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DETERMINING REGULARITIES OF THE STRESSED-STRAINED STATE OF FLEXIBLE SHELL OF THE PNEUMATIC SPRING MADE OF POLYMERIC MATERIAL

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Pneumatic springs make it possible to implement the «soft» characteristics of the suspension of vehicles, which provides comfortable conditions for passengers and reduces the dynamic load on the road surface. The issue of the strength of the flexible shells of pneumatic springs, which are made of rubber cord, remains relevant. Strains that stretch flexible shells, which arise in the process of movement, cause ruptures of rubber cord, thereby reducing their reliability. At present, there is a global tendency to replace rubber cord with polymeric materials. This paper reports a study of the strength of a two-sided flexible shell of the cylinder type under different operational modes of a pneumatic spring. The research was carried out using a finite-element method. The peculiarity of the pneumatic spring design is that the diameters of the bottoms and inter-corrugation ring are increased to the size of the outer diameter of the flexible shell in order to improve the stability and damping properties of the pneumatic suspension. The flexible pneumatic spring shell is made of polymeric material. It is proved that the stress in the material of the flexible shell increases in proportion to the air pressure in its cavity; their greatest values are observed in places where the flexible shell is fixed to the bottoms. When approaching the equator of the shell, they gradually decrease by an average of 20 % in both corrugations. The increase in the radius of the equator in both corrugations of the flexible shell did not exceed 20 mm. With a mutual transverse displacement of the bottoms by 40 mm and excessive air pressure of 0.5 and 1.0 MPa, the stress in the flexible shell material was 2.9 MPa and 5.9 MPa, respectively. This is almost five times less than the strength limit of the material for breaking (30 MPa). Thus, the selected parameters ensure the strength of the flexible pneumatic spring shell: it can be recommended for use on vehicles

Keywords: vehicle air suspension, strength of the flexible shell of a pneumatic spring, stress in the polymeric material of the flexible pneumatic spring shell

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1. Introduction

Vibrations and oscillations of vehicles when driving give rise to the issue related to providing comfortable conditions for passengers and maintaining the road surface damage-free.

The global trend for addressing this issue is the use of suspensions employing pneumatic springs (PSs). This makes it possible to implement a nonlinear characteristic and a dynamic suspension travel much larger than when using metal springs, as well as attain the natural frequency of vertical vibrations of the body of about 1 Hz – the most favorable for passengers. Air suspensions also effectively filter noise and vibration. This provides adequate comfort for passengers and reduces the dynamic load on the road surface, which contributes to prolonging its service life.

The effectiveness of air suspensions is proved by the experience of leading states such as Japan, France, China, etc., where they are used on high-speed trains and heavy trucks. Their application is considered an actual direction for improving the technical level of vehicles.

The practice of operating air suspensions revealed several problems. Among them, there is an important issue related to the strength of PS flexible shells, which are made of rubber cord whose exfoliation reduces their reliability.

That restrains the further application of air suspensions on vehicles although their effectiveness is in no doubt. Therefore, studies on the strength of PS flexible shells are relevant.

2. Literature review and problem statement

Paper [1] investigated the vibration characteristics of the Chinese Railways (CRH) train, which is equipped with an air suspension by conducting tests on the track. The vibration characteristics of the body of the car operating at a speed of 350 km/h and their evolution with a long service life were reported. The results show that vibration accelerations of vehicle components are at a low level, which indicates that the ride comfort is acceptable.

In [2], to improve the comfort of rail transportation, a technique for suppressing body vibrations with the help of PS is proposed.

In [3], it is noted that two-chamber air suspensions are used in vibration insulation systems owing to their excellent hardness and cushioning characteristics. A nonlinear integrated stiffness model is proposed, which reflects the dependence on both frequency and the amplitude of excitation. Such an accurate nonlinear model for two-chamber pneumatic springs could contribute to the effective control over vibration insulation systems.

In [4], it is noted that the travel comfort is a function of the frequency of vibration transmission to the driver depending on road irregularities. An objective function of comfort is to accelerate the driver's seat.

Studies [1–4] emphasize the relevance of the issue related to damping vibrations in transport and the effectiveness of air suspensions in solving it. However, the issue of their strength and, accordingly, reliability in operation is not detailed, which is not enough to assess the performance of PS.

