The experimental method for testing relaxation of pneumatic elements with a rubber-cord casing

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Abstract. The method for the experimental study of the viscoelastic properties of pneumatic elements with a rubber-cord casing is proposed. Based tests of relaxation in which the height of the pneumatic element is kept constant (a practically incompressible fluid is used as the working medium). The implementation of the method is illustrated by the example of the rubber-cord casing of the balloon type of model N-50. The value of the absorption coefficient (relative hysteresis) is established, which in order of magnitude coincides with the value of the absorption coefficient of tread rubbers given in literary sources. In the process of holding the height of the pneumatic element at a constant level, increments of the force of the pneumatic element and overpressure are proportional to each other with a proportionality coefficient depending on the value of the internal volume and height of the air element. The comparative analysis of the features of the operation of pneumatic elements in cases where the working medium is a gas or liquid is done. The results obtained are of interest in the development of vibration protection and vibration isolation systems for technical objects, the design of which includes air springs, air damping shock absorbers and rubber-hydraulic vibration mounts.

1. Introduction

In systems of vibration protection and vibration isolation of various technical objects, pneumatic elements (PE) with rubber-cord casings are widely used, which have a number of undeniable advantages. According to available quantitative estimates, [1] 92% rubber-cord composite consists of rubber (around to the equator of the balloon-type shell of the model N-50), although almost the entire applied load is absorbed by the cord fibre. On the other hand, according to the data of cyclic tests of tread rubber with a strain range of about 5 ... 6% at frequencies of 1 ... 10 Hz, the absorption coefficient (relative hysteresis) is of the order of 0.53 ... 0.62 [2]. In other words, the dissipated energy spent on heat generation is approximately 53 ... 62% of the work expended during loading. On the basis of this, the question naturally arises of how strongly the viscoelasticity of the rubber-cord casing material affects the operation of the pneumatic element. Experimental data of this kind are not given in the scientific and technical literature [3-7].

In mechanics of a deformable solid, the process of change deformation in time at constant stress is called creep, and the process of change in stress at constant strain is called relaxation [8]. Experimental studies of creep and relaxation processes under uniaxial tension (compression) form the basis of different versions of the technical theory of creep.

Following the terminology of the mechanics of a deformable solid, the process of changing force of the pneumatic element (and overpressure) in time of the at a constant height (coordinate) of the pneumatic element is appropriate to call relaxation, and the process of changing the height of the pneumatic element in time of at constant force – creep. Relaxation and creep tests are a convenient tool for the experimental determination of the viscoelastic characteristics of pneumatic elements with rubber-cord casing. At the same time, a certain gas or liquid (usually air or water) can be used as a working environment in the tests. Due to the great compressibility of the air with its use, it is possible to experimentally obtain the static (elastic or equilibrium) isobar characteristics of the pneumatic element with high accuracy. On the other hand, the indicated advantage of air as a working medium is a disadvantage in determining the viscous properties pneumatic element with rubber-cord casing. Small changes in the internal volume of the pneumatic element during relaxation to equilibrium are accompanied by such insignificant changes in excess pressure that they cannot be measured accurately enough. On the contrary, due to the weak compressibility of the water, even small changes in the internal volume of the pneumatic element during relaxation to equilibrium lead to significant changes in water pressure, which can be measured even with conventional manometers with high accuracy. The experimental data established in this case allow obtaining reliable results when determining the viscous characteristics of a pneumatic element (as well as elastic characteristics, but with less accuracy than in the case of air as a working medium). Thus in experimental studies of rubber elements with a rubber-cord sheath, it is advisable to use the combined method, when the elastic characteristics are determined from tests of a pneumatic element with some gas as a working environment (for example, air), and viscous characteristics are found from tests of a pneumatic element with some liquid as a working environment (for example water).

In the study of relaxation 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» [9].

