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Laboratory experimental study of contact interaction between cut shells and resilient bodies

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The study presented herein describes promising designs of shell vibration isolators. The feature of the proposed designs is the cut thin-walled shell usage as the main bearing link. These resilient elements have high load capacity and, on the other hand, can provide the desired level of damping. From the point of view of mechanics, shell resilient elements are considered as the deformable systems with dry friction. When simulating these systems, structurally nonlinear non-conservative mixed contact issues of cut shell – resilient body frictional interaction arise. In order to take into account all essential options of the aforementioned issues and specify shell resilient element peculiarities of behavior under operational loads, the authors used the method of laboratory experiments for research. We considered two different contact systems. The first one is a cylindrical shell cut along its generatrix, which contacts a deformable filler. The second system is a cylindrical shell with several incomplete slots interacting with the elastic filler. The stress state and radial displacements of the shells, pliability of the resilient elements, and energy dissipation in the contact systems were time-tracked. As a result, we obtained relations for monitored options of the contact bodies and deformation diagrams for different physical-mechanical and geometrical options of the systems It was found that for a fixed cycle asymmetry coefficient with an increase in the friction coefficient between the shell and the filler, the amount of energy dissipated per cycle gradually decreases. The idea of optimizing shell vibration protection devices according to the criterion of maximum absorption of energy from external influences by determining the required tribological properties of contacting pairs is declared.

1. Introduction

Vibration processes play a significant role in the modern industry. In most cases, vibration reduces strength, reliability, and durability of industrial machines, mechanisms, and structures, as well as adversely affects the health of support staff. Thus, the problem of vibration isolation is relevant in both technical and social terms.

Usage of vibration control devices as the shock absorbers, dampers, dynamic vibration dampers, etc., is one of the ways to solve these problems (Sarwar & Sarwar, 2019; Zheng et al., 2018; Velichkovich, 2001). Resilient elements are the main operating units of vibration control systems. A variety of technical solutions is designed for traditional vibration isolators (metal, rubber, rubber-cord, rubber-pneumatic, hydraulic, etc.) (Valeev et al., 2015; Velichkovich, 2007; Sol-Sánchez et al., 2015). Researchers theoretically and experimentally studied their properties at the level sufficient for engineering practice (Dutkiewicz et al., 2018; Velychkovych et al., 2020; Weixing et al., 2019). The development of new

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technologies for vibration isolators made possible the implementation of magnetorheological dampers (Yuan et al., 2019) and regenerative shock absorbers (Zhanwen et al., 2020).

We propose to use shell resilient elements for high loaded structures of construction, metallurgical, and oil and gas industries (Shatskyi & Velychkovych, 2019; Shatskyi et al., 2018). Vibration control devices designed on the base of such resilient elements make possible operation under high dynamic loads and provide small transverse dimensions (Velichkovich et al., 2018). The main feature of this type of designs is the thin-walled cylindrical shell cut along its generatrix (or cylindrical shell with several slots) as the main operational link. Combination of high load capacity and the required level of energy dissipation inherent to such shell resilient elements determines the prospects for their successful application for many industries.

From the point of view of mechanics, the shell resilient element is considered as the deformable system with dry friction. When simulating these systems, the issues of structurally nonlinear non-conservative mixed contact problems on frictional interaction of the cut shell and resilient body arise (Popadyuk et al., 2016, Bedzir et al., 1995). It is rather difficult to obtain analytical solutions of the aforementioned problems in the three-dimensional formulation because of the nonlinearity of mathematical models associated with friction forces and contact interactions between the structural components.

In order to take into account all essential options of the aforementioned issues and specify shell resilient element peculiarities of behavior under operational loads, the authors used the method of laboratory experiments for research.

2. State of question and statement of research problem

Contact problems for elastic systems constitute an important part of the mechanics of deformable solids, and they are widely applied in various fields of engineering (Shatskyi et al., 2019; Bulbuk et al., 2019; Shats'kyi & Makoviichuk, 2005; Vytvytskyi et al., 2017). Problem statements and methods for solving the contact problems taking into account dry friction and using continuous models of a continuous medium are commonly known (Kravchuk et al., 2007; Martynyak et al., 2015). The results obtained in these works reveal the patterns of frictional interaction of bodies and describe the general state of the problem. In addition, the mechanisms of structural energy dissipation under nonmonotonic, in particular, cyclic loading of nominally stationary or sedentary connections and systems are sufficiently studied (Shopa et al., 1989; Velichkovich et al., 1991; Shatskyi et al., 2020).

