The experimental method for determining the isobaric power characteristics of pneumatic elements with rubber-cord casing

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Abstract. A method for the experimental construction of isobaric static (equilibrium) power characteristics of pneumatic elements with a rubber-cord casing at a constant temperature is proposed. This method also allows you to determine isobar geometric characteristics, establishing a relationship between the height of the pneumatic element and the increment of its internal volume relative to some fixed position. The practical implementation of the method is illustrated by the example of a pneumatic element with a rubber-cord casing of the balloon type of the model N-50. The agreement of the experiment with the theoretical data calculated by the traditional method, widely used in the scientific literature, is analyzed. The obtained parameters are mandatory for the model of air spring and study the damping phenomenon. The results of the study are intended to develop vibration protection and vibration isolation systems for technical objects, the design of which includes air springs and air damping shock absorbers.

1. Introduction

In systems of vibration protection and vibration isolation of various technical objects, pneumatic elements with rubber-cord casings (shall), which have a number of indisputable advantages [1-5], are widely used. In the calculations, the decisive role is played by the force and geometric characteristics of the pneumatic element, which respectively establish the dependence of the force of the pneumatic element and its internal volume on the height (coordinate) of the air element at specified values of overpressure and temperature. The description of the method for constructing isobaric power characteristics of pneumatic elements with rubber-cord casing in the published materials is absent, although the results are given [5]. Therefore, for example, in the catalog of the leading American company Firestone [5], for each size of the pneumatic element, isobar performance characteristics (power and geometric) are given, obtained experimentally and related to a certain constant temperature (most likely room temperature). At the same time, the [5] catalog does not provide descriptions of the experimental stand and measurement procedures, as well as links to relevant literature. Apparently, this information is contained in reports of the company «Firestone», unpublished for reasons of trade secrets. In this regard, the situation still remains, as it was several decades ago: «Despite the widespread use of pneumatic suspensions abroad, substantial materials on their creation and research are not given in the literature. Existing publications are mostly advertising in nature and do not have practical value» [1]. Therefore, the question of exactly which experimental method can be used to construct static (equilibrium) isobaric-isothermal performance characteristics (power and geometric) of pneumatic elements of different designs with acceptable accuracy is essentially relevant.

2. Formulation of the problem

For the mathematical description of these characteristics in the scientific literature [1-10], the fundamental relations are used

$$P = p_u F_{eff}(x), \; F_{eff}(x) = \mathrm{d}V(x)/\mathrm{d}x , \tag{1}$$

obtained under the assumption that the rubber-cord shell is absolutely flexible, and its middle surface is inextensible. Here P – pneumatic element force, $p_u = p - p_{atm}$ – overpressure (p – absolute pressure, p_{atm} – atmospheric pressure), F_{eff} – effective area, V – internal volume, x – height (coordinate) of the pneumatic element. By experimentally determining P , p_u for various values, the effective area $F_{eff}(x)$ is determined by the first formula (1), and the internal volume is determined by the second formula $V(x)$:

$$V(x) = V_0 + \int_{x_0}^{x} F_{eff}(x)\mathrm{d}x \,. \quad (2)$$

Here V_0 is the internal volume of the air element at a certain value of its height x_0, for example, in the middle position of the air element. Under the conditions of fundamental theoretical concepts (1), (2), for a comprehensive mathematical description of a single pneumatic element (specific design and size), one single test is sufficient, in which (regardless of the mass of the gas contained in the pneumatic element) the force P and the excess pressure p_u are measured for different coordinates x in the working range of their change [2]. The volume V_0 is also determined in one experiment, for example, by pouring water at zero gauge pressure [2].

When directly comparing the operating characteristics of the pneumatic element obtained in the described manner for different values of overpressure p_{u0} in a static position at height x_0 (different masses of gas in the pneumatic element), a significant discrepancy is observed, indicating the presence of elastic deformation of the middle surface [2].

In the presented study, an option is proposed for a complete solution of the question in relation to power characteristics and a partial solution in relation to geometric characteristics.

3. Experimental method

3.1. Object of study

The object of study is a pneumatic element with a rubber-cord casing of this type (for example, balloon or tubular) and a size with appropriate metal fittings (see, for example, [11]). In the study, the rubber-cord casing of the balloon type of the model N-50 was used, which is commercially available from the leading domestic company FSUE «FRPC «Progress» [12]. Under normal conditions of operation of this shell, the working medium is air supplied to the internal cavity of the pneumatic element under pressure p_u = 4 bar at the initial height (coordinate) of the pneumatic element x_0 = 112 mm. The maximum compression and rebound stroke is Δx = ± 40 mm (from the initial height of the pneumatic element). The pneumatic element remains operational at ambient temperatures from – 45°C to + 50°C.

