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On the issue of using expenditure functions in simulation of pneumatic links of the "throttle - capacity" type

Leontiev D.[1], Savchenko Ye[1], Harmash A.[1], Suhomlyn O[1], Sinelnik D.[1]

[1]Kharkiv National Automobile and Highway University, Ukraine

Abstract. Problem. *When studying the work processes that occur in pneumatic or electropneumatic circuit of brake systems or pneumatic suspension systems of a wheeled vehicle, researchers use various expenditure functions on the basis of which they draw scientific conclusions and obtain scientific results, while they do not think about the fact that the functions are credible or not. The choice of the expenditure function, for researchers, is an actual scientific task, which should have a scientific justification and should not have a formalized nature.* ***Goal.*** *The aim of the study is to compare the expenditure functions to determine the nature of their influence on the dynamic processes that occur during filling or emptying links of the pneumatic circuit.* ***Methodology.*** *The approaches adopted in the work to solving the set goal are based on the analysis of the results of simulation modeling of work processes in pneumatic circuit.* ***Results.*** *A comparison of the research results obtained in this work with each other and with the results obtained in experimental studies, allowed us to establish the peculiarities of the course of work processes in the pneumatic circuit links when using different expenditure functions. It was established that, depending on the choice of the expenditure function, with the same initial conditions of simulation modeling, the results of the study can differ by up to 40%.* ***Originality.*** *The use of a universal basis of simulation modeling, based on various expenditure functions, enabled to establish that it is possible to propose new functions that better describe the working process in a pneumatic circuit than the known ones.* ***Practical value.*** *The obtained results can be recommended in the practice of simulation modeling of work processes in pneumatic or electropneumatic circuits of brake systems and systems of pneumatic suspension of wheeled vehicles.*

Key words: *expenditure function, flow function, pneumatic circuit, brake system, pneumatic suspension system.*

Introduction

The growth of the computing power of modern computer technology and the development of applied mathematical apparatus allows processing large arrays of data, creating and researching complex mathematical models, and as a result, allows reducing the number of assumptions during calculations and minimizes the error between theoretical and experimental data. This prompts a review of well-known, well-researched and previously formulated mathematical equations describing the process of movement of the working body (air) in nodes of the "throttle - capacity" type of pneumatic circuits from the point of the possibility of their use in mathematical simulation models of electropneumatic pressure control devices.

Analysis of publications

When determining the dynamic parameters of the pneumatic nodes of the brake circuit or the pneumatic suspension of a wheeled vehicle (WV) based on the same mathematical model by the authors of well-known works [1–8] use expenditure functions that differ from each other, but allow to describe with appropriate accuracy the nature of the pressure change in the drive during its filling or emptying.

It is known that the method of calculation with concentrated parameters is widely used for modeling the dynamics of filling or emptying of the node "throttle-capacity" type of pneumatic circuits [8–10]. This method is based on the statement that the movement of air in the cavities of the "throttle-capacitor" nodes is constant, and the basis of the transient process of their filling or emptying is the law of conservation of energy for thermodynamic processes.

On the basis of this law, to determine the nature of the pressure change, for example, in the node "throttle-capacity" with a change in volume of the pneumatic circuit (Fig. 1 a, d), during its filling or emptying, an equation of the form (1) can be used, if the flow function is used (2), written in universal form [7,9].

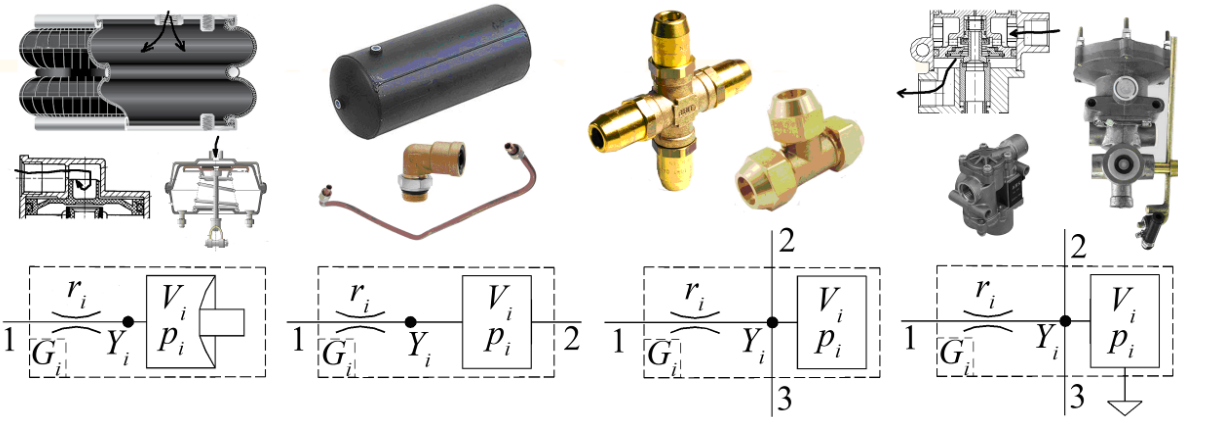


Fig. 1. Schematic designation of typical nodes of circuit elements of the pneumatic brake circuit or pneumatic suspension of a wheeled vehicle: a – non-passable node "throttle-capacity" type; b – pass-through node "throttle-capacity" type; c – pass-through node "throttle-capacity" type with several outputs; d – a through node "throttle-capacity" type with the possibility of releasing the working body into the atmosphere [9]

$$\frac{dp_i}{dt} = \frac{k \cdot R \cdot T_{i-1} \cdot \left(G_i - \sum_{j=1}^{m} G_{i+j} \right) - k \cdot \min\left(p_i; p_{i-1}\right) \cdot \frac{dV_i}{dt}}{V_i}, \tag{1}$$

$$\pm G_i = \frac{sign\left(p_i - p_{i-1}\right) \cdot \max\left(p_i; p_{i-1}\right) \cdot f \cdot \sqrt{k}}{\sqrt{R \cdot T_{i-1}}} \cdot \varphi(\sigma). \tag{2}$$

Analogously to equation (1), equation (3) can be written for constant-volume nodes with one or more outlet openings (Fig. 1 b, c) [7,9].

$$\frac{dp_i}{dt} = \frac{k \cdot R \cdot T_{i-1} \cdot \left(G_i - \sum_{j=1}^{m} G_{i+j} \right)}{V_i}. \tag{3}$$

The following notations are used in equations (1) - (3): i – index of the node "throttle-capacity" type in which the pressure is determined ($i \geq 1$); k =1.4 – adiabatic index; R = 287.14 J/(kg·K) – specific gas constant; p_i – absolute pressure after the throttle, Pa; p_{i-1} – absolute pressure in front of the node type throttle, Pa; T_{i-1} – air temperature in the node "throttle-capacity" type of the circuit in front of the throttle, K; V_i – the variable volume of the node "throttle-capacity" type of the circuit into which the air flows, m^3, m – the number of exit holes in the passing the node "throttle-capacity" type of the circuit (see Fig. 1 b, c or d). At $m = 0$ the value $G_{i+j} = 0$.

As the analysis of works [2,3,5,9] showed, the flow function $\pm G_i$ depends on the mass flow of air (expenditure function) $\varphi(\sigma)$, due to the pneumatic resistance of the node "throttle-capacity" type, which in turn [1,3] depends on the ratio of the minimum with of two pressures behind and before the throttle to the maximum pressure behind or before the throttle according to equation (4) [7,9].

$$\sigma = \frac{\min\left(p_i; p_{i-1}\right)}{\max\left(p_i; p_{i-1}\right)} \tag{4}$$

It is known from works [2,3,9] that due to the complexity of mathematical calculation of thermodynamic processes in pneumatic devices, most researchers use simplified expenditure functions $\varphi(\sigma)$, which forces them, during the simulation of the air flow through the pneumatic resistance, to use the correcting coefficient of flow μ, which is determined experimentally for the corresponding node "throttle-capacity" type of the pneumatic actuator separately [3] and is not convenient during the simulation of complex pneumatic actuators. On the other hand, there are also expenditure functions [1–4,8,9] without a corrective coefficient of flow, but they have not become widespread because they are based on the polytropy index (*n*), which depends on the temperature change in the node "throttle-capacity" type of the circuit.

