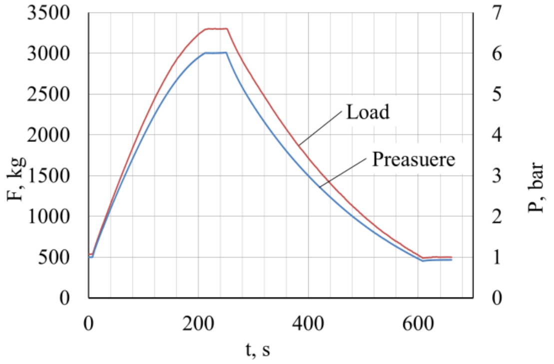

Fig. 2. Oscillogram of the working process of the pneumatic spring

the air parameters return to their initial state, in the absence of air loss due to system leaks. Some studies indicate a shift in the neutral position of the body in dynamics as a result of heat exchange and asymmetry of the shock absorbers characteristic. In the process of controlling the level of the vehicle body, the system is not closed, and after the end of the influence of the control electric valves, the processes of the system equilibration of the pneumatic body suspension system, from the point of view of load and temperature as well, take place. During the experimental study, the influence of air temperature was monitored by indirect signs, such as the change in pressure and load after closing the control valve (Fig. 5).

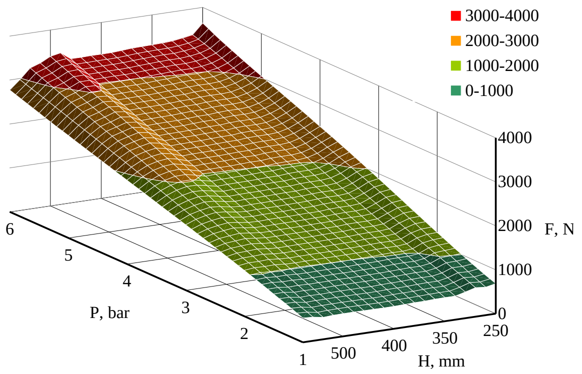

Fig. 3. The load surface of the pneumatic spring

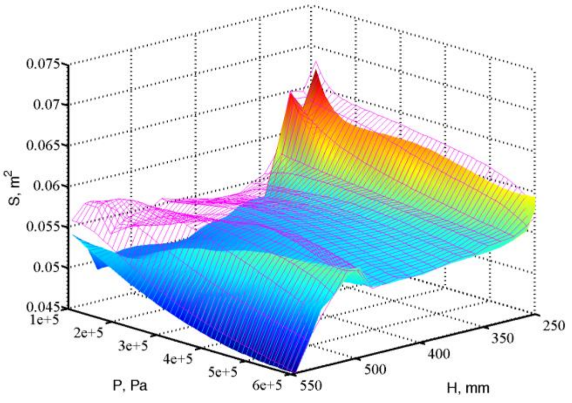

Fig. 4. Three-dimensional dependence of the effective area in the coordinates of the pneumatic spring height and air pressure

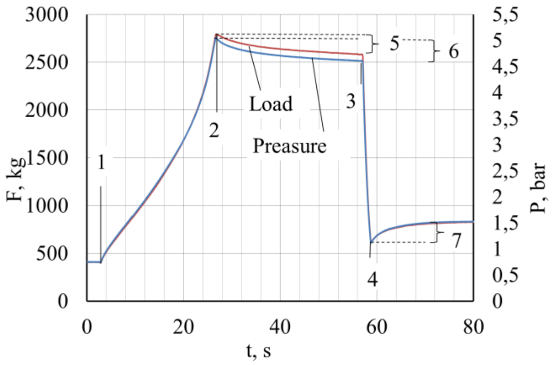

Fig. 5. The oscillogram of the working process of a pneumatic spring with an illustration of the influence of compressed air temperature

Figure 5 shows the processes of pressure and load changes during the control of valves for air intake and release in the shell of the pneumatic spring at a constant height. Accordingly, the moments of the beginning and end of air intake to the shell of the pneumatic spring are marked (points 1 and 2, Fig. 5). The beginning and end moments of air release from the pneumatic spring shell are also marked (points 3 and 4, Fig. 5). Sections 5 and 6 (Fig. 5) reflect the change in load and pressure, respectively, due to the change in temperature after closing the inlet control valve. Similarly, section 7 corresponds to the change in pressure and load with a change in temperature after closing the outlet control valve.