To obtain the static (equilibrium) performance of a pneumatic element, working environment is air (or another gas, as necessary), which has high compressibility. Due to the indicated property of the working medium, any small changes in the volume of the rubber-cord shell (at a fixed height of the pneumatic element) caused by relaxation processes in the viscoelastic material of the shell insignificantly affect the amount of internal overpressure, which is additionally maintained at a constant level with each measurement in a special way (described below). Throughout the test, the temperature of the shell and the working medium, which is equal to 20°C in the study, also remains constant.

3.2. Testing and measuring tools

The experimental stand (figure 1) is integrated into the Instron series 8805 servo-hydraulic testing machine, the built-in sensors of which are automatically recorded and transmitted to the computer for recording the force and movement of the pneumatic element. The Dynacell load sensor with integrated accelerometer compensates for the inertial load caused by heavy grips and fixtures with a relative measurement error of 0.5%. The error of the displacement sensor is 0.02 mm. Instron's servohydraulic machine software (Bluehill 3, WaveMatrix) allows for quasi-static and dynamic testing using virtually any technique with control of load (up to 100 kN) and displacement (up to 150 mm). Pressure measurement is carried out by the ZET 7112-I-Pressure-CAN intelligent overpressure sensor with a CAN interface with a relative measurement error of 0.1%, a sensitivity threshold (the minimum value by which two sequentially measured values are distinguished) 1 Pa and the maximum total data recording frequency of 12 kHz. The creation of excess pressure in the pneumatic element is carried out by a SkyWay Atlant-03 compressor with a maximum pressure of 17 atm. Maintaining excess pressure at a constant level is carried out by a screw drive of a single-acting hydraulic cylinder rod CH-80.40x630.22 with a piston diameter of 80 mm, a rod diameter of 40 mm and a maximum pressure of 20 MPa. The position of the piston of the hydraulic cylinder and the geometric parameters of the shell shape (equatorial diameter, effective shell height and the height of the air element along the flanges) are measured with two calipers with an accuracy of 0.01 mm.

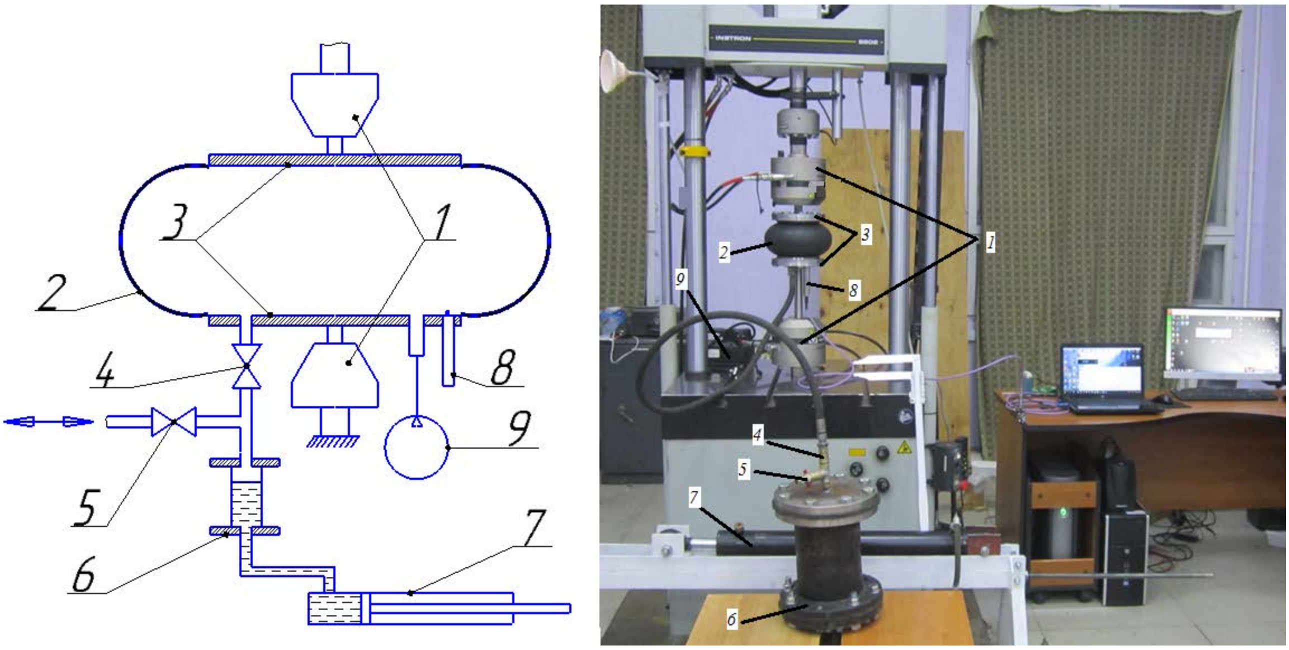

Figure 1. Scheme and general view of the experimental stand:
1 – grips; 2 – rubber cord casing (RCC); 3 – flanges; 4, 5 – valves; 6 – receiver;
7 – hydraulic cylinder; 8 – gauge overpressure; 9 – compressor

3.3. General description of the operation of the experimental stand

The pneumatic element assembly (figure 1) is installed in the grippers 1 of the Instron servo-hydraulic testing machine and is firmly held in position, changing from measurement to measurement. The pneumatic element assembly consist of a rubber-cord casing 2 and two steel flanges 3 with special holes for connecting the pressure transducer 8 and flexible branch pipe, Using flexible nozzles, the pneumatic element is connected separately to the compressor 9 and to the receiver 6, which in turn is connected to the hydraulic cylinder 7. Valve 4 is used to disconnect the pneumatic element from the receiver, and valve 5 is used to fill and drain the liquid from the receiver and hydraulic cylinder.