Purpose and Tasks

The purpose of the study is to compare the expenditure functions to determine the nature of their influence on the dynamic processes that occur during filling or emptying of the node "throttle-capacity" type of pneumatic actuator.

To achieve the goal, the following tasks must be solved:

– to isolate the common component from the equation of the flow function, so that it is possible to unify the flow functions of different authors and perform a comparative analysis of the nature of the pressure change in the node "throttle-capacity" type under the same initial modeling conditions;

– to unify the flow functions proposed by various authors, to perform a comparative analysis of their impact on dynamic processes in the circuit nodes during their filling or emptying;

– perform a simulated simulation of the dynamics of compressed air movement in the node "throttle-capacity" type of the pneumatic brake circuit and the circuit node of the pneumatic suspension under the same initial conditions but with different expenditure functions;

- perform a comparative analysis of the results of simulation modeling among themselves and compare the obtained results with experimental studies of a typical node of the brake circuit and a typical node of the pneumatic suspension circuit;

- to make recommendations regarding the use of appropriate expenditure functions during the simulation of the node "throttle-capacity" type of the pneumatic circuit.

Analysis of expenditure function determination methods used in pneumatic circuit modeling

The analysis of scientific and technical literature [1–4] showed that equations for determining the expenditure function can be based on isochoric, adiabatic, isothermal and polytropic processes. Since the calculation of the polytropy index depends on many factors and is quite resource-intensive, most authors simplify their equations, assuming that the compressed air movement process is adiabatic or isothermal, although in fact the real compressed air movement process in the node "throttle-capacity" type of pneumatic circuit is polytropic in nature.

To determine the mass flow of air in the case of a heat-insulated (adiabatic) process of its flow through the node "throttle-capacity" type of a pneumatic circuit, in most scientific works, the Saint-Venant and Wanzel function is used [1]. The expenditure function φ(σ) for the subcritical flow regime ($\sigma > \sigma_c = 0.528$) and the supercritical regime ($\sigma \le \sigma_c = 0.528$) after the unification adopted in this work will have the form

$$\varphi(\sigma)=\mu\cdot\begin{cases}\sqrt{\dfrac{2}{k-1}\cdot\left(\sigma^{\frac{2}{k}}-\sigma^{\frac{k+1}{k}}\right)}, \text{ at } \sigma_c<\sigma<1,\\ \left(\dfrac{2}{k+1}\right)^{\frac{1}{k-1}}\cdot\sqrt{\dfrac{2}{k+1}}, \quad \text{at } 0<\sigma\le\sigma_c\end{cases} \qquad (5)$$

For practical application, the authors of the work [2] consider it possible to use a simpler expression for determining the mass flow of air through the pneumatic resistance of the node "throttle-capacity" type of the circuit in the form (6), also after the unification adopted in this work.

$$\varphi(\sigma)=\mu\cdot\begin{cases}\sqrt{\dfrac{2}{k}\cdot\sigma\cdot(1-\sigma)}, & \text{at } \sigma_c<\sigma<1,\\ \sqrt{\dfrac{1}{2\cdot k}}, & \text{at } 0<\sigma\le\sigma_c.\end{cases} \qquad (6)$$

However, such an entry also requires the mandatory presence of two flow regimes (supercritical when $\sigma \le \sigma_c$ and subcritical when $\sigma > \sigma_c$), which does not simplify the mathematical model and the calculation procedure, but on the contrary, complicates it, since the number of equations in the pneumatic circuit model increases in geometric progression depending on the increase in the number of the node "throttle-capacity" type that make up the circuit.

It is known that the critical mode of air flow in real valves, pneumatic devices, and pipelines is reached at values of σ that are much smaller than σ_c, or not reached at all, therefore, some authors attempted to describe the nature of the air flow in the node "throttle-capacity" type with a single expenditure function. One of the first such functions was proposed in [3,8] based on experimental studies of air flow through tubes with a diameter of 3 to 20 mm and a length of up to 30 m. After the unification adopted in this work, the function of the author of the work [8] will have the form:

$$\varphi(\sigma)=\mu\cdot\sigma_c\cdot\sqrt{1-\left(\frac{\sigma-\sigma_c}{1-\sigma_c}\right)^2}\,. \qquad (7)$$

This approach gradually gained recognition during the last decade and was adopted as the basis of the method laid down in the regulatory document [10], which allows the calculation of cost characteristics in the chains of systems that use a compressed working body (air).

However, the author himself in work [8] believes that the use of function (7) does not simplify the process of modeling the flow of compressed air in the node "throttle-capacity" type, since before modeling it will be necessary to determine the correcting coefficient of flow μ experimentally for each specific pneumatic resistance of the node "throttle-capacity" type.

The condition for the critical ratio of pressures can also not be fulfilled if we use the equation (8), which was proposed by the authors of the work [2], while it is necessary to calculate, in addition to the correcting coefficient of flow μ, also the resistance coefficient ζ of the node "throttle-capacity" type [11]. After the unification adopted in this work, the expenditure function of the authors of the work [2] will take the form (8).

$$\varphi(\sigma)=\frac{\mu}{\sigma_c}\cdot\sqrt{\frac{1-\sigma^2}{2\cdot k\cdot(\zeta-\ln\sigma)}}\,, \qquad (8)$$

where ζ is the resistance coefficient of the node "throttle-capacity" type [11].

Similar in structure to equation (8), equation (9) was proposed in work [12], which in this work, taking into account unification, has the form (9).

$$\varphi(\sigma)=\frac{\mu}{\sigma_c}\cdot\sqrt{\frac{1-\sigma^{\frac{2}{k}}}{2\cdot(k\cdot\zeta-\ln\sigma)}}\,. \qquad (9)$$

Analyzing the calculation process by function (8), the author of the work [3] claims that this function does not have an analytical solution, and therefore cannot be used during practical calculations of real nodes of the brake circuit of a wheeled vehicle. This prompted the author of work [3] to propose in work [4] a hyperbolic expenditure function (10), which, in his opinion, sufficiently allows determining the mass flow of air both in the simplest and in complex multi-circuit pneumatic circuits. In a unified form, the function can be written as:

$$\varphi(\sigma)=\mu\cdot A\cdot\frac{1-\sigma}{B-\sigma}\,, \qquad (10)$$

where A and B are constant coefficients that determine the shift of the horizontal and vertical asymptotes of the hyperbola and are related by the following equation [4]:

$$A=\frac{h}{B-1}=B\cdot\varphi_{\max}(\sigma)\,, \qquad (11)$$

where h is the value characterizing the shape of the hyperbola.

The average values of coefficients A and B, as the analysis of the literature [3] showed, can be taken as equal: A = 0.654, B = 1.13. These coefficients are obtained as a result of statistical processing of experimental data based on 194 tests of the node "throttle-capacity" type of the brake circuit with various parameters.

It is obvious that the proposed function (10) has a simpler notation than the functions (5) - (9) and does not require taking into account air flow modes and determining the resistance coefficient (ζ) of the node "throttle-capacity" type. Such equation requires only the determination of the correcting coefficient of flow (μ), so it found the most common use during calculations of the brake circuit of wheeled vehicles [5,6,9,12–18].

