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

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Abstract. The method for experimentally constructing the geometric characteristics of pneumatic elements with rubber-cord casing at zero and quasi-zero pressure is proposed. The practical implementation of the method by the example of the rubber-cord shell of the balloon type of model N-50 is illustrated. The processed experimental data in an analytical form presents the empirical dependences of the internal volume on the height of the pneumatic element at zero and quasi-zero overpressure. The obtained parameters are mandatory for the model of air spring and study the damping phenomenon. The results obtained are intended 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.

1. Introduction

With the automotive field development, it has become increasingly relevant the inclusion of new technologies in a city car that improve driver and passengers' comfort and that help vehicle drivability [1]. Pneumatic elements with rubber-cord casing of various designs are widely and successfully used in vehicle suspensions and damping systems for stationary objects, which make it possible to effectively absorb static, dynamic and shock loads. When calculating the operation parameters of pneumatic elements, an important role is played by the geometric characteristic, which determines the dependence of the internal volume on the height of the pneumatic element and internal overpressure.

The description of the method for constructing geometric characteristics in the published materials is absent, although the results are given [2]. The reason, apparently, is traditional - a trade secret. In this regard, the situation still remains, as it was dozens of years ago (almost all published and publicly available materials belong to domestic authors): «Despite the widespread use of air 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» [3]. Therefore, at this point in time there is no opportunity to exhaustively discuss the issue raised.

The presented study touches upon a special case that is important for practice and relates to small (quasi-zero) excess pressure values, when a priori we can consider the influence of relaxation processes to be negligibly small and follow the method proposed in [4]. The indicated two geometrical characteristics at quasi-zero pressure in combination with isobar force characteristics is quite sufficient for a complete mathematical description of the properties of pneumatic elements [5, 6].

2. Formulation of the problem

In the theoretical description of this characteristic, it is traditionally assumed that the rubber-cord casing is absolutely flexible with an inextensible middle surface. As a result, the fundamental relationships are established [4, 7]

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

that bind the force P, overpressure $p_u = p - p_{atm}$ (p – absolute pressure, p_{atm} – atmospheric pressure), effective area F_{eff}, internal volume V and height (coordinate) of the pneumatic element x. Determining experimentally P, p_u at different values x the effective area $F_{eff}(x)$ is found by the first formula (1), and the internal volume $V(x)$ is determined by the second formula:

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

The volume V_0 at a fixed value x_0 is determined experimentally, for example, by pouring water at zero gauge pressure. An alternative method [4, 7] is also possible, when the $V(x)$ dependence is experimentally determined by pouring water, and then the $F_{eff}(x)$ dependence is determined by differentiation.

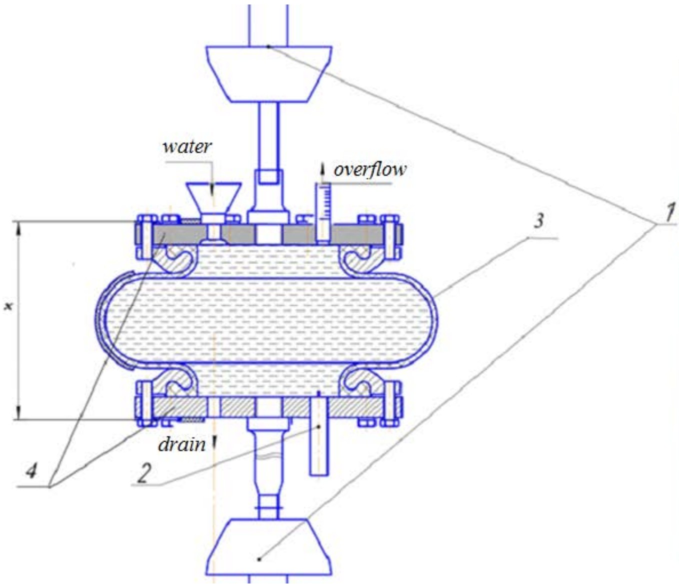
A direct comparison with the known experimental data [2] indicates a large error in formulas (1), (2) associated with the dependence of the internal volume V not only on height x but also on excess pressure p_u due to deformability of the middle surface of the rubber-cord shell [5, 6].