The working environment in the piston cavity of the hydraulic cylinder is boiled water (or other liquid, as necessary), which is practically incompressible in the studied range of operating pressures. The rod cavity of the hydraulic cylinder is in communication with the atmosphere. The volume of the receiver must be larger than the maximum volume of the piston area of the hydraulic cylinder, so that the boundary between the gas (pneumatic element) and liquid (hydraulic cylinder) phases is constantly inside the receiver.

When shifting the upper grip controlled through a personal computer using Bluehill 3 software from one fixed position to another fixed position, the excess air pressure in the pneumatic element changes (increases during compression and decreases during rebound). To return the excess air pressure to the set value, the piston of the hydraulic cylinder is forced (manually) by means of a screw drive connected to the rod (the volume of the piston cavity of the hydraulic cylinder increases during compression and decreases during rebound). Throughout the test, continuous monitoring of the readings of the gauge of overpressure with proper adjustment of the position of the piston of the hydraulic cylinder is carried out. Due to this, the error in maintaining a constant value of excess air pressure in the pneumatic element was 0.001 bar in the test with an overpressure of 0.1 bar, and in tests with an overpressure of 1 bar and higher, 0.01 bar. The test report contains the measurement results — forces and displacements of the upper grip, overpressure, the coordinates of the piston of the hydraulic cylinder (with a fixed conditional reference point), the equatorial diameter and effective height of the shall, the height of the pneumatic element.

When recalculating the magnitude of the force of the pneumatic element by the force at the gripper, the weight of the movable upper flange and the rigidly metallic parts of the bench, equal to 56.3 N. The increment of the internal volume of the pneumatic element

$$\Delta V_{p_u,x_{\max}}(x) = V(x_{\max}, p_u) - V(x, p_u) \tag{3}$$

with respect to the internal volume in the extreme upper position of the pneumatic element with the maximum value of the height (coordinate) of the pneumatic element $x_{\max}$ was calculated on the basis of equality (figure 1)

$$V_{water} + V_{air} = V + V_{cyl} + V_{rec}, \tag{4}$$

where V_{water} is the total volume of water in the hydraulic cylinder, receiver and branch pipe, V_{air} is the total volume of air in the pneumatic element, receiver and branch pipe, V is the internal volume of the pneumatic element, V_{cyl} is the internal volume of the hydraulic cylinder, V_{rec} is the internal volume of the receiver and branch pipe. Since, in isobaric-isothermal conditions, the volumes V_{water}, V_{air}, V_{rec} keep their value unchanged, it follows from (4) that $\Delta V = -\Delta V_{cyl}$, or taking into account the expression (3)

$$\Delta V_{p_u,x_{\max}}(x) = S\left[L_{cyl}(x, p_u) - L_{cyl}(x_{\max}, p_u)\right], \tag{5}$$

where S is the area of the piston cavity of the hydraulic cylinder, L_{cyl} is the coordinate of the piston of the hydraulic cylinder. Having the empirical dependence (5), it is possible, for example, to determine the increment of the internal volume of the pneumatic element relative to the internal volume in the average position of the pneumatic element and the average value of the height (coordinate) of the pneumatic element x_0:

$$\Delta V_{p_u,x_0}(x) = V(x_0, p_u) - V(x, p_u). \tag{6}$$

The formula following from (3) serves this purpose

$$\Delta V_{p_u,x_0}(x) = \Delta V_{p_u,x_{\max}}(x) - \Delta V_{p_u,x_{\max}}(x_0). \tag{7}$$

In both cases (3), (6) to determine the internal volume of the pneumatic element according to the calculation formulas

$$V(x, p_u) = V(x_{\max}, p_u) - \Delta V_{p_u,x_{\max}}(x),\ V(x, p_u) = V(x_0, p_u) - \Delta V_{p_u,x_0}(x)$$

it is required to have one more experimentally obtained value of the internal volume of the pneumatic element at a certain fixed coordinate of the pneumatic element and a given pressure. Obviously, the indication of the experimental method for determining the additional value of the internal volume of the pneumatic element, for example, $V(x_{\max}, p_u)$ or $V(x_0, p_u)$, is equivalent to the indication of the experimental method of direct construction of the geometric characteristics of $V(x, p_u)$. At the current time, such an experimental method is unknown (or is contained in unpublished reports), its development requires a separate study, which is beyond the scope of this article. Nevertheless, even a partial solution of the problem by means of geometric characteristics (5), (7) is of great importance in assessing the accuracy of the fundamental theoretical dependences (1), (2) obtained by the traditional method, as well as similar theoretical dependencies of the refined method, for example, the proposed at [13, 14].