On the other hand, in the scientific and technical literature [1–3,8,9,18] the equation (12) and (13) are known, which, in contrast to the previously given cost functions, do not require the determination of even the correcting coefficient of flow (μ), but such equation have not become widespread because they do not have an analytical solution:

$$\varphi(\sigma)=\sigma_c\sqrt{\frac{2}{k-1}\cdot\left(\sigma^{a_1}-\sigma^{a_2}\right)}\,, \qquad (12)$$

where a_1, a_2 are exponents of the expenditure function (12), which can be determined by the corresponding equations [5,9,19]:

$$a_1=\frac{2\cdot\min\left(p_i;p_{i-1}\right)}{\min\left(p_i;p_{i-1}\right)+p_a\cdot(k\frac{T_{i-1}}{T_a}-1)}\,;$$

$$a_2=\frac{2\cdot\min\left(p_i;p_{i-1}\right)+p_a\cdot(k\frac{T_{i-1}}{T_a}-1)}{\min\left(p_i;p_{i-1}\right)+p_a\cdot(k\frac{T_{i-1}}{T_a}-1)}\,.$$

The expenditure function obtained for the polytropic process, in the case of its use in equation (2), has the form:

$$\varphi(\sigma)=\sqrt{\frac{2}{k-1}\cdot\left(\sigma^{\frac{2}{n}}-\sigma^{\frac{n+1}{n}}\right)}. \qquad (13)$$

With the development of modern software, for example, MATLAB, mathematical models based on differential equations do not require an analytical solution, therefore obtaining modeling results using functions (12) and (13) is limited only by the philosophy of determining the components of these equations. In this work, we will compare the results of modeling the expenditure function (12) with the expenditure functions (5) - (10), which are most often cited in scientific works during the study of dynamic processes in the pneumatic circuit of brakes or pneumatic suspension systems.

Initial data and typical elements of a pneumatic circuit

Before modeling the dynamics of filling and/or emptying of a pneumatic circuit (be it brakes or suspension of a wheeled vehicle), it is necessary to determine the initial data of the typical elements of the circuit, the working process of which is simulated. For the convenience of recording the output data for circuit simulation, we will use the tabular form of their presentation (Table 1 and Table 2).

In Table 1 shows the initial data of several typical nodes of the brake circuit: the dimensions of the circuit tubes, the dimensions of the branches, the dimensions of the brake chambers [20].

In Table 2, according to a similar principle, we present the output data of several typical nodes of the pneumatic circuit of the suspension: the dimensions of the circuit tubes, the dimensions of the branches, the dimensions of the pneumatic balloon [21].

The order of arrangement of the nodes "throttle-capacity" type in the table corresponds to the scheme of the pneumatic actuator kennel shown in Figure 2.

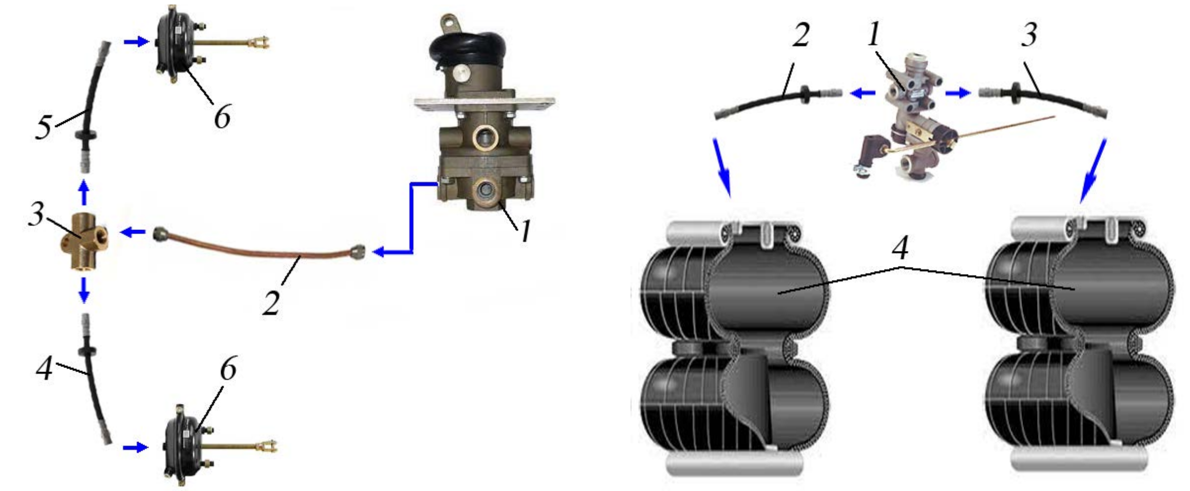
We would like to note that the mathematical model of the change in the volume of the final nodes "throttle-capacity" type is not given in this work and will be considered in the following works of the authors as a separate concept for modeling the dynamic nodes of the pneumatic circuit.

Table 1. Output data for modeling transient processes in the nodes of the pneumatic circuit of the brake system of a wheeled vehicle

Typical nodes "throttle-capacity" type of a pneumatic brake circuit		Volume of the nodes "throttle-capacity" type (V), m ^{3}	The correcting coefficient of flow (μ) / the resistance coefficient of the nodes "throttle-capacity" type (ξ)	Area of the intake throttle, m ^{2} (internal diameter of the throttle d = 0.01 m)	Let's take the air temperature in the circuit as constant, K / °C	The pressure to which the filling takes place, MPa
1. Section of the brake valve		0.000006254	0.30 / 9.0	0.00007854	293 / 20	0.9 (for comparison with experimental data, calculations were also performed at a pressure of 0.4)
2. Tube before branching		0.00047123 9	0.30 / 9.0			
3. Tee (branching)		0.000003927	0.30 / 9.0			
4. The left tube after branching in front of the brake chamber		0.000117810	0.30 / 9.0			
5. The right tube after branching in front of the brake chamber		0.000117810	0.30 / 9.0			
6. Brake chamber	Type 9	0.000261225	0.30 / 9.0			
	Type 24	0.000928800	0.35 / 7.5			
	Type 36	0.001764720	0.40 / 6.0			

Table 2. Output data for the simulation of transient processes in the nodes of the pneumatic circuit of the suspension of a wheeled vehicle

Typical nodes "throttle-capacity" type of the pneumatic suspension circuit	Volume of the nodes "throttle-capacity" type (V), m^3	The correcting coefficient of flow (μ) / the resistance coefficient of the nodes "throttle-capacity" type (ξ)	Area of the intake throttle, m^2 (inner diameter of the throttle d = 0.01 m)	Let's take the air temperature in the circuit as constant, K / °C	Initial pressure in the pneumatic balloon, MPa
1. Floor level regulator (branching)	0.000004925	0.30 / 9.0	0.00007854	293 / 20	0.5
2. The tube after the regulator before the first pneumatic balloon	0.000117810	0.30 / 9.0			
3. The tube after the regulator in front of the second pneumatic balloon	0.000117810	0.30 / 9.0			
4. Pneumatic balloons	The volume is indicated in the range from - to depending on the stroke of the balloon				
1M1A-0	0.000064 - 0.00023	0.30 / 9.0			
1T15T-1	0.0013 - 0.0083	0.35 / 7.5			
1T19L-11	0.0084 - 0.034	0.40 / 6.0			