2. Experimental method

2.1. Object of study

The pneumatic element with a rubber-cord of casing he balloon type of the model N-50 has an average height (coordinate) x = 112 mm, the maximum compression and rebound stroke is Δx = ± 40 mm (from the average position of the pneumatic element). Under normal operating conditions, the working medium is air supplied to the internal cavity in the middle position of the pneumatic element under overpressure p_u = 4 bar. The shell maintains its operability at a temperature from – 45°C to + 50°C.

2.2. Working environment.

Boiled water was used as the working environment. At a test temperature of 20°C, the volume of water is associated with overpressure p_u by the equation of state

$$V = V_0\left(1 - \beta_\theta p_u\right), \tag{1}$$

where $\beta_\theta = 4.525 \cdot 10^{-10}\ \text{Pa}^{-1}$ is the coefficient of isothermal compressibility of water [10], V_0 is the experimentally determined volume of water poured into the pneumatic element at zero overpressure in a fixed (arbitrarily specified) position of the pneumatic element with coordinate x_0.

2.3. 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 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. The volume of liquid being poured is measured by a 500 ml measuring cylinder with an error of 2.5 ml.

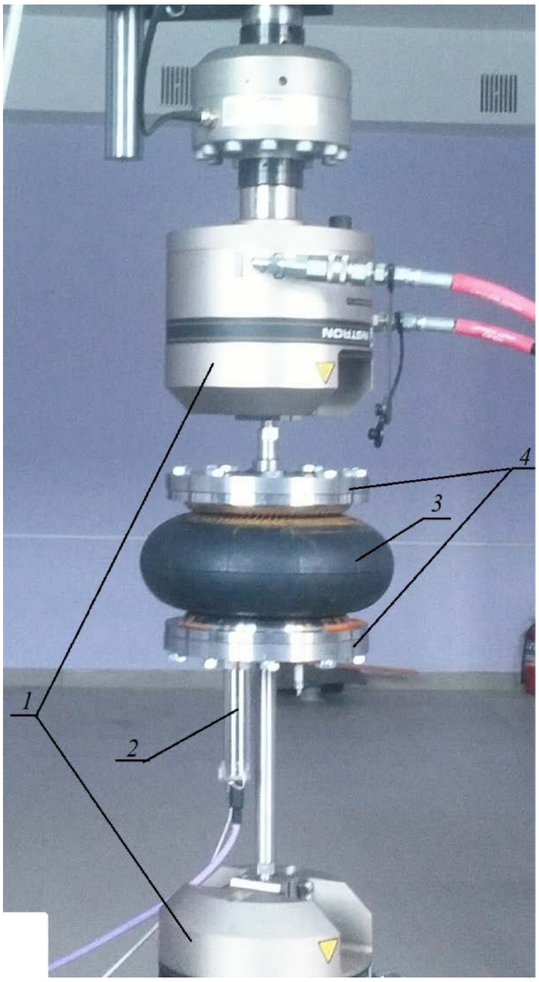

Figure 1. Scheme and general view of the experimental stand:
1 – grips; 2 – gauge overpressure 3 – rubber cord casing (RCC); 4 – flanges;

2.4. Test methodology

After installation in Instron grips, the pneumatic element is displayed at the initial height between the flanges x_0. By means of Bluehill 3 software, this position is assigned as the reference point for the movements of the upper grip. Then the pneumatic element is filled with a measured volume of liquid V_0 and sealed. The movements of the upper grip are controlled via a personal computer using the Bluehill 3 software using the three-stage program shown in figure 2.