3.4. Testing procedure

Tests are carried out alternately at overpressure values of 0.1 bar and 1 ... 10 bar with an interval of 1 bar. In each individual test, the pneumatic element installed in Instron clamps is initially displayed to a height between flanges = 155 mm (maximum working height of the pneumatic element) and is filled with air to an overpressure value slightly higher than the set value using a compressor (figure 1, position 9). In this case, the valves (figure 1, position 4, position 5) are in the “closed” position, as a result of which the internal cavities of the pneumatic element and the receiver with the hydraulic cylinder are disconnected. In turn, the piston of the hydraulic cylinder is in a position in which the volume of the piston cavity is slightly larger than its minimum value. Then the valve (figure 1, position 4) is put into the “open” position. The overpressure in the cavities of the pneumatic element and the receiver with the hydraulic cylinder is equalized, slightly different from the value specified in the conducted test. Bringing overpressure to the required value and subsequent continuous monitoring of maintaining it at a constant level is carried out by proper displacement of the hydraulic cylinder rod by rotating the screw drive handle. After that, the values of the above listed measured parameters related to the first step of the test are entered into the test report.

In the subsequent steps of the test, the upper clamp of the Instron power grip (figure 1, position) moves down with an interval of 5 mm to a value = 65 mm (minimum working height of the air element). At each step, measurement and recording in the protocol of test parameters is carried out with constant monitoring of the readings of the gauge of excessive pressure. Capture control (displacement with force limitation) is carried out through a personal computer using the Bluehill 3 software.

After reaching the minimum air element height $x_{\min}$ = 65 mm, the test procedure is reversed. The upper grip (figure. 1, pos. 1) rises step by step with an interval of 5 mm to the maximum value of the height of the pneumatic element $x_{\max}$ = 155 mm. Subsequently, the previous sequence of actions described above is retained.

4. Experiment Results

For the analytical description of empirical dependencies describing the force of the pneumatic element and the coordinate of the hydraulic cylinder as functions of the height (coordinate) of the pneumatic element x at a constant value of overpressure p_u , the cubic regression equations were used

$$P(x) = a_P + b_P(x - x_0) + c_P(x - x_0)^2 + d_P(x - x_0)^3 , \tag{8}$$

$$L(x) = a_L + b_L(x - x_0) + c_L(x - x_0)^2 + d_L(x - x_0)^3 . \tag{9}$$

The values of the regression coefficients determined by the least squares method are given in table 1. In turn, the empirical dependence (9) determines the empirical dependence for the increment of the internal volume (3) at constant overpressure in accordance with the formula (5):

$$\Delta V(x) = S[L(x) - L(x_{\max})], \tag{10}$$

where S = 54.82 cm2. The graphs of empirical dependencies (8), (10) are presented in figure 2, figure 3.

Table 1. Numerical values of the coefficients of the regression equation.

Overpressure p_u , bar	coefficients of the regression							
	a_P , kN	b_P , kN/m	c_P , kN/m^2	d_P , 10^3 kN/m^3	a_L , m	b_L	c_L , m^{-1}	d_L , m^{-2}
0.1	0.204	-2.985	-53.72	-1.203	0.181	-4.552	23.088	49.537
1	2.414	-23.02	-184.4	-1.565	0.226	-4.931	21.605	232.117
2	4.873	-46.28	-337.8	-2.099	0.197	-4.963	23.522	136.024
3	7.500	-68.29	-456.0	-3.222	0.226	-5.124	22.759	124.968
4	10.27	-88.72	-506.9	-5.835	0.208	-5.254	22.234	88.225
5	13.02	-110.22	-579.7	-7.926	0.269	-5.340	23.093	66.114
6	15.90	-130.89	-640.3	-9.988	0.268	-5.488	21.843	90.217
7	19.09	-149.44	-627.4	-13.15	0.240	-5.663	21.436	88.274
8	22.10	-168.70	-673.5	-17.71	0.251	-5.717	21.810	51.596
9	25.32	-189.44	-633.1	-19.26	0.255	-5.775	20.103	50.880
10	28.57	-209.02	-593.5	-23.24	0.249	-5.950	21.831	64.961