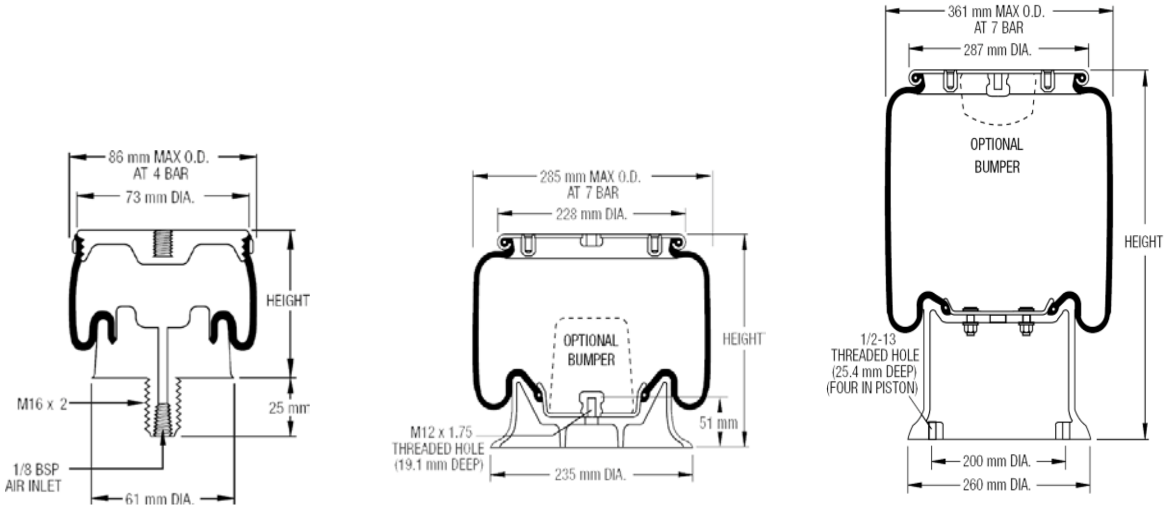
a b

Fig. 2. Scheme of the pneumatic drive: a – nodes of the pneumatic circuit of the brake system (designations 1 – 6 correspond to the numbers in Table 1); b – noses of the pneumatic circuit of the suspension (designations 1 - 4 correspond to the numbers in Table 2)

Since for the scheme shown in Figure 2, the final nodes "throttle-capacity" type (brake chambers of the brake circuit and pneumatic balloons of the suspension) have different standard sizes [5,6,22], then for comparative modeling we will take the extreme and average standard sizes of these nodes as the objects on which we will investigate the workflow of their filling and emptying.

In this case, the working process of other standard sizes of such nodes will be between the pressure curves of the nodes selected for modeling.

The geometric dimensions of the pneumatic balloons, which were used during the simulation of the work process in the pneumatic suspension, are shown in Figure 3, and their corresponding characteristics are shown in Figure 4, Figure 5 and Figure 6 [21].



a b c

Fig. 3. Features of the construction of pneumatic balloons [21]: a – pneumatic balloon 1M1A-0; b – pneumatic balloon 1T15T-1; c – pneumatic balloon 1T19L-11

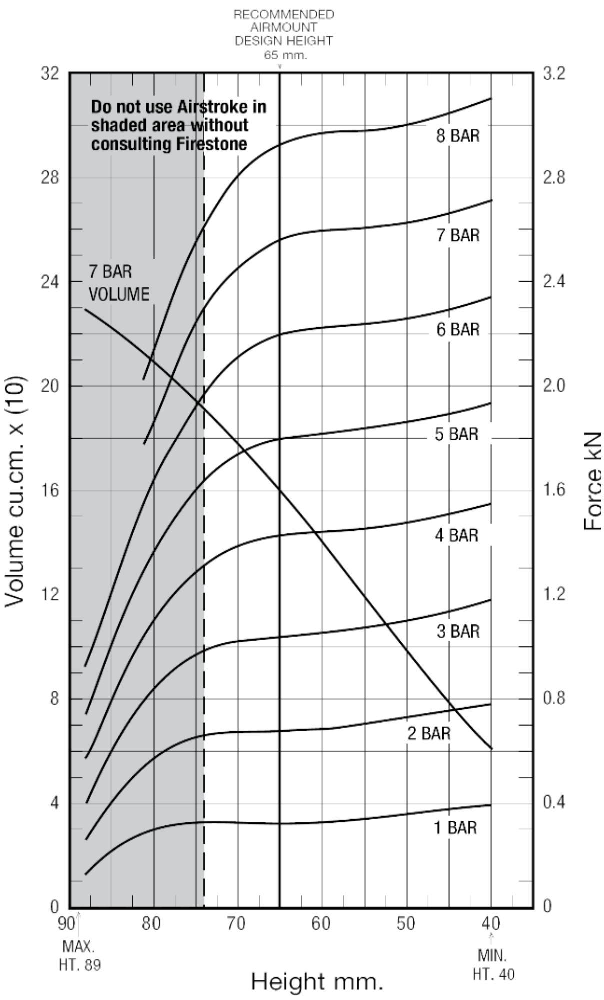


Fig. 4. Characteristics of the pneumatic balloon 1M1A-0 [21]

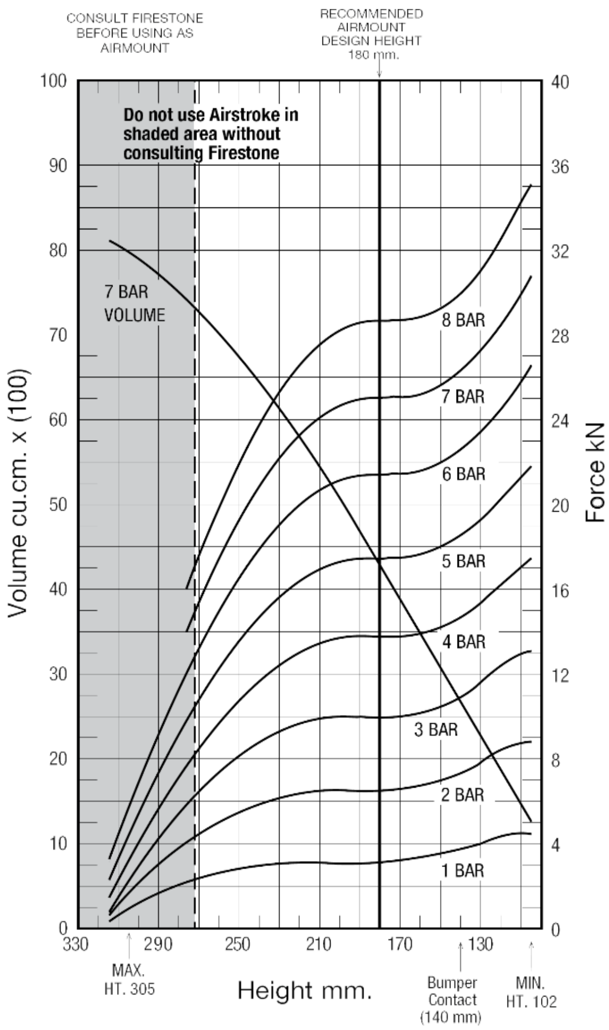


Fig. 5.Characteristics of the pneumatic balloon 1T15T-1 [21]

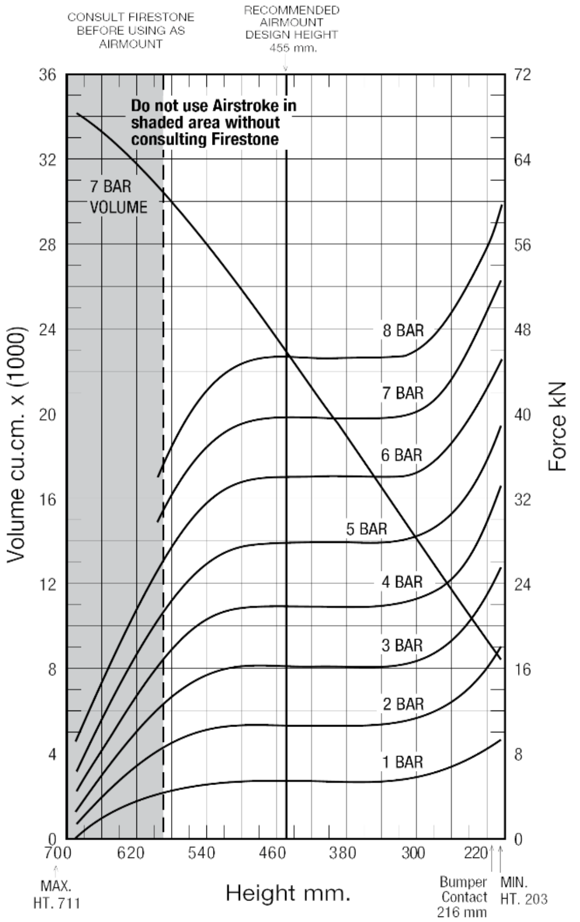


Fig. 6. Characteristics of the pneumatic balloon 1T19L-11 [21]

A feature of the modeling process of work processes that occur in the nodes of the pneumatic brake circuit of the braking system of a wheeled vehicle (Fig. 2 a) and in the nodes of the pneumatic circuit suspension (Fig. 2 b) is the symmetry of the location of the final nodes "throttle-capacity" type (brake chambers and pneumatic balloons) relative to the branching (tee (Fig. 2 a) and floor level regulator (Fig. 2 b), so the simulation results in these nodes are symmetrical, which makes it possible not to overlap them. This approach, adopted during modeling, simplifies the consideration of the nature of the workflow obtained in the nodes "throttle-capacity" type of circuit according to various expenditure functions (5) - (10) and (12), which are considered in this paper.