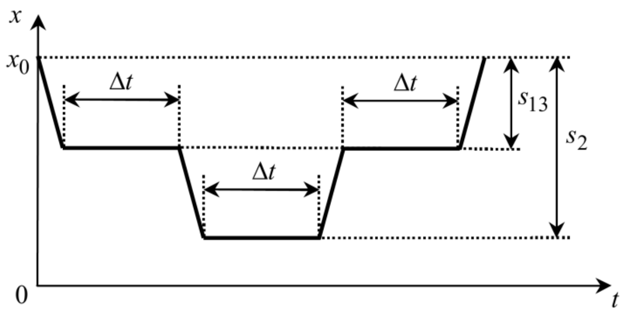

Figure 2. Relaxation test program

At each of the three stages, the capture for a period of time Δt = 40 ... 60 min (longer exposure time is needed in tests with a greater load of the pneumatic element, so that the relaxation process to equilibrium is closer to its completion) is maintained in a fixed position, which corresponds to the displacement s_{13} (for the first and third stage) and s_2 (for the second stage). The values s_{13}, s_2 are set separately for each test, as the values of the initial height x_0 and constant values of the speeds of movement of the upper grip between the steps, the same in absolute value. The values of the initial height x_0, fluid volume V_0, and displacement s_{13} at the first and third stages are determining for a separate test and subsequent processing of experimental data, the auxiliary displacement value at the second stage was assigned from the condition $s_2 = (1.12...2)s_{13}$. Here it was important to ensure that the overpressure during displacement does not reach the pressure of the destruction of the pneumatic element.

Throughout the test, the force at the upper grip, the displacement of the upper grip and the overpressure using Bluehill 3 and ZETlab software were automatically recorded on a computer (with a given frequency of data acquisition).

Subsequently, the force on the upper grip was recalculated taking into account the weight of the upper flange and the parts rigidly connected with it, equal to 56.3 N.

The experiment is repeated for all initial heights and displacements of interest s_{13}, s_2.

3. Experiment Results

We illustrate the results of the study using the test example with the initial height of the pneumatic element x_0 = 155 mm, the displacement of the first and third steps s_{13} = 60 mm, the displacement of the second stage s_2 = 68 mm. The volume of liquid poured V_0 = 3.709 liter. The exposure time Δt = 60 min, the speed of capture between the steps of 0.5 mm / s.