Paper [5] reports the analysis and optimization of an air suspension system with the adjustment of the height of the auto-coupling relative to the rails. That allowed the authors to improve the stability of system adjustment. At the same time, there are no possible structural implementations of the elements of the adjustment system.

In [6], modeling was employed to investigate air suspensions for passenger vehicles and precise vibration insulation of equipment. That makes it possible at the stage of designing air suspensions to assess their effectiveness in operation. However, there are no possible structural executions of elements of air suspensions that have sufficient strength and reliability.

Paper [7] reports the results of studying the dynamic load and strength of the components of containers on a platform car. By computer simulation, it was established that during shock interaction there are increased stresses in the structural elements of the platform car. To ensure the strength of the container platform car, it is proposed to install viscoelastic links between them. However, there are no possible design executions of elastic elements that have sufficient strength and reliability.

The authors of [8] built dynamic models of the carrier system of a gondola car, which take into consideration the wear of its elements and make it possible to predict the technical condition. It is argued about the feasibility of the proposed solutions to improve the technical level of the gondola. At the same time, there are no possible structural executions of suspension elements.

Paper [9] outlines a method to study the influence of structural parameters and properties of materials on the characteristics and stressed state of rubber cord cylinders of tire-pneumatic couplings. However, it is not defined how to use the method to calculate the strength of cylinders that are made without cord.

In [10], the theory of the strength of the air suspension is presented; the influence of the design parameters and properties of the rubber cord on the characteristics and stressed state of flexible shells is investigated. However, it is not determined how to apply a given theory to calculate the strength of cylinders that are made of polymers.

Work [11] investigates the strength of a PS diaphragm flexible shell. It is concluded that the design and parameters of the flexible PS shell ensure its strength during operation. However, the issue of the strength of multi-corrugation flexible shells is not explored.

The authors of [12] examine the strength of a single-corrugation PS flexible shell in a vehicle. The stresses in its material are investigated with mutual transverse displacements of the bottoms. The greatest stress in the material of the PS flexible shell did not exceed 11 MPa even at twice the nominal air pressure and transverse mutual displacements of the bottoms of 40 mm, much less breaking strength (30 MPa). It is concluded that the design and parameters of a PS flexible shell of the cylinder type ensure its strength during operation. However, the issue of the strength of multi-corrugation flexible shells and the impact exerted on their strength by transverse and angular displacements of the bottoms that occur in operation is not clarified.

Thus, the task to improve the reliable operation of the pneumatic strings whose flexible shells are made of polymeric materials requires further research.

The above allows us to suggest that it is advisable to continue research into attaining a satisfactory stressed state of flexible shells at loads observed in rolling stock.

That could refine the approach to the calculation and design of complex polymer shells, taking into consideration the elastic physical and mechanical properties of polymers. Despite the widespread use of air suspensions on trains and cars, there are outstanding issues related to their strength and properties regarding damping, which restrains their application. Addressing these issues will contribute to the widespread introduction of air suspensions on vehicles, which could increase their competitiveness.

3. The aim and objectives of the study

The purpose of this research is to determine the laws of the stressed-strained state of the cylinder type PS with a two-corrugation flexible shell and an increased diameter of the bottoms in different configurations and modes of their load.

This will make it possible at the design stage to define the rational parameters for the improved air suspension.

To accomplish the aim, the following tasks have been set:

– to determine the features of the structure and parameters and build an estimation scheme of the improved two-corrugation PS;

– to carry out computer simulation of the stressed state of the flexible shell of the improved PS during loads and strains observed on vehicles;

– to identify the dependence of the amount of stresses in the material of the flexible shell on loads and strains;

– to choose the material for the flexible PS shell.

4. The study materials and methods

The object of this study is the improved pneumatic spring of the cylinder type, which, in contrast to a standard one, has increased diameters of the bottoms and inter-corrugation ring.

The rationale for this is that the cylinder-type PS can implement sufficient damping of oscillations [13] while the diaphragm one cannot. Therefore, along with it, there are always fluctuation dampers, which, unfortunately, are expensive and not reliable enough [14].