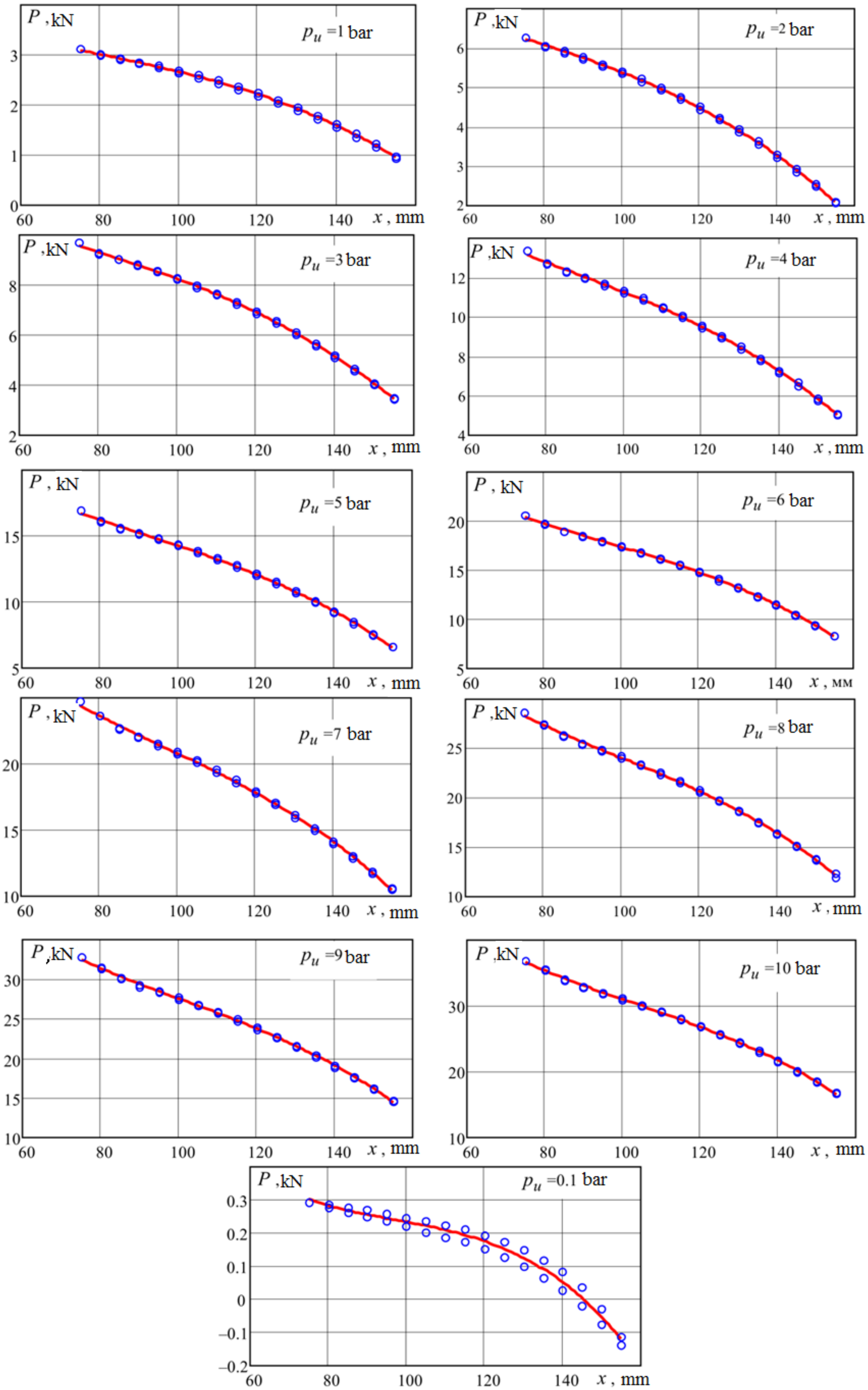

Figure. 2. Isobaric power characteristics of a pneumatic element with RCC model N-50: solid line is an empirical relationship; points – primary experimental data