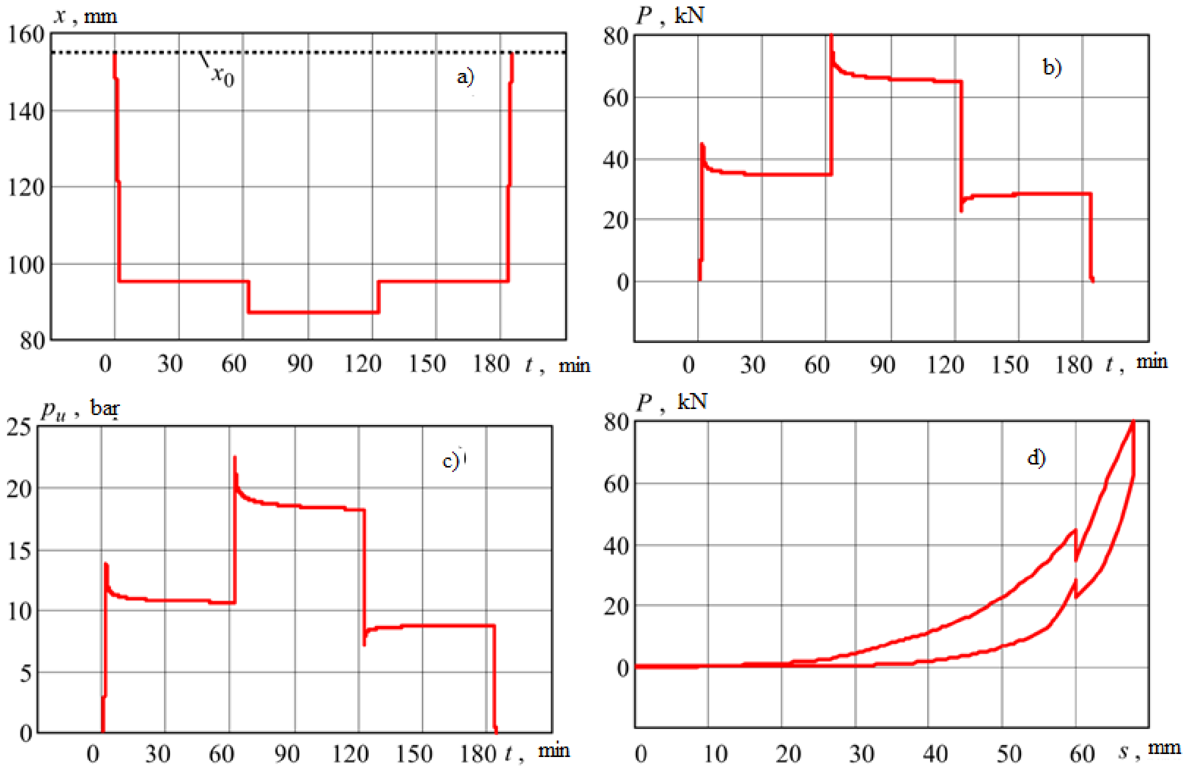

Figure 3. Primary experimental test data for relaxation of a PE with a RCC of the balloon type of the model N-50 at x_0 = 155 mm, s_{13} = 60 mm, s_2 = 68 mm:
a – the height of the PE depending on time; b – PE force depending on time;
c – overpressure depending on time; d – indicator chart

The primary experimental test data are presented in Fig. 3 in the form of four graphs: the specified law of change in the height (coordinate) of the pneumatic element (figure 3, a) established by measuring the law of change in the force of the pneumatic element (figure 3, b) and the law of change of overpressure (figure 3, c), and the indicator diagram *force* P *– displacement* s (figure 3, d), which visually reflects the ongoing relaxation processes from an energy point of view. In this test, closed by displacements, the absorbed work equal to the area of the hysteresis loop is 584.1 J, and the work performed during loading (during compression from coordinate x_0 to coordinate $x_0 - s_2$) is 1058.4 Joule. Therefore, the absorption coefficient, as the ratio of the indicated values, has a value $\psi = 0.552$, which in order of magnitude coincides with the previously mentioned value of the absorption coefficient (relative hysteresis) of tread rubber [2].

4. The discussion of the results

Relate the graphs of the force of the pneumatic element (figure 3, b) and overpressure (figure 3, c) to the total time reference for all three stages of the test at a constant height of the pneumatic element (figure 4). After 60 minutes of exposure at the first test stage, the force of the pneumatic element and overpressure reach 34.2 kN and 10.7 bar, at the second test stage - 64.9 kN and 18.2 bar, and at the third test stage - 28.0 kN and 8.7 bar. If we trace the evolution of the behavior of the force of the pneumatic element and overpressure for only one stage of the test, not paying attention to the other two stages (figure 4), then the corresponding (indicated) values could be taken as the equilibrium values of the force of the pneumatic element and overpressure. However, when the first and third stages of testing become the object of attention at the same time (figure 4), then two options seem possible:

1) at a fixed height of the pneumatic element, there are two (significantly different from each other) equilibrium values of the force of the pneumatic element (and overpressure) depending on the sign of the speed with which the height of the pneumatic element was changed until it was fixed;

2) at a fixed height of the pneumatic element, the equilibrium value of the force of the pneumatic element (and overpressure) is unique, it is located exactly somewhere between the corresponding (above) values for the first and third stages, probably coinciding (or maybe not) with the average value (between first and third steps), equal to 31.1 kN (and 9.7 bar).

If proceed from the fact that the rubber-cord composite in addition to its elastic properties has plastic properties (by the type of dry friction between solids), then the first option will be legitimate. On the contrary, if we assume that the rubber-cord composite has elastic and viscous properties (like internal friction in a liquid), then the second option should be recognized as legitimate. Moreover, the effective viscosity of the rubber-cord composite is so large that, according to preliminary rough estimates, the time to reach the equilibrium state (in the test) is many orders of magnitude greater than the age of the Universe, which is about 14 billion years.