The experimental determination of the general dependence $V(x, p_u)$ is associated with significant difficulties. In [4] it is proposed to measure the internal volume of a pneumatic element by pouring liquid (for example, water) into it and compressing it under a press to a predetermined pressure recorded by a manometer. Pouring different amounts of liquid and measuring the corresponding height of the pneumatic element, you can get a number of points of the curve of the dependence of volume V on height x at a given overpressure p_u. However, the results obtained in this way significantly depend on the sequence of measurements. For example, if a pneumatic element with a filled volume of liquid begins to compress from the unloaded state to a predetermined height value x, and then withstand for a long time (one to two hours) at $x = const$, the excess pressure, which reached a certain value by the time the withstand starts, will decrease monotonously (first quickly, and at the end of the exposure is negligible), assuming the value of the p'_u by the time the withstand ends. If the pneumatic element (with the same filled liquid volume) is stretched from the loaded state to a previously set height value x, and then it is withstand for a long time at $x = const$, then the excess pressure, which has reached a certain value by the time the withstand starts, will increase in a similar manner. taking the value p''_u at the end of the exposure. The difference between the values p'_u, p''_u, can reach several atmospheres (bar), which indicates a negligible rate of relaxation to the equilibrium state. As a result, the true value of the equilibrium overpressure lying between p'_u and p''_u is undefined. How to get around this difficulty is currently unknown. The catalog of the leading American company Firestone [2] for pneumatic elements of different designs provides experimental geometric characteristics related to constant pressure p_u = 7 bar.

3. Experimental method

3.1.Description of the experimental stand, means of testing and measurement, the object of study The experimental stand (Fig. 1), mounted in the grips of an Instron 8805 servohydraulic testing machine, is rigidly held in a predetermined position, changing from measurement to measurement. The stand includes a rubber-cord casing (RCC) of the balloon type of the model N-50 (figure 1, position 3), closed from the ends by steel flanges (figure 1, position 4). On the flanges there are special openings for filling and draining the liquid (if necessary, sealed with plugs), in which silicone tubes are fixed (figure 1, position 5). The volume of liquid being poured is controlled by a measuring cylinder. Grip control (displacement with force limitation) is carried out through a personal computer using the Bluehill 3 software.

The force on the grip is measured by a Dynacell load cell with a relative error of 0.5%. Move on the grip is controlled by a built-in displacement sensor with an absolute error of 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 12000 Hz. The volume of liquid being poured is measured by a 500 ml measuring cylinder with an error of 2.5 ml.



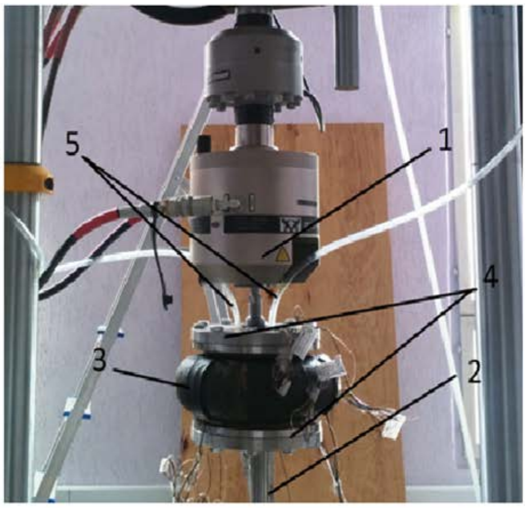


Figure 1. Scheme and general view of the experimental stand:
1 – grips, 2 – overpressure sensor, 3 – RCC, 4 – flanges, 5 – nozzles.

The pneumatic element with a rubber-cord casing of the balloon type of the model N-50, which is commercially available from the leading domestic company FSUE «FRPC «Progress» [8], was taken as an object of study. Under normal operating conditions, 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).