The PS flexible shell is made of the polyurethane «Adiprene 167» with the following mechanical properties: 15 MPa elasticity module; 6.68 MPa shear module; a Poisson coefficient of 0.496, a tensile strength of 30 MPa [15].

The drawing of the pneumatic spring (Fig. 1) is reproduced in 3D format using the SolidWorks software (USA) [16].

Our hypothesis assumes the possibility to improve the stressed state of a flexible shell, with given mutual flatly parallel displacements of the bottoms, by making it a multi-corrugation one.

Given the small range of changes in the temperature of compressed air in the air suspension, it was considered constant and equal to the ambient temperature, that is, 293 K.

With the development of computer technologies, it became possible to conduct studies into the strength of the material of flexible pneumatic spring shells when varying their configuration and loads.

Our study was carried out by simulating changes in the magnitude of stresses in the material of a flexible shell using a finite-element method.

The research methodology involving the *SolidWorks* software package (USA) [16] implied the following:

– to derive the fields of the distribution of stresses in the material of the flexible shell under the action of internal excess air pressure in the middle of PS in its nominal position;

– to determine stress distribution fields in the material of the flexible shell at transverse and rotating displacement of its upper bottom and varying the internal excess air pressure inside it;

– to test the ability to maintain the PS shape with mutual transverse displacements of its upper bottom;

– to prove the adequacy of the results obtained regarding the stresses in the material of the flexible shell.

The excess air pressure inside PS was chosen equal to nominal and double the nominal, which can occur at the maximum expected dynamic loads.

5. Results of investigating the strength of the flexible pneumatic spring shell

5. 1. Features of the structure, parameters, and estimation scheme of the pneumatic spring

PS (Fig. 1) consists of a two-corrugation flexible shell, at the ends of which there are the upper and lower bottoms; between the corrugations, there is a ring. The bottom and ring are made of steel.

An air suspension with the regular PS H-5 of the cylinder type was used for one section of the cargo diesel locomotive 2TE116 No 184-b. It has successfully passed dynamic and track tests and two years of operational tests. That proved the expediency of using a cylinder-type PS in vehicle suspensions.

During the tests, it was found that the standard PS, the type H5, demonstrates insufficient stability: there were cases when the corrugations of the flexible shells touched the journal boxes, which led to their destruction. That was due to the loss of shape by the flexible shells, which were made of rubber cord, with mutual transverse displacements of the bottoms in the process of movement. It was possible to get rid of this disadvantage by some increase in the diameters of both bottoms and ring [17].

Cord threads almost do not stretch, so flexible shells containing cord do not make it possible to implement mutual transverse displacements of the bottoms of PS. Therefore, the idea was born to replace the rubber cord with a modern polymer.

Taking into consideration the experience gained in the operation of the diesel locomotive, an improved cylinder-type PS with a two-corrugation flexible shell and an increased diameter of the bottoms (Fig. 1) [18] was designed.

The estimation scheme of PS and the fastening of the lower bottom are shown in Fig. 2; the finite-element grid is in Fig. 3.

In the process of vibration of the body on the air suspension, the air pressure in its cavity changes continuously, which causes appropriate changes in the forces acting on the flexible shell.

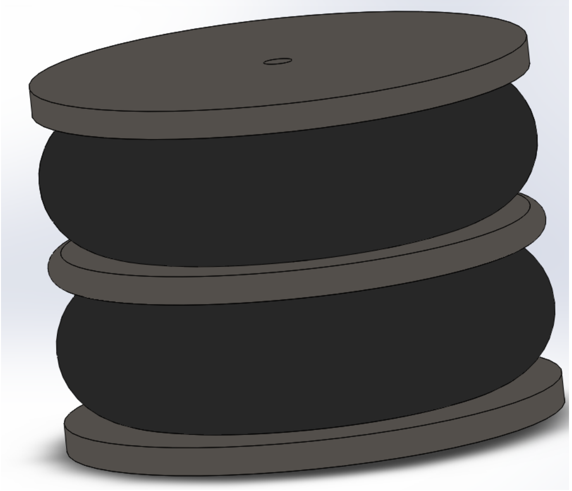

Fig. 1. Diagram of a cylinder-type pneumatic spring with a two-corrugation flexible shell and an increased diameter of the bottoms