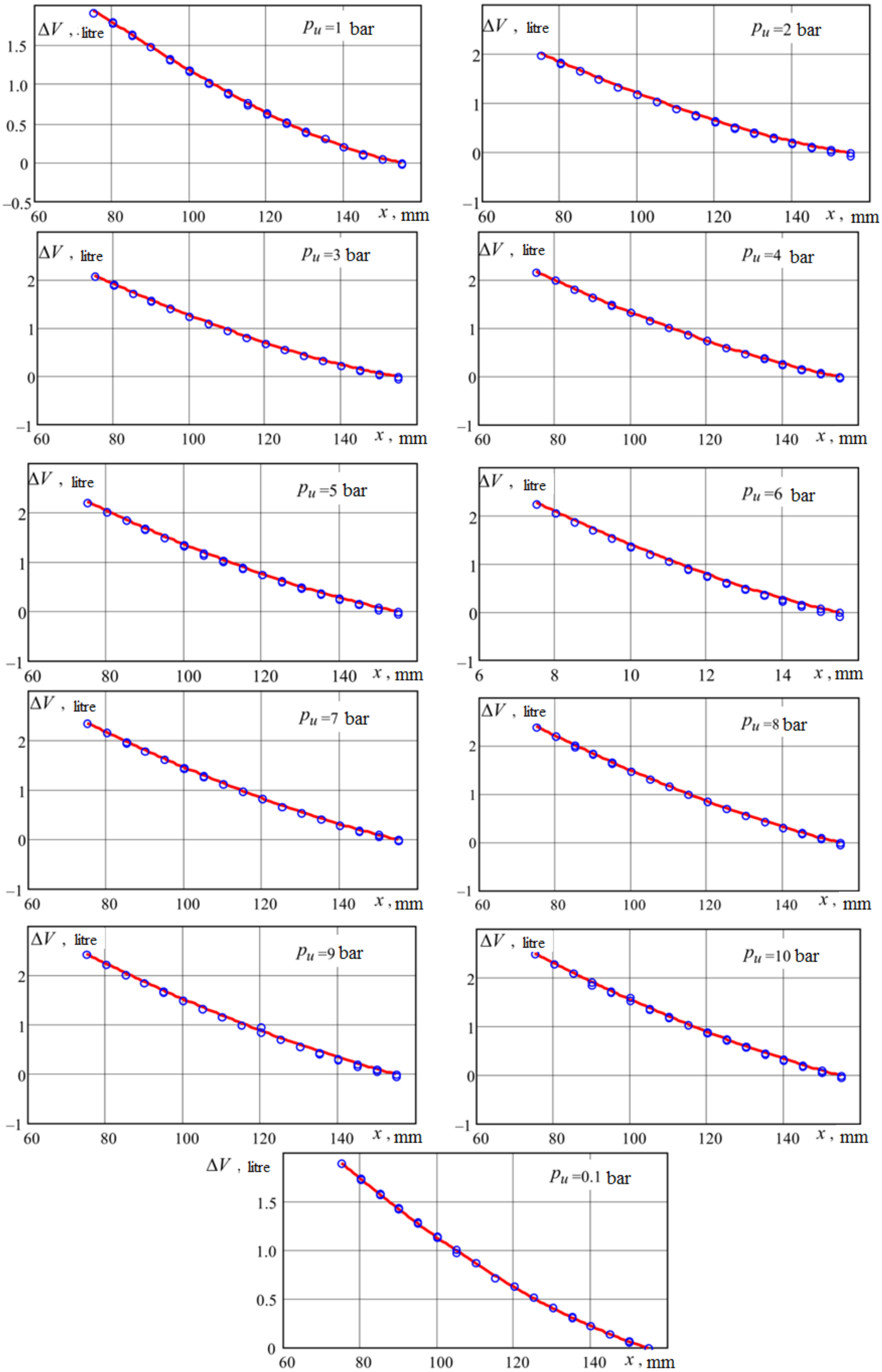

Figure 3. Isobaric geometrical characteristics of a pneumatic element with RCC model N-50: solid line is an empirical relationship; points – primary experimental data

5. The discussion of the results

The degree of accuracy of the empirical dependence (8) for the force of the pneumatic element and the scatter of the corresponding primary experimental data (relative to the empirical dependence) can be estimated using the generally accepted error measure [15, 16] – the root-mean-square deviation of an individual measurement s_P, as well as the average relative deviation ε_P, which are calculated by the formulas

$$s_P = \sqrt{\frac{1}{N}\sum_{k=1}^{N}\left[P_k - P(x_k)\right]^2}\ ,\ \varepsilon_P = \frac{100}{N}\sum_{k=1}^{N}\left|\frac{P_k - P(x_k)}{P_k}\right|.$$

Here N is the total number of experimental points, P_k is the primary experimental value ($k = 1,...,N$). Reasoning by the values of deviation measures (table 2) and the location in figure 2, figure 3 primary experimental data (indicated by dots) obtained during testing separately during compression and rebound, we can conclude that the scatter of the primary data relative to the averaged curves is small enough so that it can be assumed that the empirical dependences (8) are (10) describe the static (equilibrium) characteristics of a pneumatic element with acceptable accuracy. The isobaric power characteristic that corresponds to the lowest (in the tests) excess pressure of 0.1 bar (figure 2, table 2) is exception. Since conditionally (by agreement) the positive compressive forces of the pneumatic element are taken, the negative values of the force on the force characteristic at = 0.1 bar (figure 2) indicate the predominant contribution of tensile forces in the rubber-cord shell compared to air pressure forces. Therefore, the relaxation processes occurring in the rubber-cord composite have a more significant effect on the magnitude of the force at low excess pressures than at high excess pressures. This conclusion does not apply to increments of the internal volume of the pneumatic element at = 0.1 bar (figure 3), because the relaxation changes in the internal volume are extremely small in comparison with the absolute value of this volume.

Table 2. Koot-mean-square deviation and average relative deviations of an individual measurement of the force of an air element.