Consider the increment of the force of the pneumatic element and overpressure from the point in time t_0 - the beginning of the exposure of the height of the pneumatic element constant:

$$\Delta P(t) = P(t) - \Delta P(t_0), \quad \Delta p_u(t) = p_u(t) - \Delta p_u(t_0) \tag{2}$$

Based on the time dependencies in figure 4 and assuming without loss of generality $t_0 = 0$, it is possible to construct graphs of the dependence between the increments (2), which are presented in figure 5. As you can see, the functional relationship between the increment of the force of the pneumatic element and the increment of excess pressure is almost linear.

In other words, at each of the three steps, the increments $\Delta P(t)$ and $\Delta p_u(t)$ are proportional to each other with a proportionality coefficient equal to the slope of the corresponding segments of straight lines starting from the origin (in figure 4, marked with a dot). For the first and third stages, the indicated proportionality coefficients coincide with high accuracy, and for the third stage it is noticeably larger in magnitude. This fact is of great importance in the mathematical modeling of the viscoelastic properties of rubber-cord casing that are part of pneumatic elements.

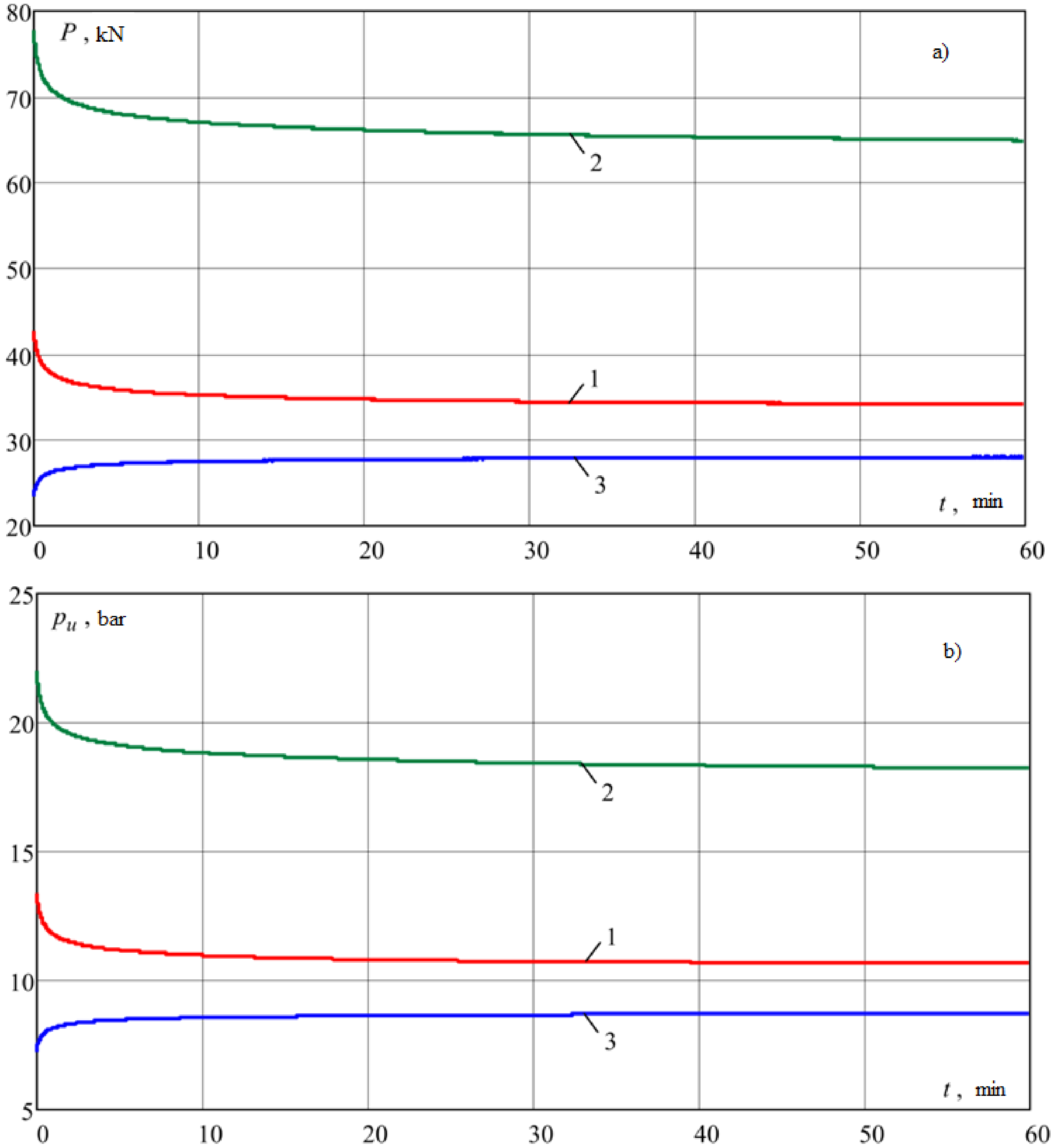