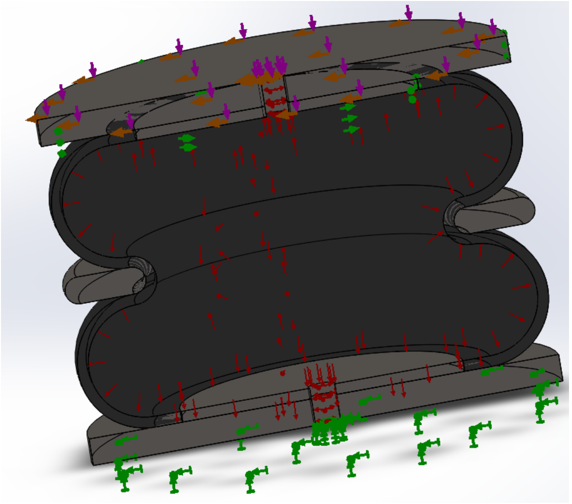

Fig. 2. The estimation scheme of the pneumatic spring: the arrows indicate the direction of air pressure in the cavity of the pneumatic spring and the fastening of the lower bottom

Fig. 3. A finite-element grid of the pneumatic spring in 3D format

Therefore, we calculated its strength for two modes of loading PS: nominal, that is, constant, and double load, which is selected for equivalent to the dynamic load.

5. 2. Simulating the stressed state of the flexible shell of the improved pneumatic spring

We investigated the strength of a PS flexible shell of the cylinder type, made of the polymeric material «Adipren 167», for the following PS configurations and load modes:

– the initial configuration of PS;

– the configuration of PS with transverse displacement of the upper bottom by 40 mm relative to the lower one;

– the configuration of PS with angular displacement of the upper bottom by 3.5° relative to the lower one;

– a PS configuration with transverse displacement of the upper bottom by 60 mm and 80 mm relative to the lower one.

The study was carried out with the following difference in excess pressure in the PS cavity: 0, 0.5, and 1.0 MPa.

Fig. 4, 5 show the fields of the distribution of stresses in the material of the flexible shell at an excess air pressure in its cavity of 0.5 and 1.0 MPa, respectively.

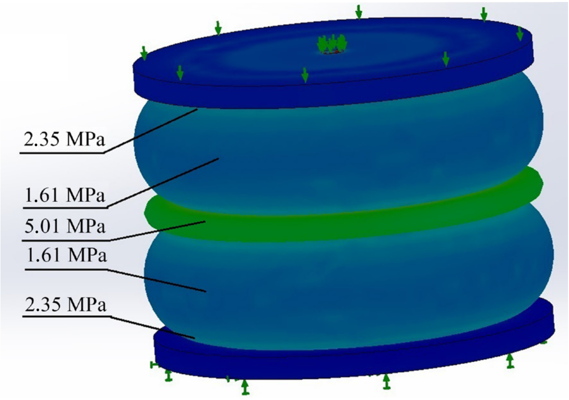

Fig. 4. Stress in the material of the flexible shell at an excess air pressure in its cavity of 0.5 MPa

Our comparison of Fig. 4, 5 proves that with an increase in the excess air pressure in the PS cavity to nominal, the largest stretching stress is 2.35 MPa near the bottoms. Stresses gradually decrease as they approach the equator to 1.61 MPa. With an increase in the excess air pressure, the stress of stretching doubles to 4.7 MPa near the bottoms and to 3.21 MPa at the equator. The increase in the radius of the flexible shell was 38.0 mm.

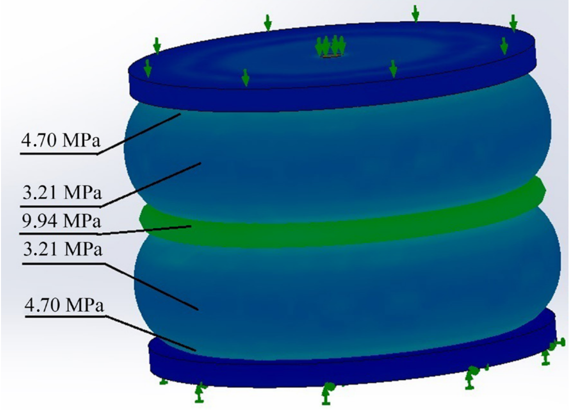

Fig. 5. Stress in the material of the flexible shell at excess air pressure in its cavity of 1.0 MPa

Thus, the stress in the material of the PS flexible shell does not exceed 4.7 MPa and is much smaller than the tensile strength limits (30.0 MPa). The increase in the radius of the flexible shell, in this case, amounted to 39.0 mm.