Simulation modeling of the work process in typical nodes "throttle-capacity" type of pneumatic circuit according to various expenditure functions

We will perform modeling of the work process in typical nodes "throttle-capacity" type of pneumatic circuit based on the creation of a universal model of nodes based on dependencies (1) and (2). The block diagram of the general model of the corresponding circuit is shown in Figure 7 and Figure 8.

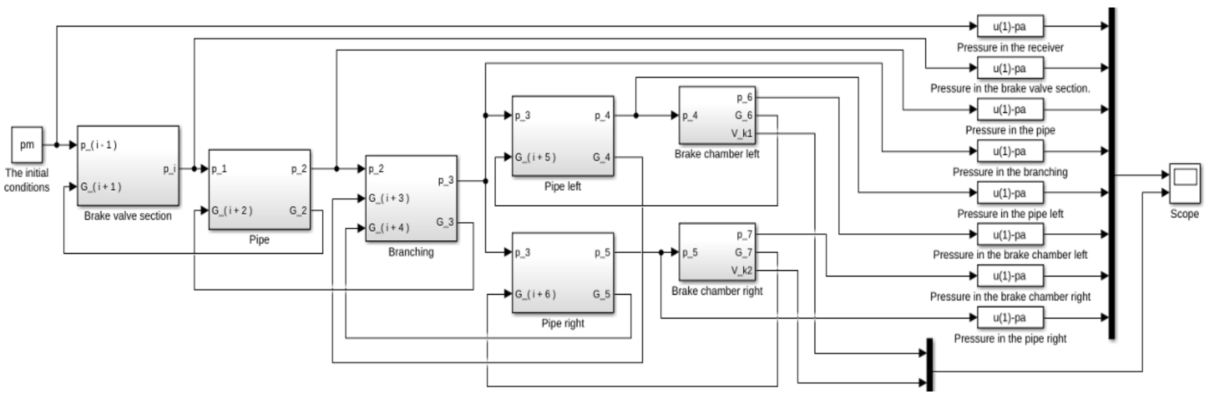


Fig. 7. Block scheme of the contour of the pneumatic circuit of the brake system of a wheeled vehicle in accordance with the scheme shown in fig. 2 a

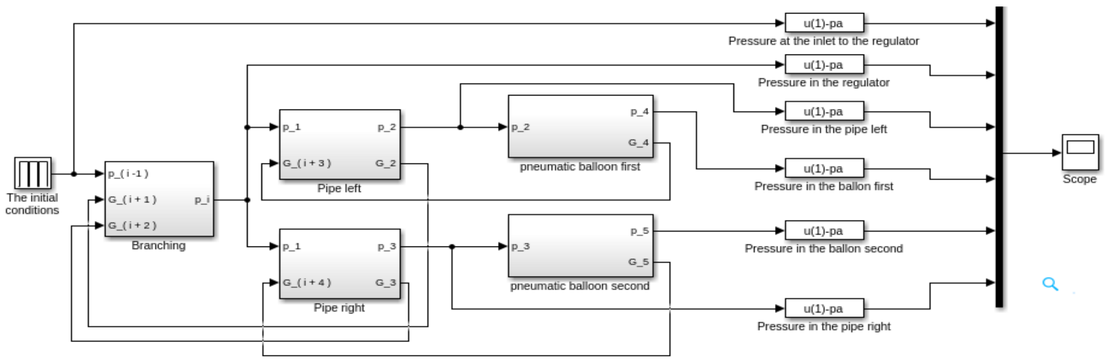


Fig. 8. Block scheme of the nodes of the pneumatic circuit of the suspension of a wheeled vehicle in accordance with the scheme shown in fig. 2 b

Based on the expenditure functions (5) - (10) and (12), we will first calculate the working process of filling the nodes of the pneumatic circuit of the brake system of a wheeled vehicle in each nodes "throttle-capacity" type. A typical example of filling nodes "throttle-capacity" type of the circuit of the WV pneumatic brake circuit, for example, made according to the expenditure function (10) for brake chambers of type 16, is shown in Figure 9.

Similar results were obtained for other dependencies, but in this work they will not be given, since they characterize intermediate results for determining the work process of filling the final node "throttle-capacity" type of the circuit (brake chamber), so we will present only the results of calculations for the final nodes "throttle-capacity" type (Fig. 10 – Fig. 12) to show the difference between the expenditure functions considered in this work.

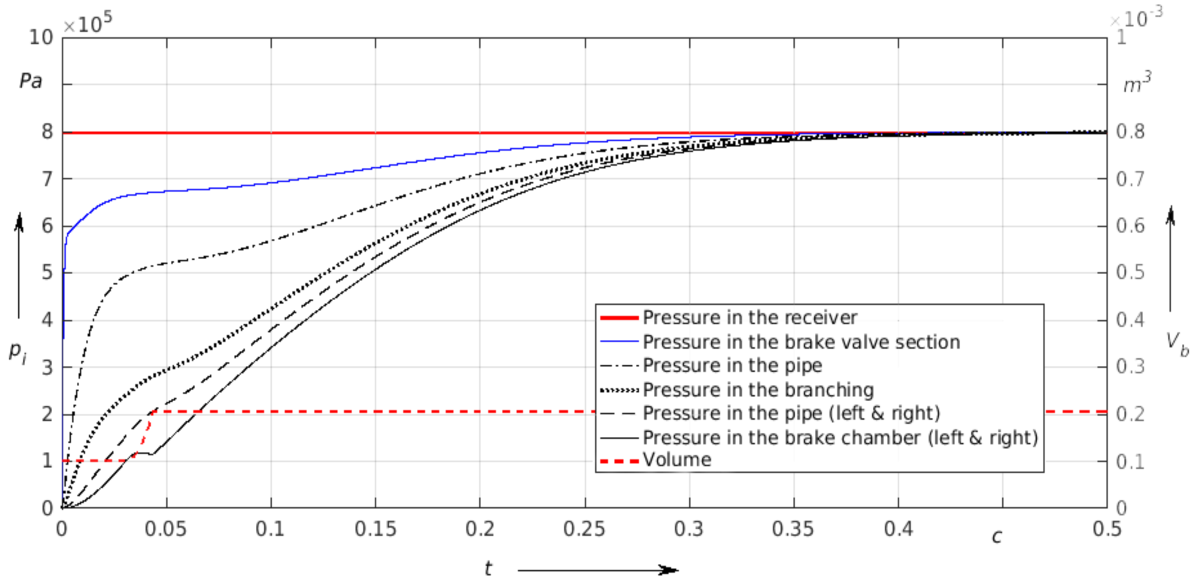


Fig. 9. Results of simulated modeling of the working process of filling the nodes of the pneumatic circuit of the braking system of the WV (the nature of the increase in pressure in each node "throttle-capacity" type of the circuit)