Figure 4. Force of the pneumatic element (a) and overpressure (b) during relaxation to equilibrium: 1 – the first stage of the test; 2 – the second stage of the test; 3 – third stage of the test

Finally, according to the equation of state of water (1) and the initial experimental data for overpressure (figure 3, c), it is possible to estimate how much the magnitude of the internal volume of the pneumatic element changes during the test (figure 6).

The maximum absolute deviation of the internal volume of the pneumatic element from its initial value V_0 = 3.709 liter is an extremely small value: 3.778 milliliters, which allows us to speak about the constancy of the internal volume of the pneumatic element with an accuracy of 0.102%. In the case of air used as the working medium of the pneumatic element, such small changes in volume lead to the same small (0.102% for ideal gas) increments of overpressure (and the force of the pneumatic element), which can be neglected with sufficient accuracy for practice

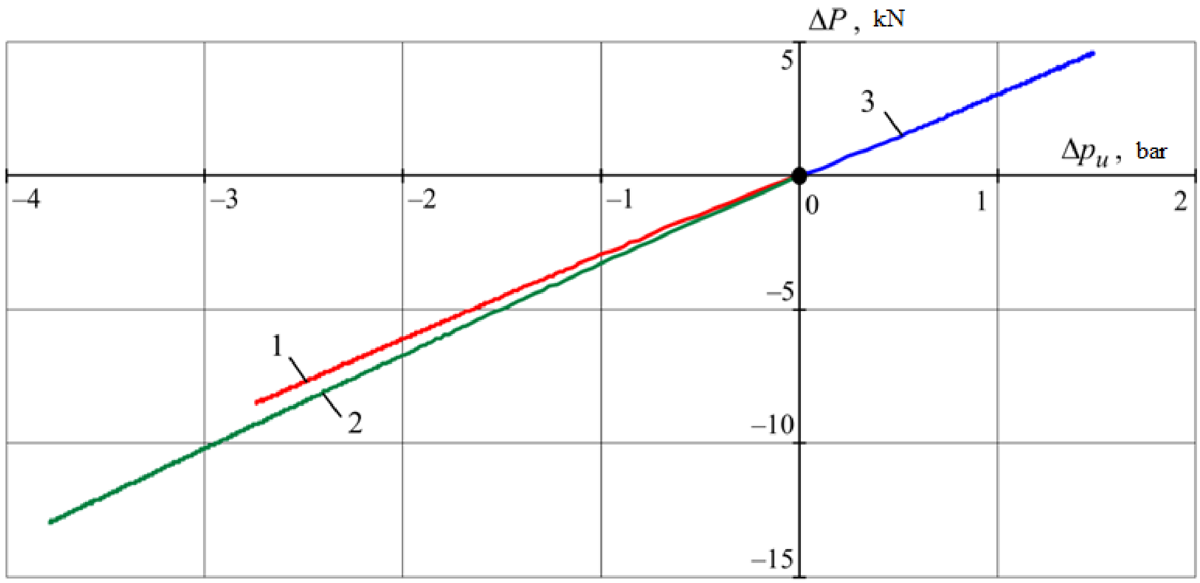

Figure 5. Functional relationship between increments of the force of the pneumatic element and excess pressure during relaxation to equilibrium (the lines come from the origin, marked by a point): 1 - the first stage of the test; 2 - the second stage of the test; 3 - third stage of the test