Deviation measure	Overpressure p_u, bar										
	0.1	1	2	3	4	5	6	7	8	9	10
s_P, N	19.53	27.15	30.81	45.51	76.23	83.97	101.0	130.9	141.3	155.2	162.3
ε_P, %	22.3	1.37	0.72	0.61	0.70	0.54	0.51	0.59	0.55	0.53	0.51

To evaluate the accuracy of two theoretical formulas (1), in figure 4 shows the graphs of the effective area of the $F_{eff}(x) = P(x)/p_u$ in, constructed according to empirical dependencies (8). We see, different curves correspond to different values of overpressure. The averaged curve (not shown in figure 4) practically coincides with the curve corresponding to overpressure p_u = 5 bar. The scatter in the values of the effective area relative to the average curve is 8.51% at the height of the pneumatic element $x_{\min}$, with an average value of the height x_0 – 8.41%, and at the height of the air element $x_{\max}$ – 26.3%.

On the other hand, according to definition (3), by the second formula (1) find

$$F_{eff}(x) = -\mathrm{d}\Delta V(x)/\mathrm{d}x.$$

Substituting the empirical dependence (10) into this expression, which corresponds to excess pressure p_u = 5 bar, and calculating the force of the pneumatic element according to the first formula (1), it is possible to construct theoretical isobar force characteristics and compare them with experimentally obtained characteristics (figure 5).

Thus, to increase the accuracy of calculations of pneumatic elements, one should take into account the elastic deformations of the middle surface of the rubber-cord casing, using for this purpose one or another refined method, for example, the thermodynamic method proposed in [13, 14].

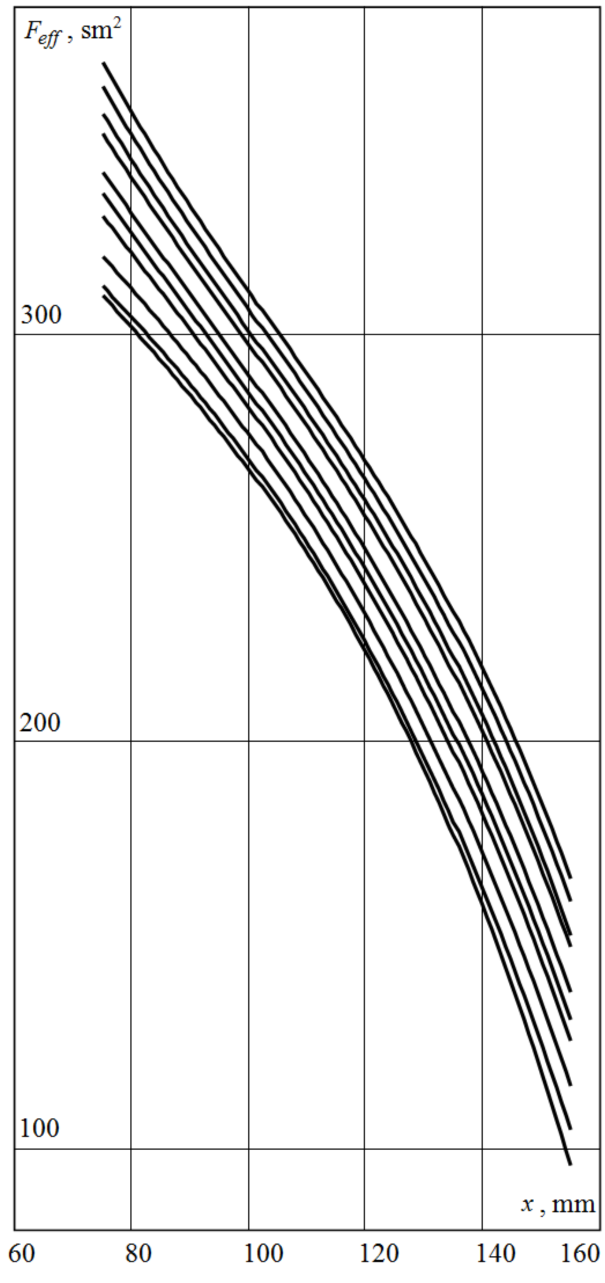

Figure 4. Isobaric dependences of the effective area from the height of the pneumatic element with RCC model N-50 at excess pressure (bottom-up position), bar: 1; 2; 3; 4; 5; 6; 7; 8; 9; 10