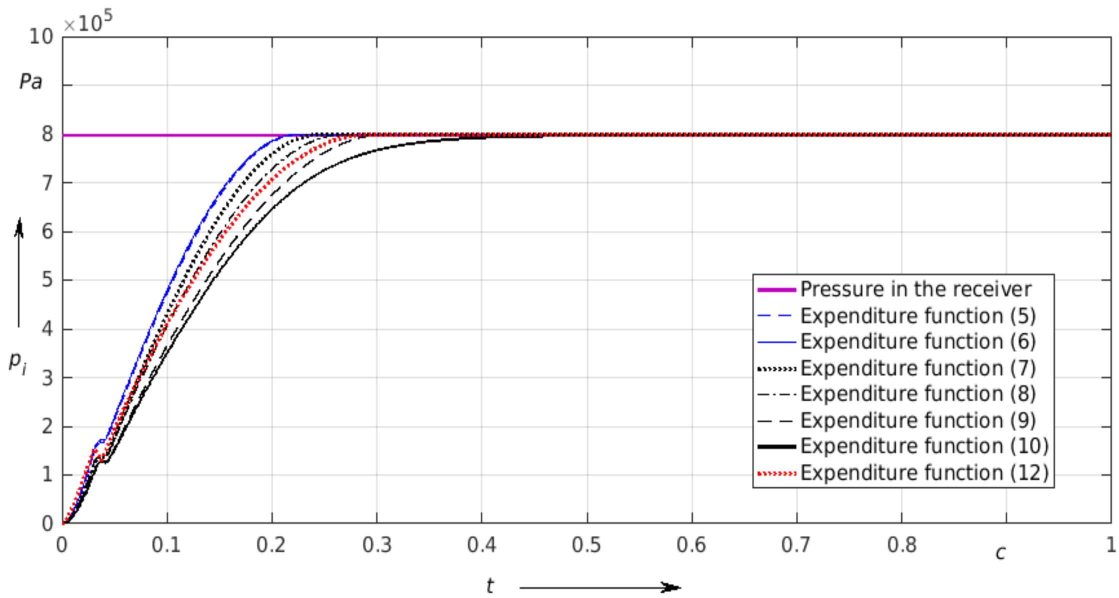


Fig. 10. Results of simulated modeling of the working process of filling the brake chamber type 16 of the pneumatic circuit of the brake system of the WV when using the expenditure functions (5) – (10), (12) and the same initial conditions

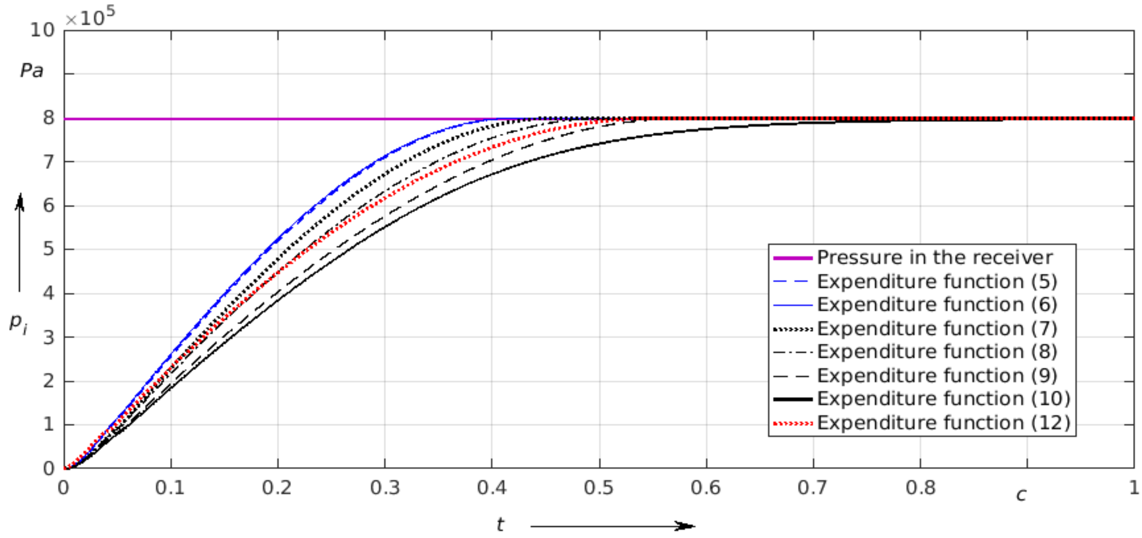


Fig. 11. Results of simulated modeling of the working process of filling the brake chamber type 24 of the pneumatic circuit of the brake system of the WV when using the expenditure functions (5) – (10), (12) and the same initial conditions

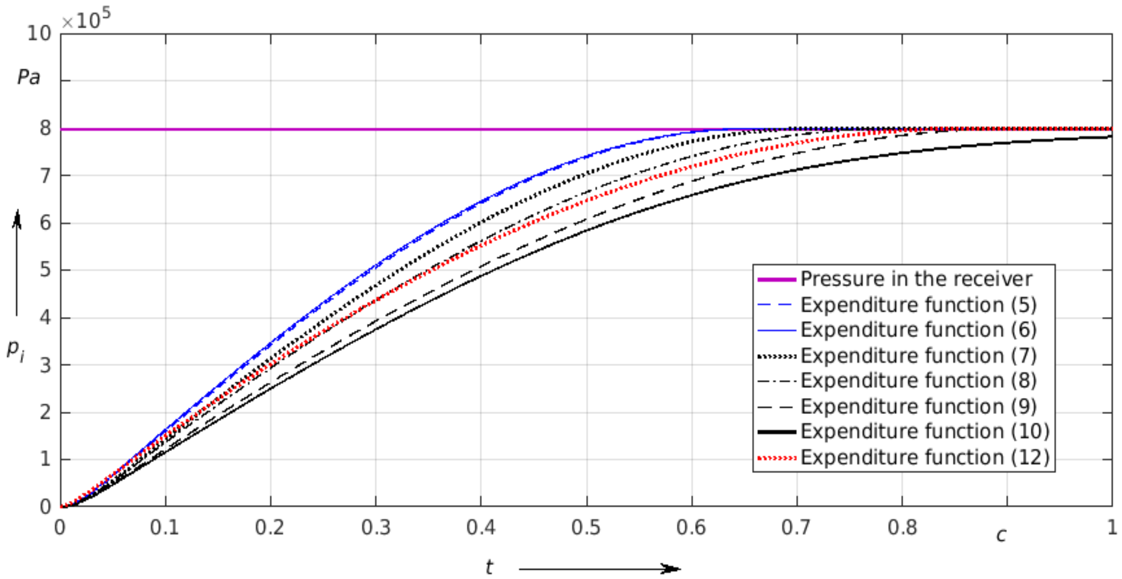


Fig. 12. Results of simulated modeling of the working process of filling the brake chamber type 36 of the pneumatic circuit of the brake system of the WV when using the expenditure functions (5) – (10), (12) and the same initial conditions

It should be noted that, in contrast to expenditure functions (5) – (10), function (12), as shown by the simulation results, has a more dynamic response to an increase in the volume of the brake chamber as a result of moving its stem (see Fig. 13) and somewhat different in nature from other work processes performed under the same initial conditions.

During the modeling of the work process according to the expenditure function (12), which is shown in Figure 10 - Figure 12, the temperature of the working fluid (air) in the nodes "throttle-capacity" type was taken as a constant value, i.e. $T_{i-1} = T_a$.

If we assume that the air temperature in the nodes "throttle-capacity" type of the circuit will increase, for example, by 20 ºC ($T_{i-1} > T_a$), then the work process will be slower (Fig. 14), and the pressure rise time will increase.

If the air temperature decreases, for example, by 20 ºC ($T_{i-1} < T_a$), on the contrary, the pressure rise time will decrease, and the working process in the nodes of the pneumatic circuit will be more dynamic (Fig. 14).