The forced change in the height of the pneumatic spring (Fig. 6) is also accompanied by a change in pressure and load with the subsequent change of these parameters after the fixation of the height of the pneumatic spring due to a change in temperature inside. The obtained data were used to verify the heat transfer coefficient in the mathematical model. Figure 6 shows the processes of pressure and load changes during the control of valves for air intake and release into the shell of the pneumatic spring at a constant height. Accordingly, the moments of the beginning and end of air release from the shell of the pneumatic spring are marked (points 1 and 2, Fig. 6). The moments of the beginning and end of air intake to the shell of the pneumatic spring are also marked (points 3 and 4, Fig. 6). Sections 5 and 6 (Fig. 6) reflect the change in pressure and load due to the change in temperature after closing the outlet control valve. Similarly, sections 7 and 8 correspond to the change in pressure and load when the temperature changes after closing the inlet control valve. Reproduction of this process by means of mathematical modeling made it possible to identify the heat transfer coefficient of the balloon elements α=5 degrees/s. The corresponding process of pressure change during mathematical modeling is superimposed on the experimental data (Fig. 6).

The error in the simulation of the working process does not exceed 3.3% for pressure and 2.1% for load.

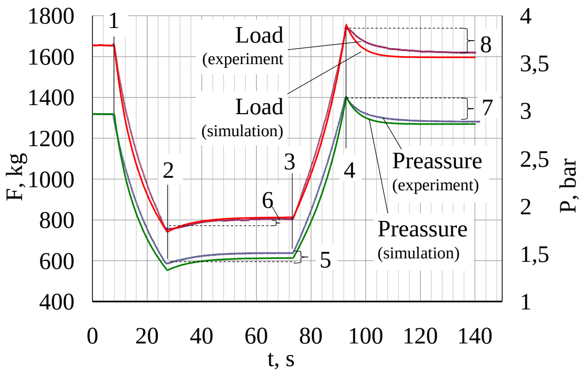

Fig. 6. Verification of the pneumatic spring model

3. THE METHOD OF CONTROLLING THE LEVEL OF THE VEHICLE BODY

Based on the characteristics of the pneumatic spring, we will propose three principles for controlling the level of the vehicle body to achieve comfort, positioning accuracy, as well as to minimize the loss of compressed air and the number of strokes of the electro-pneumatic control valve core.

Comfort when changing the body level is achieved by limiting the derivative acceleration of the body (jerk). This parameter is not regulated by the rules, but the need to limit it should ensure the smoothness of transition processes and prevent a negative impact on the well-being of passengers. For example, for high-speed elevators, the comfort jerk value less than 1.0 m/s^3, and according to research a jerk less than 0.2 m/s3 does not cause a person to feel acceleration or deceleration [22-25]. If the pneumatic part of the suspension control system provides significant dynamics of changing the position of the body, it becomes necessary to limit the dynamics of gas-dynamic processes in the drive. This is usually achieved by switching the state of the electropneumatic valves, scilicet by abidancing the conditions of the system (1).

$$\begin{cases} EK1 = 0V \ \forall \ \frac{d^3H}{dt^3} > 0{,}6m/s^3 \\ EK2 = 0V \ \forall \ \frac{d^3H}{dt^3} < -0{,}6m/s^3 \\ \mathrm{EK1} = 24\mathrm{V} \ \forall \ H < h \\ \mathrm{EK2} = 24\mathrm{V} \ \forall \ H > h \end{cases} \tag{1}$$

To determine the method of ensuring positioning accuracy, consider the process of adjusting the position of the body in the coordinates of the function P=f(H), which corresponds to the dependence of the pressure in the shell of the pneumatic spring on the height of the vehicle body. The zero value of the body height will correspond to the transport position of the body. At the start of the body level control process, the electro-pneumatic control valve opens and the body mass does not change any further. If the characteristic from Figure 3 is expressed in the form of pressure, it will become clear that with an open volume, namely, with the control solenoid valve open, the pressure in the shell of the pneumatic spring will correspond pressure curve under constant load on the pneumatic spring (Fig. 7).