Boiled water was used as a working medium, which, at sufficiently small excess pressures, can be considered incompressible with accuracy acceptable for practice. The tests were carried out in isothermal conditions at a temperature of 20°C.

3.2. Test procedure at zero gauge pressure

After installation in Instron gripps, the pneumatic element is displacement to a height between the flanges x = 155 mm and is filled with water using a measuring cylinder through silicone tubes (figure 1). The amount of water filled corresponds to the volume of the shell $V(x_{\max})$. Then the pneumatic element is compressed by a grip to a position with a minimum coordinate ($x_{\min}$ = 75 mm) in successive steps of 5 mm. At each step, the amount of water displaced during shell deformation is measured. In the described way, the empirical values of the internal volume of the shell are found, depending on the coordinate of the mutual arrangement of the flanges at zero overpressure, indicated by dots in figure 2.

3.3. Test procedure for quasi-zero gauge pressure (0.1 bar, 0.2 bar)

After installation in Instron gripps, the pneumatic element is displaysment to a height between the flanges = 155 mm and is filled with water (the volume of fluid is known from previous experience). Then the filler holes are hermetically sealed with plugs. Then the pneumatic element is compressed by the grip until an excess pressure of 0.1 bar (0.2 bar) is created inside the shell and the corresponding coordinate x value is determined. Then the pneumatic element returns to its original position (x = 155 mm) and, with open plugs, the traverse is compressed by 5 mm. Water is displaced and a liquid volume remains in the shell corresponding to the new position (x = 150 mm) at zero gauge pressure.

Then the holes are sealed with plugs and the procedures and measurements are repeated, as in the previous step of the experiment.

The grip compression cycles are repeated to the position x_{min} = 75 mm (with the plug open) in successive steps of 5 mm. At each step, a pressure steady of 0.1 bar (0.2 bar) is monitored and the corresponding coordinate value is measured. In this way, the values of the internal volume of the pneumatic element are obtained depending on the coordinate of the relative position of the flanges at an overpressure of 0.1 bar and 0.2 bar (figure 2).

4. Experiment Results

For the analytical description of the obtained empirical dependencies, the cubic regression equation was used:

$$V(x) = a_V + b_V(x - x_0) + c_V(x - x_0)^2 + d_V(x - x_0)^3, \quad (3)$$

Where x_0 = 112 mm - the coordinate of the pneumatic element in its middle position. The values of the regression coefficients given in the table were determined by the least squares method. The graphs of the corresponding empirical dependences together with the initial experimental data are presented in figure 2. On average, the relative error for all three empirical dependencies (3) does not exceed 0.112%.

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

Overpressure p_u, bar	coefficients of the regression			
	a_V, liter	b_V, liter /m	c_V, liter /m^2	d_V, liter /m^3
0	2.921	24.350	–113.984	–606.824
0.1	2.967	24.672	–105.759	–409.96
0.2	3.004	25.155	–104.57	–513.239