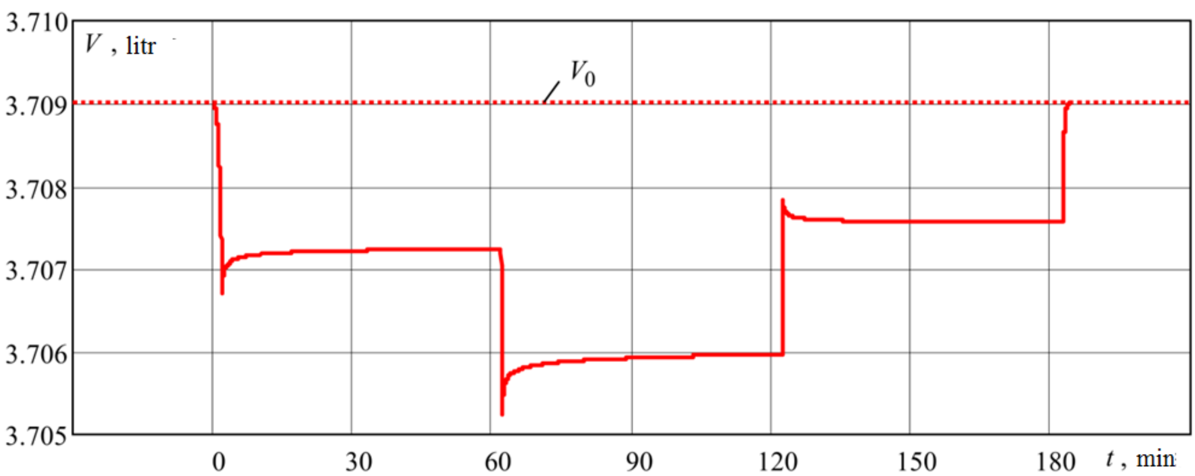

Figure 6. Change in the internal volume of the pneumatic element (volume of flooded water) in the relaxation test at x_0 = 155 mm, s_{13} = 60 mm, s_2 = 68 mm

5. General conclusions

The rubber-cord composite consists of reinforcing cords and a rubber matrix. Cord nylon fabrics, widely used in the manufacture of rubber-cord cases, have pronounced elastic properties and have an elongation at break of slightly less than 30% [11]. Rubber (and other elastomers) exhibit the viscoelastic properties of [12]. During the deformation of rubber, the internal viscous forces slightly dominate the internal elastic forces [2]. Therefore, if there is no slippage of the cord relative to the rubber matrix, the rubber cord composite is a viscoelastic material. If slippage occurs, then in addition to the viscoelastic properties, the rubber-cord composite will also have plastic properties such as dry friction. To increase the durability of rubber-cord cases, in their manufacture, special technological methods are used for the best adhesion of the cord threads and the rubber matrix. Therefore, from a technical point of view, the rubber-cord composite is a viscoelastic material. Further, the metal reinforcement of the pneumatic element can be considered undeformable with high accuracy, and the work of the forces of interaction between the reinforcement and the rubber-cord cases at their contact points is negligible due to the high adhesion of the coating rubber to the metal. From the foregoing, on the basis of the study, the following two conclusions can be drawn:

1) in the process of relaxation at a fixed height of the pneumatic element, the equilibrium values of the force of the air element and overpressure are unique;

2) even at very low deformation rates, the work of the internal viscous forces of the rubber-cord casing of the N-50 model is about 55.2% of the work spent during loading (the latter means the excess of the internal forces of viscous resistance over the internal elastic forces of the shell).