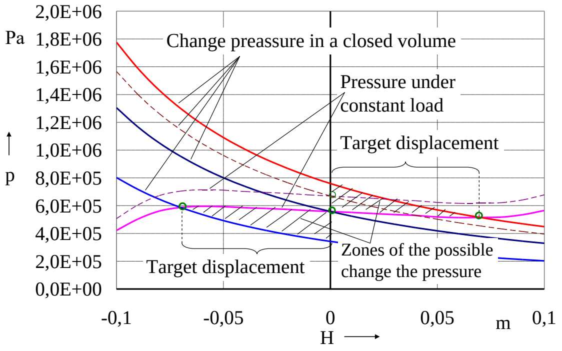

Fig. 7. Determination of zones of permissible pressure change during control of the vehicle body level

At the end of the process of changing the level of the body, when it has taken the target position, the control solenoid valve is closed, that is, the shell of the air spring becomes a closed system. In this case, the pressure will change according to polytrope (Fig. 7). From Figure 7, it becomes clear that in order to accurately position the body in the target position, it is necessary that the ratio of the pressure in the shell of the pneumatic spring and the height of the body satisfies the condition of being in the zone of possible change the pressure (Fig. 7). Mathematically, these limits can be described based on the value of the effective area of the pneumatic spring (Fig. 4) and its volume by expressions (2) and (3).

$$p_s(H) = \frac{F_s}{S_a(H)} = \frac{m \cdot g}{S_a(H)} \tag{2}$$

$$p_b(p_{st}) = \frac{m \cdot g}{S_a(H)} \cdot \frac{[V(H_t)]^n}{[V(H)]^n} \tag{3}$$

To make it clearer, let's present the working processes in the specified coordinates when adjusting the height of the body level under the condition of late closing of the electropneumatic valve (Fig. 8).

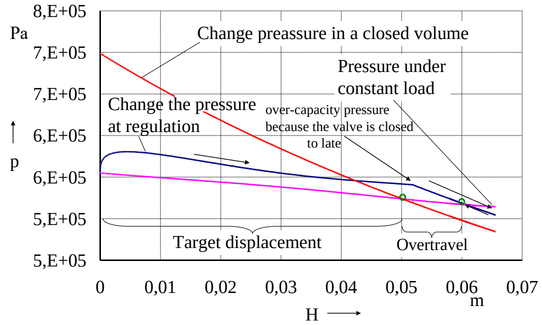

Fig. 8. Illustration of the working process of controlling the level of the vehicle body when over-adjusting the pressure

We present the working process of controlling the floor level with timely closing of the electromagnetic control valve, as well (Fig. 9).

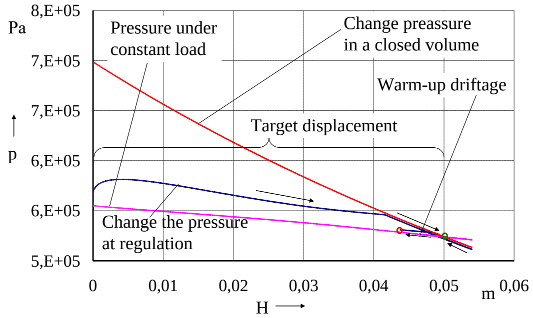

Fig. 9. Illustration of vehicle body level control and the effect of temperature change on target level accuracy

As can be seen in Figures 8 and 9, in both cases there is a fluctuation around the value of the target level due to the properties of the components of the oscillating suspension system, as well as the mass of the body. A positive feature of this regulation is the possibility of a one-time opening of the electropneumatic control valve.

It is possible to eliminate over-adjustment by using a method based on the balance of the kinetic energy of the body and the work that remains to be done by the air spring to reach the target level. Equation (4) shows the mathematical notation of the balance, and system (5) shows the operation of the controller based on the balance of energy and work.

$$\frac{m\cdot\left(\frac{dH}{dt}\right)^2}{2} = b\cdot\frac{dH}{dt}\cdot\frac{(h-H)}{2} \tag{4}$$

The graphic interpretation of the method (Fig. 10) of determining the moment of turning off the electropneumatic control valve clearly demonstrates how the process parameters change. Namely, the kinetic energy of the body during the process of its lifting and the work that must be done to lift the body from the current position to the target level. As you can see, at the end of the lift, the body accelerates enough to perform the work of lifting it to the target level due to inertia. This moment is marked as "balance point" (Fig. 10).