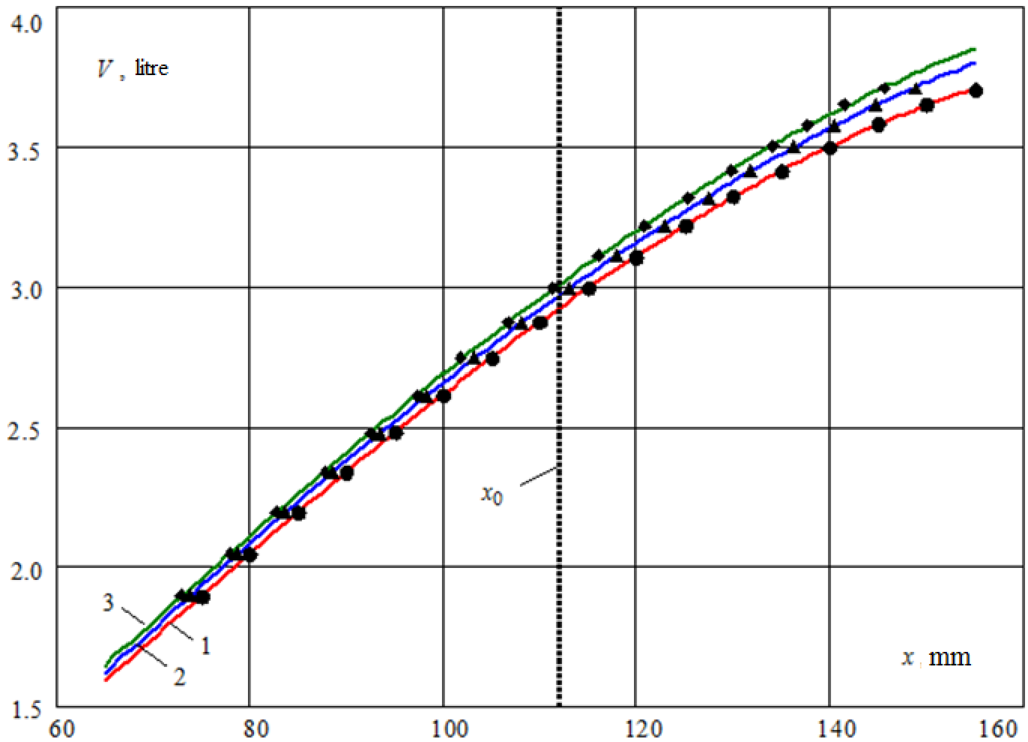


Figure 2. Empirical geometric characteristics (solid lines) pneumatic element with RCC model N-50 and primary experimental data (points) at constant overpressure: 1 p_u – = 0; 2 p_u – = 0.1 bar; 3 p_u – = 0.2 bar.

5. The work results

The obtained parameters are mandatory for the model of air spring and study the damping phenomenon. The relaxation effect strongly affects the fineness of the experimental results. The average relative error with quasi-pressure does not exceed for all data $\varepsilon_V = 0.112\%$.

6. Conclusions

Using the example of a pneumatic element with a rubber-cord casing of a balloon type of model N-50, an experimental method for constructing isobar geometric characteristics that describe the dependence of the internal volume of a pneumatic element on its height is illustrated. The accuracy of the results obtained by the described method is significantly affected by the amount of overpressure for which the corresponding isobaric characteristic is built. The reason for this is the viscoelasticity of the rubber-cord casing and the small changes in the internal volume of the casing associated with it: at the withstand stage, at a constant height of the pneumatic element, the casing volume under the influence of excessive pressure slowly and monotonously changes, striving for a certain limiting (equilibrium) value. At the same time, due to the low compressibility of the working medium (water), even a slight change in volume (by hundredths of a percent) leads to a significant change in pressure (and the force of the pneumatic element). The process of transition to an equilibrium state is extremely long and takes a lot of time. Therefore, in tests at high pressures (from 1 bar and above) it is not possible to achieve an equilibrium state in an acceptable period of time. A more general experimental method for constructing isobaric geometric characteristics of pneumatic elements at finite excess pressures with sufficient accuracy at the current time is unknown or is contained in unpublished reports of shell manufacturers.

An alternative to the indicated general method of direct experimental construction of isobar geometric characteristics of pneumatic elements is a calculation-experimental method based on the thermodynamic description of isobar force characteristics determined in tests of pneumatic elements with air (or any other gas) as a working environment. Due to the high compressibility of the air, minor changes in the internal volume of the pneumatic element during relaxation to equilibrium cause negligibly small concomitant changes in the internal pressure (and the efforts of the pneumatic element). To construct isobar geometric characteristics at any pressure using the thermodynamic method proposed in [5, 6], it is enough to have experimental values of the internal volume at two different values of internal overpressure, moreover, for one fixed value of the height (coordinate) of the pneumatic element. The need for these additional data is exhaustively ensured by the construction of isobar geometric characteristics at small (quasi-zero) values of excess pressure, when a priori the influence of relaxation processes can be considered negligible. In the study, the values of 0.1 bar and 0.2 bar are conventionally taken as quasi-zero values.

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 pneumatic air damping shock absorbers with rubber-cord casing.

7. References

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