According to the theorem on the change in kinetic energy, the rate of change of kinetic energy is equal to the sum of the powers of external and internal forces. If, for simplicity of analysis, we restrict ourselves to rather slow processes of changing the height of the pneumatic element (as in the tests) and conditionally set the absolute pressure in the environment surrounding the pneumatic element to zero, then the work of external forces applied to the pneumatic element assembly will be equal to the work of the internal forces of the pneumatic element taken with the opposite sign. In turn, taking into account the foregoing, the work of the internal forces of the pneumatic element will consist of the work of the internal forces of the rubber-cord shell and the work of the internal forces of the working environment.

When the working environment in the pneumatic element is some practically incompressible fluid, as for example in rubber-hydraulic vibration mounts [13], the work of the internal forces of the working medium is zero. Therefore, the work of external forces coincides in modulus with the work of the internal forces of the rubber-cord case, in which the proportion of the work of internal viscous forces predominates. From this we conclude that in the mathematical modeling of rubber-hydraulic vibration mounts, it is necessary to take into account the inelasticity of the rubber-cord sheath material in order to ensure acceptable accuracy of engineering calculations.

In most technical applications, [3-7] air is used as the working environment in the pneumatic element. In this case, the work of the internal forces of the working medium is nonzero and, as a rule, significantly exceeds the work of the internal forces of the rubber-cord casing. Indeed, with the traditional method of calculating pneumatic elements [4, 5], it is assumed that the rubber-cord casing is absolutely flexible and its middle surface is inextensible. Therefore, the work of the internal forces of the rubber-cord shell is zero, and the work of external forces is completely determined by the work of the internal forces of the working medium, which have an overwhelming elastic character (the dynamic viscosity coefficient of air and other gases is extremely small). When comparing with experimentally obtained static (equilibrium) isobar power characteristics of [7] pneumatic elements, the traditional method shows a large error reaching 10 ... 50% for rubber-cord shells of balloon type [14] and 60 ... 90% for rubber-cord casing of sleeve type [15]. An acceptable agreement between the experimental and calculated data can be achieved by taking into account the elastic deformations of the rubber cord casing [14, 15]. Therefore, the noted relative errors indicate the order of magnitude of the correction for the contribution of the internal elastic forces of the rubber-cord membrane to the force of the pneumatic element. On the other hand, as shown above, the internal elastic forces of the rubber-cord shell are smaller by an order of magnitude than the internal viscous forces. It follows that, depending on the design and size of the pneumatic element, the work of the internal viscous forces of the rubber-cord shell will be about 10% and higher from the work of external forces applied to the pneumatic element. Of course, this estimate is approximate, but it allows us to draw a qualitative conclusion about the need for additional theoretical and experimental studies of the viscous properties of pneumatic elements with a rubber-cord shell in order to increase the accuracy of calculations of vibration-proof and vibration-insulating systems, which include pneumatic and hydraulic elements with a rubber-cord casing.

6. Conclusions

The proposed experimental method is based on a three-stage test program for the relaxation of rubber-cord casing of pneumatic elements using a fluid as a working medium. Due to this, the relaxation curves for the first and third stages of the test, at which the height of the pneumatic element has the same value, but different signs of the rate of change before retention, it is possible to more reliably estimate the values of the force of the pneumatic element and overpressure, which are achieved after an extremely long process of relaxation to equilibrium . At all three stages of holding the height of the pneumatic element at a constant level, the functional relationship between the increment of the force of the pneumatic element and the increment of overpressure is almost linear. This fact is of great importance in the mathematical modeling of the viscoelastic properties of rubber-cord casing that are part of pneumatic elements.

In experimental studies of pneumatic elements with a rubber-cord casing, it is advisable to use the combined method, when the elastic characteristics are determined according to tests of a pneumatic element with air as a working medium, and viscous characteristics are found according to tests of a pneumatic element with water as a working environment.

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.

7. References

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