The stretching stress in the steel ring was 9.94 MPa.

Fig. 6–8 show the stress fields in the flexible shell material at excess air pressure in its cavity of 0 MPa, 0.5 MPa, and 1.0 MPa, and transverse displacement of the upper bottom relative to the lower one by 40 mm.

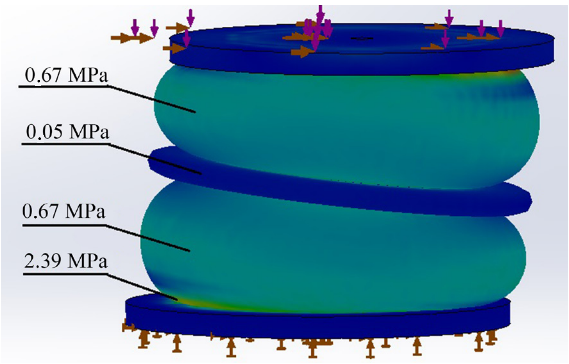

Fig. 6. Stress in the material of the flexible shell at excessive air pressure in its cavity of 0 MPa and transverse displacement of the upper bottom relative to the lower one by 40 mm

It follows from Fig. 6 that the transverse displacement of the upper bottom relative to the lower one causes relatively small stresses in the material of the flexible shell, the largest of which occur near the bottoms (2.39 MPa). There is an appearance of a slope of the ring within 14°.

With an increase in the excess pressure in the PS cavity to 0.5 MPa and 1.0 MPa, together with a transverse displacement of the upper bottom relative to the lower one by 40 mm, the stress in the flexible shell material increases proportionally (Fig. 7, 8).

The greatest stresses are observed near the contacts of the flexible shell with the bottom and ring and reach 2.85 and

5.91 MPa; at the equator, they are less by an average of 19 %. The increase in the radius of the flexible shell was 37.0 mm.

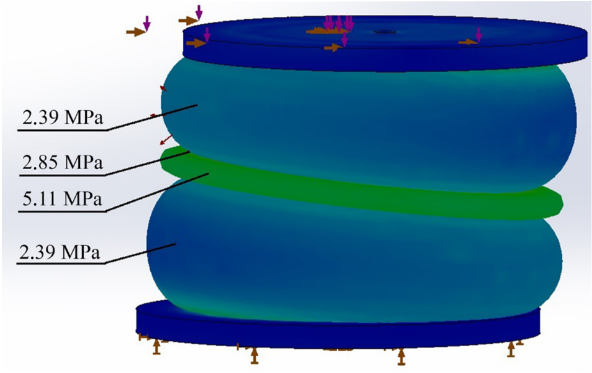

Fig. 7. Stress in the material of the flexible shell at excessive air pressure in its cavity of 0.5 MPa and transverse displacement of the upper bottom relative to the lower one by 40 mm

Thus, the stresses in the material of the flexible shell at excessive air pressure in its cavity are greater than at its absence but remain much smaller than the tensile strength limit (30.0 MPa). The largest displacement of the front point at the equator of the flexible shell at a pressure of 1 MPa was 22 mm in the direction of displacement, which is half that of a single-corrugation shell.

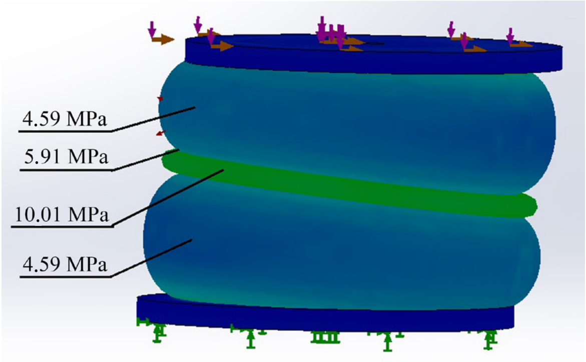

Fig. 8. Stress in the material of the flexible shell at an excess air pressure in its cavity of 1.0 MPa and with transverse displacements of the upper bottom relative to the lower one by 40 mm

The stress in the steel ring (10.01 MPa) has not changed much. The angle of inclination of the ring decreased slightly and amounted to 8°, that is, decreased by 30 %.