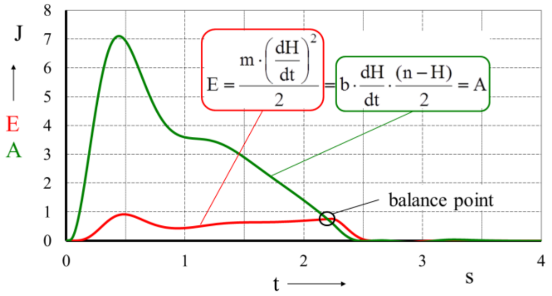

Fig. 10. Illustration of the principle of balancing the operation of the pneumatic spring and the kinetic energy of the vehicle body

$$\begin{cases} EK1 = 0V \ \forall \ \frac{m\cdot\left(\frac{dH}{dt}\right)^2}{2} > b\cdot\frac{dH}{dt}\cdot\frac{(h-H)}{2} \\ EK2 = 0V \ \forall \ \frac{m\cdot\left(\frac{dH}{dt}\right)^2}{2} < b\cdot\frac{dH}{dt}\cdot(h-H) \\ \mathrm{EK1} = 24\mathrm{V} \ \forall \ H < h \\ \mathrm{EK2} = 24\mathrm{V} \ \forall \ H > h \end{cases} \tag{5}$$

The closing moment of the electromagnetic control valve calculated by this method makes it possible to control the system by opening the valve once. It should be especially noted that there is no dead zone with this adjustment, which guarantees stable operation of the body level control system. The working process of the level controlling of the vehicle body when using the energy and work balance method is shown in Figure 11.

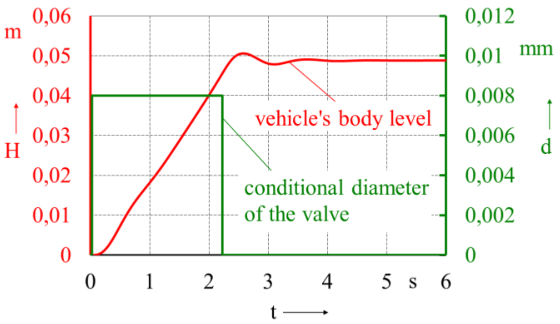

Fig. 11. The working process of setting the target level of the vehicle body with one control action on the solenoid valve

As you can see, the level of the body during lifting does not exceed the target value (in this case, 0.05 m), and the steady value of the level after the end of control corresponds to Figure 12.

In almost the entire range of target levels, we have an error within 1-2 mm below the target body level. Apparently, this error is caused by a change in pressure in the pneumatic spring due to a change in air temperature after closing the solenoid valve. Let’s determine the additional time for air intake to compensate for temperature changes in the pneumatic spring. To do this, we will use the equality of the ratio of the polytropic process parameters.

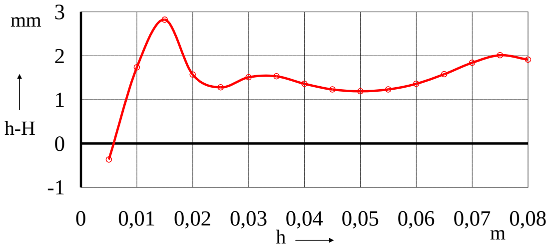

Fig. 12. The accuracy of setting the target level of the motor vehicle body by the regulator according to system (5)

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{n-1} \tag{6}$$

Let's express the ratio of volumes

$$\frac{V_1}{V_2} = \frac{V_2-\Delta V}{V_2} = 1-\frac{\Delta V}{V_2} \tag{7}$$

Taking into account that$\Delta V \propto \Delta H > \Delta V = \Delta H\cdot f(H)$. In this way, it is possible to write the dependence of the change in the height of the cylinder upon the change in the temperature of the compressed air in the pneumatic spring in the form of equation (8).

$$\Delta H_T = \left(1 - \sqrt[n-1]{\frac{T_2}{T_1}}\right) \cdot \Delta H \cdot f(H) \tag{8}$$

Thus, system (5) will look as follows

$$\begin{cases} EK1 = 0V \ \forall \ \frac{m\cdot\left(\frac{dH}{dt}\right)^2}{2} > b \cdot \frac{dH}{dt} \cdot \frac{(h+\Delta H_T - H)}{2} \\ EK2 = 0V \ \forall \ \frac{m\cdot\left(\frac{dH}{dt}\right)^2}{2} < b \cdot \frac{dH}{dt} \cdot (h + \Delta H_T - H) \\ \mathrm{EK1} = 24\mathrm{V} \ \forall \ H < h \\ \mathrm{EK2} = 24\mathrm{V} \ \forall \ H > h \end{cases} \tag{9}$$

Adding compensating height to the target level provides a pre-adjustment to reach the target level in a steady state when the body is lifting. Accordingly, when lowering the body level, the value ΔH_T will be negative.