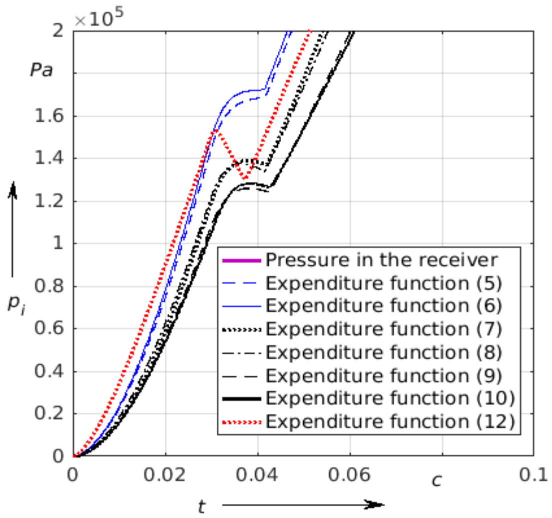


Fig. 13. Results of simulated modeling of the final pressure in the type 16 brake chamber in case of an increase in its volume as a result of the movement of the chamber rod

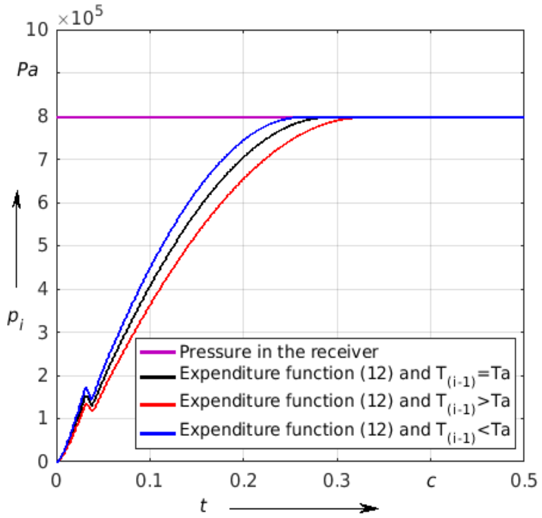


Fig. 14. Results of simulated modeling of the effect of the temperature of the working fluid (air) on the course of the work process in the brake chamber type 16 when using the expenditure function (12)

From the point of view of the adequacy of simulation modeling, it is interesting to compare the results of the virtual model with the results of a real experimental study. Therefore, we will perform such a comparison, for example, for the rear pneumatic circuit of the brake system of the MAZ-256200 bus, since it is the most similar to the model adopted in this work in terms of the length of the nodes "throttle-capacity" type.

The results of the experimental study of the pneumatic circuit of the MAZ-256200 bus will be compared with the simulation results shown in Figure 10, since brake chambers type 16 are installed on the bus. The comparison of the results of the experimental study and simulation modeling is shown in Figure 15.

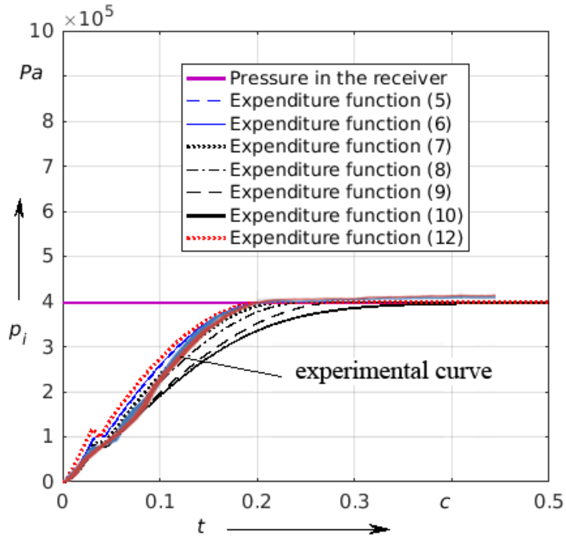


Fig. 15. Comparison of the results of simulation modeling and experimental studies of pressure growth in the node of the brake circuit of the MAZ-256200 bus

From Figure 15, it can be seen that the results of experimental studies at the beginning of the simulation more closely match the nature of the workflow obtained by using expenditure functions (9) and (10), but over time, the result of experimental studies becomes more similar to the result of simulation obtained using expenditure functions (5)-(7).

The results of simulated modeling based on expenditure functions (8) and (12) after comparison with the results of an experimental study showed that, on average, they allow to describe with sufficient accuracy the process of filling the node "throttle-capacity" type of such circuit, if there is no need to estimate the time parameters of the activation of the pneumatic circuit of the braking system of a wheeled vehicle.

When using the function (12), there is one peculiarity, with a decrease in the initial conditions, for example, in the case of a decrease in the pressure in the receiver to 0.4 MPa (Fig. 15), the function becomes more dynamic and, by the nature of the implementation of the work process, approaches the expenditure functions (5) and (6). That is, function (12) can be recommended for modeling fast-acting nodes "throttle-capacity" type, such as electro-pneumatic pressure modulators.

The simulation results also made it possible to establish that there is almost no difference between the expenditure function (5) and (6), the work process according to these functions coincides, both in the form of the process and in terms of the time parameters of the filling of nodes "throttle-capacity" type.

The analysis of potential modification possibilities of expenditure functions (5) – (10) and (12) showed that to describe the filling dynamics of acting nodes "throttle-capacity" type of the circuit, function (7) can be modified into expenditure function (14) by replacing step 2 with step 5, which gives an almost exact match of the simulation results with the real process of filling the brake chamber type 16 shown in Figure 15.

$$\varphi(\sigma) = \mu \cdot \sigma_c \cdot \sqrt{1 - \left(\frac{\sigma - \sigma_c}{1 - \sigma_c} \right)^5} . \qquad (14)$$

If you look at the results of the simulated modeling, which are shown in Figure 10 - Figure 12, as well as in Figure 15, you can see that the expenditure functions (7) - (9), (12), (14) provide simulation of the work process of pressure growth in drive without going beyond the limits of modeling the work process in the circuit when using expenditure functions (5), (6) and (10). Therefore, we will use the function (5), (10) and the modified expenditure function (14) to simulate the work process in the nodes of the pneumatic suspension circuit.

The results of simulation modeling of the course of the work process in the nodes of the pneumatic circuit of the suspension, according to the expenditure functions (5), (10) and (14), for the convenience of analysis, are shown in Figure 16.

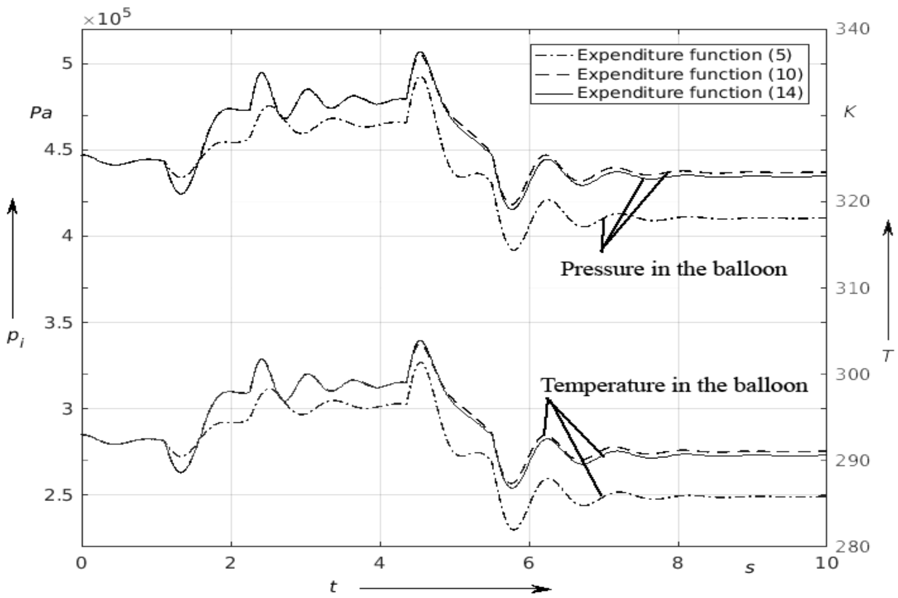


Fig. 16. Results of simulated modeling of pressure changes in a pneumatic balloon of standard size 1T15T-1 when using expenditure functions (5), (10), (14) and the same initial conditions

During the simulation, the concept of determining the temperature change in the pneumatic balloon was used, which will not be considered in this paper, but the results of the simulation of the temperature change will be presented for the convenience of understanding what happens during the pressure change in the node of the pneumatic circuit of the suspension with a balloon of standard size 1T15T-1.