Fig. 9–11 demonstrate the distribution of stresses in the material of the flexible shell at an excess air pressure in its cavity of 0.0 MPa, 0.5 MPa, and 1.0 MPa with simultaneous rotation of the upper bottom relative to the lower one by an angle of 3.5°.

It follows from Fig. 9 that with excessive air pressure in the cavity of a flexible shell of 0.0 MPa and with an angular displacement of the upper bottom relative to the lower one by 3.5, relatively small stresses are observed in the shell material. The largest of them occur near the bottoms (0.35 MPa).

With an increase in excess air pressure in the PS cavity to 0.5 MPa and 1.0 MPa, along with an angular displacement of the upper bottom relative to the lower one by 3.5°, the stress in the flexible shell material increases proportionally (Fig. 10, 11).

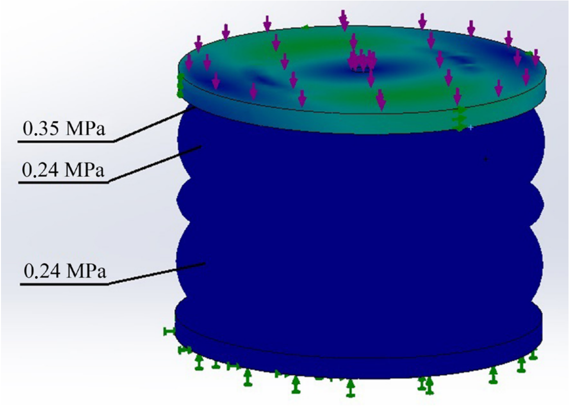

Fig. 9. Stress in the material of the flexible shell at excessive air pressure in its cavity of 0.0 MPa and with an angular displacement of the upper bottom relative to the lower one by 3.5°

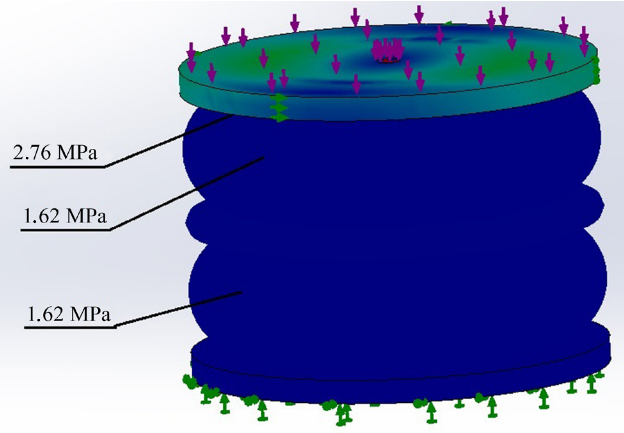

Fig. 10. Stress in the material of the flexible shell at excessive air pressure in its cavity of 0.5 MPa and with an angular displacement of the upper bottom relative to the lower one by 3.5°

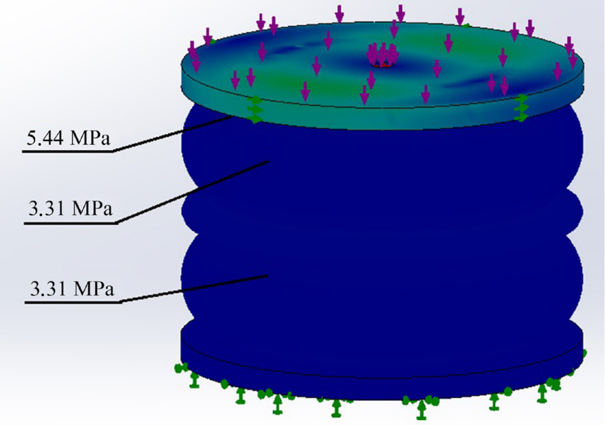

Fig. 11. Stress in the material of the flexible shell at an excess air pressure in its cavity of 1.0 MPa and with an angular displacement of the upper bottom relative to the lower one by 3.5°

The greatest stresses are observed near the contacts of the flexible shell with the bottoms and ring and reach 2.76 and 5.44 MPa, respectively, and, at the equator, they are less by an average of 40 %. No increase in the radius of the flexible shell was observed.