As can be seen from equation (8), to implement the idea of compensation height, it is necessary to know the polytropy index, T_2 andT_1. With a certain error, the polytropic exponent can be replaced by the adiabatic exponent. Temperature T_2 is the current temperature of the cylinder wall. It is this temperature that will be set in the pneumatic spring in a stable mode. Therefore, it can be determined by the direct method of measuring with a temperature sensor, because the temperature of the shell of the pneumatic spring changes slowly enough. Difficulties arise when determining the temperatureT_1.

In real conditions, the determination of the current air temperature in the pneumatic spring will lead to an error related to the inertia of the temperature sensor. For an indirect definition, you can use the known dependence of the ratio of the parameters of a polytropic or, as we propose for simplification, an adiabatic process.

$$\frac{T_1}{T_0} = \left(\frac{P_1}{P_0}\right)^{\frac{k-1}{k}} \tag{10}$$

Thus, the current temperature in the middle of the pneumatic spring can be determined by dependence (11)

$$T_1 = T_0 \cdot \left(\frac{P_1}{P_0}\right)^{\frac{k-1}{k}} \tag{11}$$

Positioning accuracy for all three regulators determined by systems (1), (5) and (9) can be seen in Figure 13.

It should also be noted that the regulator operating according to system (1) provides the specified accuracy when five control pulses are applied to the solenoid valve. This is due to the need to ensure the specified value of the third derivative of H. Also, stable operation of this regulator is ensured with an insensitivity zone equal to 6 mm. When the insensitivity zone is reduced, the controller becomes unstable. Regulators built according to systems (5) and (9) provide the given characteristics with just one control effect on the solenoid valve, which will significantly increase the service life of the solenoid valve. Also, the last two regulators do not have a zone of insensitivity, so they are not prone to unstable operation.

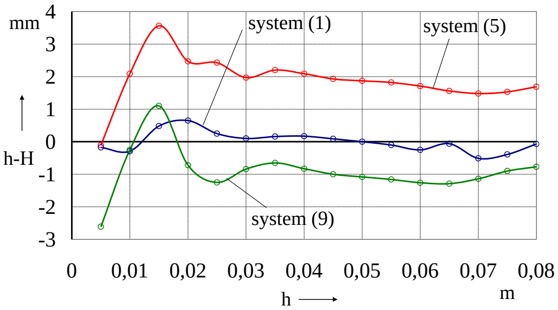

Fig. 13. Comparison of the accuracy of setting the level of the motor vehicle body by the considered regulators

4. CONCLUSIONS

The field of the loading characteristic of the pneumatic spring for both filling and emptying was experimentally determined. This made it possible to determine the three-dimensional surface by calculation, which characterizes the change of the effective area in the coordinates of the pneumatic spring height and the pressure in the middle. It was determined that for a surface area in the range from 2e5 to 6e5 Pa and from 320mm to 460mm, the absolute deviation of the effective area does not exceed 0.00145 m^2

The working process of controlling the level of the motor vehicle body in a stationary state is analyzed. Permissible pressure limits for reaching the target level are defined. The effect of temperature on the process of setting the target body level is shown.

A regulator based on the balance of the work of the pneumatic spring on the kinetic energy of the vehicle body is proposed. The peculiarity of the regulator is the absence of an insensitivity zone and the ability to perform regulation with one control effect on the electropneumatic valve. To increase the accuracy of the mentioned regulator, a compensatory component was additionally introduced, which takes into account the effect of temperature changes in the middle of the pneumatic spring.

In addition, an indirect method of determining the current air temperature in the middle of the pneumatic spring during pressure control is proposed.

According to the simulation results of the working process of controlling the vehicle body level, the proposed controller provided a positioning error of no more than 1.1 mm (excluding the target level of 0.005 m).

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Declaration of competing interest: *The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.*

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