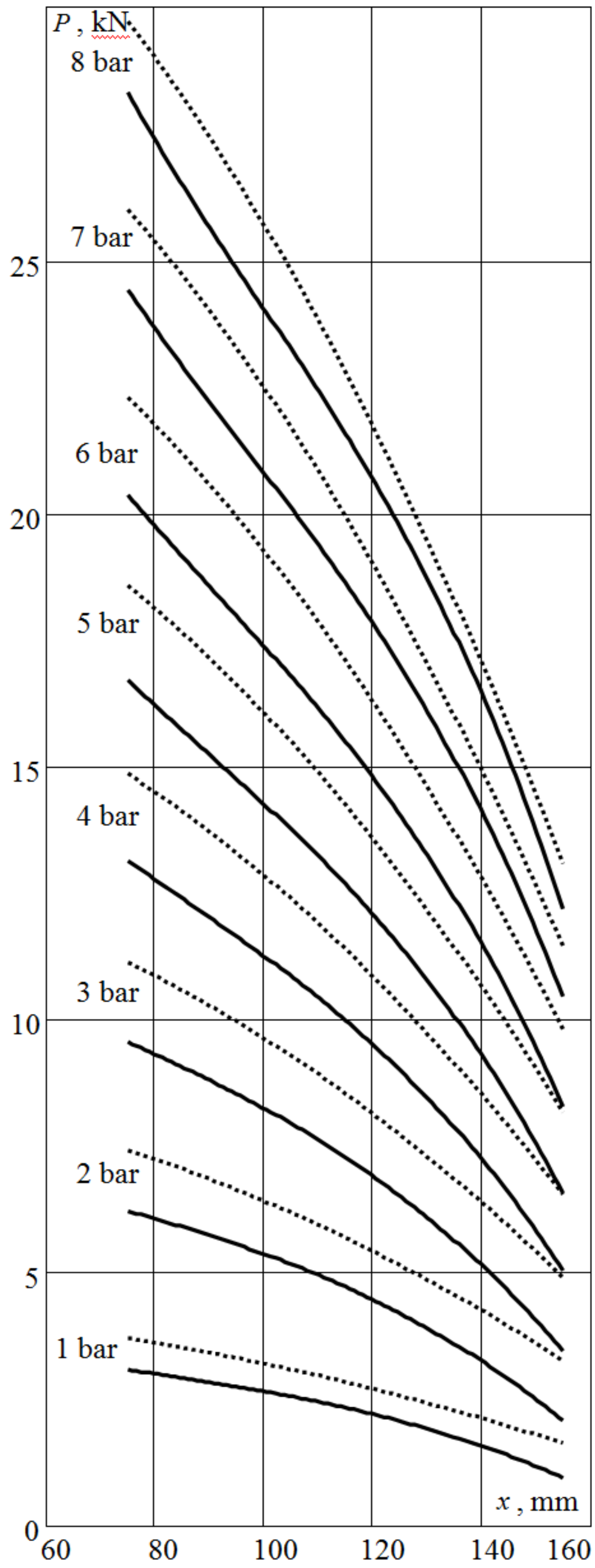

Figure 5. Experimental (solid lines) and isobar power characteristics calculated by the traditional method (points) of a pneumatic element with an RCC model N-50

6. The work results

The obtained parameters are mandatory for the model of air spring and study the damping phenomenon. The average relative error with quasi-pressure does not exceed for all data ε_P = 1.37% at pressures above 1 bar. It was revealed that, to increase the accuracy of calculations of pneumatic elements, one should take into account the elastic deformation of the middle surface of the rubber-cord casing.

7. Conclusions

The experimental method and described in detail for constructing the static (equilibrium) isobar force characteristics of pneumatic elements with a rubber-cord shell at a constant temperature has been developed. The proposed method also allows you to build isobar geometric characteristics of the air element, which determines the relationship between the height (coordinate) of the air element and the increment of its internal volume relative to the internal volume in a certain fixed position of the air element. The practical application of the developed experimental method is illustrated by the example of a pneumatic element with a rubber-cord casing of the balloon type of the model N-50. Empirical relationships in the form of cubic regression equations are established by mathematical processing of the primary experimental data. With an increase in overpressure, the root-mean-square deviation of an individual measurement of the force of the pneumatic element with respect to the corresponding empirical dependence increases from 27.15 N at an overpressure of 1 bar (force in the middle position of the pneumatic element 2414 N) to 162.3 N at overpressure 10 bar (force at the average position of the pneumatic element 28567 H). In this case, the average relative deviation of an individual measurement of the force of the pneumatic element decreases from 1.37% at an overpressure of 1 bar to 0.51% at an overpressure of 10 bar. A small scatter of the initial experimental data on the averaged curves indicates that the empirical dependences obtained by the proposed experimental method describe the static (equilibrium) characteristics of the pneumatic element with accuracy acceptable for practice. An exception is isobar force characteristics corresponding to small excess pressures of the order of 0.1 bar and lower, due to the significant effect on the magnitude of the force of the pneumatic element of relaxation processes occurring in the rubber-cord composite when the equilibrium state is reached. However, this conclusion does not apply to the geometric characteristics of the pneumatic element (increments of the internal volume of the pneumatic element) at low excess pressures due to extremely small relaxation changes in the internal volume compared to the absolute value of this volume.

The accuracy of the fundamental theoretical relations of the traditional method for calculating pneumatic elements based on the assumption that the rubber-cord casing is absolutely flexible and its middle surface is inextensible is estimated. A comparison of the corresponding calculated and experimental data convincingly indicates the need to take into account the elastic deformations of the middle surface of the shell in order to significantly increase the accuracy of calculation of pneumatic elements, for example, by the refined thermodynamic method proposed in [13, 14].

The results obtained are intended, first of all, for the development of vibration protection and vibration isolation systems for technical objects, the design of which includes air springs and air damping shock absorbers with rubber-cord casing.

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