The stress in the steel ring (10.01 MPa) has not changed much. The appearance of the angle of inclination of the ring was not observed.

5. 3. Dependence of the amount of stress in the material of the flexible shell on loads and strains

Our studies have shown that with an increase in excess pressure in the PS cavity to 0.5 MPa and 1.0 MPa, the stress in the material of the flexible shell increases proportionally (Fig. 4, 5).

With an increase in excess pressure in the PS cavity to 0.5 MPa and 1.0 MPa, together with a transverse displacement of the upper bottom relative to the lower one by 40 mm, the stress in the flexible shell material increases almost proportionally (Fig. 7, 8). The same is observed with an increase in excess pressure in the PS cavity to 0.5 MPa and 1.0 MPa, along with angular displacements of the upper bottom relative to the lower one to 3.5° (Fig. 10, 11).

Thus, it can be argued that there is a direct proportional relationship between the strains of the flexible shell and the stresses in its material.

The results of our study into the distribution of stresses in the material of the flexible shell with excessive transverse displacements of the upper bottom relative to the lower one are shown in Fig. 12, 13.

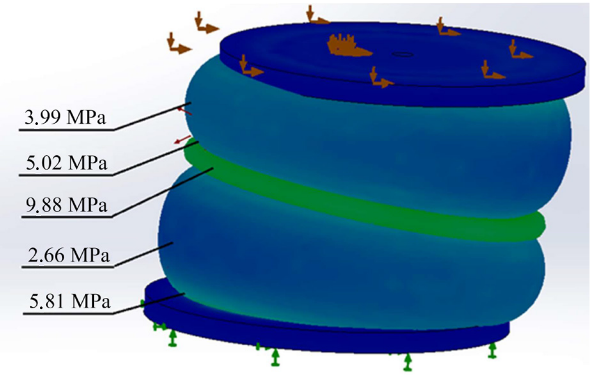

Fig. 12. Stress in the material of the flexible shell at an excess air pressure in its cavity of 1.0 MPa and with transverse displacements of the upper bottom relative to the lower one by 60 mm

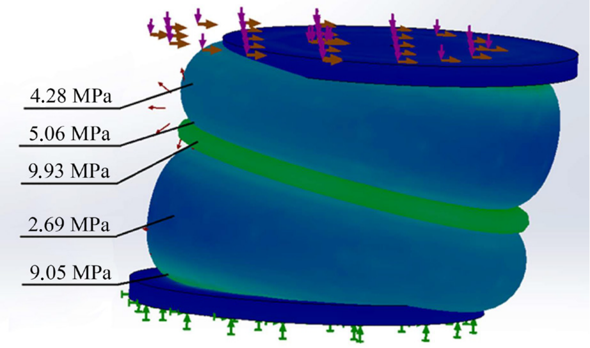

Fig. 13. Stress in the material of the flexible shell at an excess air pressure in its cavity of 1.0 MPa and with transverse displacements of the upper bottom relative to the lower one by 80 mm

The comparison of configurations of the flexible shell in Fig. 8, 12, 13 proved that it retains stability only when the upper bottom is shifted relative to the lower one by 40 mm. This is due to the fact that the contacts of its outer surface have already reached the cylindrical surfaces of the bottoms. With greater displacements, its configuration is lost: there is contact of the surface of the flexible shell with the cylindrical parts of the bottoms, which can be considered beyond the stability of the flexible shell. The stress in the material near the bottoms increases, and the angle of inclination of the ring has almost doubled: up to 15°, which can lead to its further «slide» to contact with the bottoms observed during PS bench tests.

The greatest stresses in the material of the two-corrugation flexible shell and the largest displacement (22 mm) of its front point at the equator were half that of a single-corrugation shell [12].

5. 4. Selecting material for the flexible pneumatic spring shell

The selected material for the flexible shell, «Adipren 167», and its thickness (8 mm), allowed us to attain a three-fold margin of its safety. This is observed with the simultaneous action of internal pressure (1.0 MPa), transverse displacement by 40 mm, and angular displacement of the upper bottom relative to the lower one by 3.5°.