Modeling of standard sizes of pneumatic balloon 1M1A-0 and 1T19L-11 showed similar results of pressure changes as in the pneumatic balloon 1T15T-1, so we will not give them in this work, but based on these studies, we can state , that dynamic functions (5), (6), (12), in contrast to functions (7) - (10) and (14), manage to reduce the pressure in the pneumatic balloon of the suspension by 0.3 MPa, which is a significant result that can to affect the further course of the work process of raising/lowering the body of a wheeled vehicle, or to readjustment during the operation of the automated system for adjusting the floor level of the WV.

Conclusions

The following conclusions can be drawn on the basis of the performed simulation modeling and comparison of some modeling results with experimental studies of the dynamics of pressure growth in the nodes "throttle-capacity" type of the pneumatic circuit.

The expenditure functions used in the simulation of the nature of the pressure change in the nodes "throttle-capacity" type of the pneumatic circuit, whether it is a brake system or a pneumatic suspension system of a wheeled vehicle, with the same initial conditions of simulation, give different results that can have a discrepancy of up to 40%.

The proposed expenditure function (14) showed better dynamic properties than other expenditure functions (5) - (10), (12) used for modeling in this paper. It should be noted that function (14) has the best convergence with the nature of the workflow in the high-speed brake circuit of the MAZ-256200 bus, which was obtained experimentally.

The expenditure function (12), which does not require the use of the correcting coefficient of flow (μ), showed a good convergence with other expenditure functions (5) – (10), (14), which was used during the modeling of the pneumatic circuit workflow in this work.

During the simulated simulation, it was established that the peculiarity of using the expenditure function (12) is that when the pressure in the simulated circuit is reduced, this function becomes more dynamic and, according to the nature of the workflow in the circuit, coincides with the expenditure functions (5) and (6).

Modeling of the work process that takes place in the nodes "throttle-capacity" type of the pneumatic circuit of the suspension system of a wheeled vehicle showed that the dynamic expenditure functions (5) and (6), as well as the expenditure function (12) at pressures in the drive up to 0.6 MPa allow obtaining results simulation, which may differ by 20% from the simulation results obtained by functions (7) – (10) and (14). Such a percentage of discrepancy in the simulation results of circuit having nodes "throttle-capacity" type with large volumes (from 0.0083 $м^3$ to 0,034 $м^3$) can lead to incorrect simulation results of the work process of raising / lowering the body of a wheeled vehicle, or to over-adjustment during the operation of an automated suspension system body of a wheeled vehicle.

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Conflict of interests

The authors declare that there is no conflict of interests regarding the publication of this scientific paper.

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Leontiev Dmytro[1], DSci (Eng.), Prof., Prof. of the Departament of Automobiles named after A. B. Gredeskul, e-mail: dima.a3alij@gmail.com, Phone.: +38(095) 903-68-88,
ORCID: http://orcid.org/0000-0003-4255-6317
Savchenko Yevhen[1], Assist. Departament of Automobiles named after A.B.Gredeskul,
e-mail: ev.gentleman@ukr.net
Phone.: +38(050) 343-81-00
ORCID: http://orcid.org/0000-0001-5898-7694
Harmash Anton[1], graduate student, Assist. Departament of Automobiles named after A.B.Gredeskul, e-mail: expertgaranto@gmail.com
Phone.: +38(099) 731-03-90
ORCID: http://orcid.org/0000-0002-3812-6181
Suhomlyn Oleksandr[1] graduate student Departament of Automobiles named after A.B. Gredeskul
e-mail: suhomlin.alexandr@gmail.com,
Phone.:+38(099) 770-14-28
ORCID: http://orcid.org/0000-0002-2275-6891
Sinelnik Danylo[1], graduate student Department of Automobiles named after A.B.Gredeskula,
e-mail: danilsin1997@gmail.com
Phone.: +38(068) 728-48-32
ORCID: https://orcid.org/0000-0001-7111-1881

[1]Kharkiv National Automobile and Highway University, Yaroslava Mudrogo str., 25, Kharkiv, Ukraine, 61002

Щодо питання використання витратних функцій при моделюванні пневматичних ланок типу «дросель – ємність»

Анотація. Проблема. *Під час дослідження робочих процесів, які відбуваються в пневматичних або електропневматичних приводах гальмових систем або систем пневматичного підресорювання кузова колісного транспортного засобу, дослідники використовують різні витратні функції на основі яких роблять наукові висновки й отримують наукові результати, при цьому не замислюючись над тим, чи достовірні залежності вони використовують в своїх дослідженнях. Вибір витратної функції, для дослідників, є актуальним науковим завданням, яке повинно мати наукове обґрунтування і не повинно мати формалізований характер.* ***Мета.*** *Метою дослідження є порівняння витратних функцій для визначення характеру їх впливу на динамічні процеси, що відбуваються під час наповнення або спорожнення ДЄ-ланок пневматичного приводу.* ***Методологія.*** *Прийняті в роботі підходи до вирішення поставленої мети базуються на аналізі результатів імітаційного моделювання робочих процесів в пневматичних приводах.* ***Результати.*** *Співставлення результатів дослідження отриманих в даній роботі один до одного, а також до результатів отриманих в наслідок експериментальних досліджень дозволили встановити особливості перебігу робочих процесів в ланках привода при використанні різних витратних функцій. Встановлено, що в залежності від вибору витратної функції, при однакових початкових умов імітаційного моделювання, результати дослідження можуть відрізнятися до 40%, що може вплинути на висновки, зроблені науковцями, при аналізі отриманих результатів імітаційного моделювання.* ***Оригінальність.*** *Використання універсальної основи імітаційного моделювання, що базується на різних витратних функціях, дозволив встановити, що можна запропонувати нові функції, що краще описують робочий процес в пневматичному приводі аніж відомі. Порівняння результатів імітаційного моделювання між собою дозволив визначити динамічність функцій та їх вплив на перебіг робочих процесів в ланках пневматичного привода.* ***Практичне значення.*** *Отримані результати можуть бути рекомендовані в практиках імітаційного моделювання робочих процесів в пневматичних або електропневматичних приводів гальмових системи та систем пневматичного підресорювання кузова колісних транспортних засобів.*

Ключові слова: *витратна функція, функція витрати, пневматичний привід, гальмова система, система пневматичного підресорювання.*

Леонтьєв Дмитро Миколайович[1], д.т.н., проф., професор кафедри автомобілів ім. А. Б. Гредескула, e-mail: dima.a3alij@gmail.com,
тел.: +38(095) 903-68-88,
ORCID: http://orcid.org/0000-0003-4255-6317
Савченко Євген Лукич[1], асистент кафедри автомобілів ім. А. Б. Гредескула,
e-mail: ev.gentleman@ukr.net
тел.: +38(050)-343-81-00
ORCID: http://orcid.org/0000-0001-5898-7694
Гармаш Антон Андрійович[1], аспірант, асистент кафедри автомобілів ім. А. Б. Гредескула,
e-mail: expertgaranto@gmail.com
тел.: +38(099)-731-03-90
ORCID: http://orcid.org/0000-0002-3812-6181
Сухомлин Олександр Вячеславович[1] аспірант кафедри автомобілів ім. А. Б. Гредескула,
e-mail: suhomlin.alexandr@gmail.com,
тел.:+38(099)-770-14-28
ORCID: http://orcid.org/0000-0002-2275-6891
Сінельнік Данило Богданович[1], аспірант кафедри автомобілів ім. А. Б. Гредескула,
e-mail: danilsin1997@gmail.com
тел.: +38 (068) 728 48 32
ORCID: https://orcid.org/0000-0001-7111-1881

[1]Харківський національний автомобільно-дорожній університет, вул. Ярослава Мудрого, 25, м. Харків, Україна, 61002.