The design, the selected material for the two-corrugation PS flexible shell of the cylinder type ensure its stability with transverse displacements of the bottoms up to 40 mm. Our results do not contradict previous studies into the strength of a single-corrugation flexible shell [19].

6. Discussion of results of studying a flexible shell

Our comparison of the improved two-corrugation PS with a similar single-corrugation one proves that the level of stress in its flexible shell is less than that in a single-corrugation by almost twice [11].

The comparison of the improved two-corrugation PS with the diaphragm one proves that the stresses in their flexible shells are approximately the same [12].

The design, the selected material, and the thickness (8 mm) of the two-corrugation flexible shell of the cylinder-type PS ensure its strength and stability during transverse displacements of the bottoms up to 40 mm.

The greatest stresses in the material of the improved two-corrugation PS flexible shell of the cylinder type are observed in places where it is fixed to the bottom. This is observed in all types of loads and strains of the shell. For example, with a flat-parallel displacement of the bottoms by 40 mm, the stress increases from 4.59 MPa at the equator of the shell to 5.91 MPa at the places of its fastening to the bottoms (Fig. 8).

At the shell equator, stresses are reduced by an average of 19 %. The largest increase in the radius of the equator of the flexible shell was 19 mm (Fig. 8). The distribution of stresses in both shell corrugations is identical (Fig. 8–12).

The greatest stresses in the material of the ring do not exceed 10.01 MPa (Fig. 8) and are observed at an excessive pressure in the PS of 1.0 MPa, and at transverse displacement of the bottoms by 40 mm. This load mode is most unfavorable in terms of ring strength and flexible PS shell (Fig. 8).

That makes it possible to fabricate the ring not only from steel but also from aluminum, glass plastic, and other materials (Fig. 8, 12).

With an angular displacement of the upper bottom relative to the lower one by 3.5°, the greatest stresses in the flexible shell material (5.44 MPa) are also observed in places where it is fixed to the bottom, and, at the equator of the shell, they decrease by an average of 39 % (Fig. 11).

Our results regarding the increased stresses when approaching the bottoms can be explained by the fact that the plane of concentric annular sections of the flexible shell decreases if its thickness is constant (Fig. 4–13).

Therefore, in the future, as an option, it is possible to propose in the process of designing a flexible shell to gradually increase its thickness when approaching the bottoms, which could reduce the stress in its material. Thus, one can recreate an evenly strong flexible shell but this requires additional research.

Our study of the improved two-corrugation PS has proven that with the selected material and parameters, it has sufficient strength. Its advantage in comparison with a single-phase pneumatic spring [12] is to reduce stresses in the material of the flexible shell under the strains of the displacement of the bottoms by almost two times.

This will have a positive effect on its reliability in operation, so it can be recommended as a component of air suspensions for vehicles.

7. Conclusions

1. Special feature of the constructed estimation scheme for the improved two-corrugation PS is to take into consideration the increase in the diameters of the bottoms and ring to the size of the outer diameter of the flexible shell.

2. Simulating the stressed state of the flexible shell of the improved PS with changes in the internal air pressure up to 1 MPa observed on vehicles has made it possible to obtain stress distribution fields in its constituent parts and to find that they increase in proportion to the pressure close to a linear dependence. At the equator, they are 3.21 MPa and reach a maximum value of 5.91 MPa near the bottoms. The results of the simulation are close to the calculated ones, which are obtained by classical methods, which confirms their adequacy.

3. It has been found that the diameter of the flexible shell increases approximately in proportion to the air pressure in its cavity. The value of this growth reached 19 mm at an air pressure of 1.0 MPa. With the simultaneous transverse displacement of the bottoms by 40 mm, the displacement of the front point at the equator was in the direction of displacement of the bottom of 30 mm, and on the opposite side 12 mm. Compared to the single-corrugation pneumatic spring shell [12], these displacements are about half that, which is important if there is a shortage of space for its placement in a vehicle.

4. Our comparison of the stresses obtained during the simulation in the material of a flexible shell (not more than 10 MPa) with the permissible for the polymer «Adiprene 167» (30 MPa) substantiates the selection of this material for a two-corrugation pneumatic spring.

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