The works (Ropyak et al., 2019; Pryhorovska & Ropyak, 2019; Tatsiy et al., 2019) present analytical approaches to strength and rigidity calculation of layered structures under local, arbitrarily oriented, and temperature loads. The works (Shatskii & Perepichka, 2013; Shats'kyi & Struk, 2009) studied nonstationary processes in one-dimensional elastic systems in conditions of inelastic interaction with a surrounding base. The work (Shats'kyi et al., 2016) presents the method to determine contact stresses on the surfaces of conjugate parts and to specify a relation between the loads and slip zone dimensions for friction contact. Application of modern methods is important for designing contact pairs to provide the desired properties of contact surfaces and wear resistance of parts (Li et al., 2019; Saakiyan et al., 1987; Saakiyan et al., 1989). It is also important to perform correct estimations or design calculations for complex geometric shapes (Panevnik & Velichkovich, 2017; Dalyak, 2019) and elements with stress concentrators, in particular for inhomogeneous solids near cavities and foreign inclusions (Kolesov et al., 1992; Kolesov et al., 1993; Dalyak, 2004). It should be mentioned the class of problems related to the effect of contact interaction of crack lips in thin shells (Shats'kyi & Makoviichuk, 2009; Shatskii & Makoviichuk, 2011), studies of cracked defect healing effectiveness (Shats'kyi, 2015), and calculation of stress and ultimate state of bodies with surface defects and coatings (Shatskyi et al., 2020). In order to provide safe operation of long objects, models of rod surface and elastic or inelastic medium contact interaction should be clarified (Grydzhuk et al., 2019; Chudyk et al., 2020). These models are relevant for pipelines in landslide areas (Kryzhanivs'kyi et al., 2004) and areas with unstable or damaged bases (Velychkovych et al., 2019). This way, mathematical modeling of rod system statics and dynamics in relation to issues of drilling tool sticking elimination (Levchuk, 2017; Levchuk, 2018) and modeling of contact interaction of a tool and layered or heterogeneous structure (Pryhorovska & Chaplinskiy, 2018; Pryhorovska, 2018) are relevant too. Approaches that use models and methods of theories of rods, shells, and plates are appropriate for engineering, and especially for analytical research of frictional interaction of solids. Dimensionality reduction in models of elastic bodies simplifies derivations and solutions of equations compared to the three-dimensional problems of the theory of elasticity. In this case, the main difficulties in contact problems for thin-walled structures arise within modeling the object of study or choosing an adequate model. Contact problems for thin-walled elements have their own specifics associated with irregular contact stresses, additional zones of detachment, adhesion, etc. The issues become even more problematic if there is dry friction on the contact surfaces.

In the previous works, in order to describe deformations of cut shells of resilient elements, there have been developed the mechanical-mathematical models for cut shells, in particular, the slotted shell and the shell with the cut along its generatrix for analytical studies (Bedzir & Shopa, 2010). The obtained analytical results made possible estimation of shell damper behavior under cyclic loads and carrying out engineering calculations of their pliability and bearing capacity, focusing on practical needs. However, the one-dimensional analytical models used in the previous studies did not allow taking into account a number of features of the design behavior.

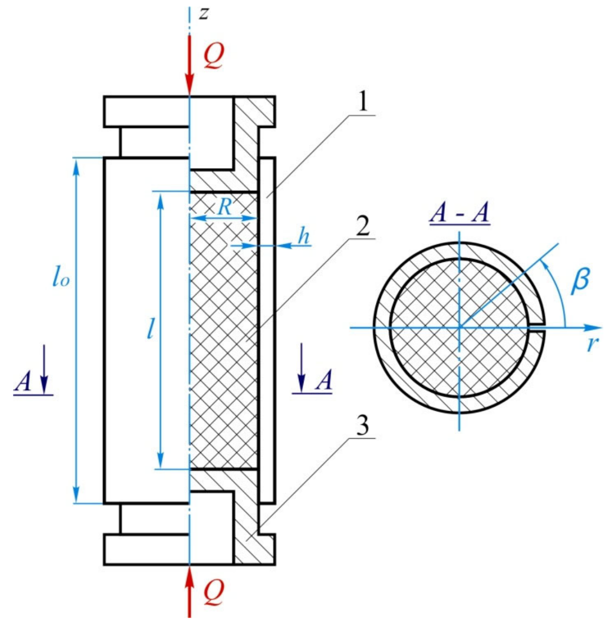
Aim of our research are:

- to study the influence of main structural and technological factors on the pliability of the cut shell resilient elements, in particular, shell length, thickness, shell-filler friction coefficient, number of slots, etc.;
- to obtain experimental hysteresis loops of cut shell resilient elements under non-monotonic loading;
- to obtain data to evaluate the correctness and accuracy of previously obtained theoretical results and conclusions, and, if necessary, to adjust the developed mathematical models; and
- to develop a database of experimental data for new analytical and numerical mathematical model verification.

3. Main Content of the Paper

3.1 Shell resilient element cut along its generatrix

Fig.1 shows the general view (industrial design) and schematic diagram of the shell resilient element cut along its generatrix. Mainly, the operation of shell resilient elements with deformable filler is based on the following principle. An external load Q acts on the pistons and causes them to move towards each other, compressing the filler. The deformable filler changes its shape and interacts with a thin-walled working link (it can be a continuous cylindrical shell, shell with a slit, shell with slots, a package of shells, etc.). As a result, the shell deforms and accumulates the potential energy of elastic deformation. When the external load disappears (decreases), the movable parts of the system return to the initial (intermediate) position due to the accumulated energy. Part of the external energy supplied to the system is dissipated mainly due to mutual slippage with the shell-filler friction.



a b

Fig. 1. Shell resilient element cut along its generatrix:
industrial design (a); schematic diagram (b)

The feature of the presented model is the cut in the bearing shell along its generatrix. This design of the shells made it possible to obtain structurally anisotropic bearing links with stiffness in the circular direction lower than the stiffness along the generatrix. This approach made it possible to reduce the stiffness of the shell resilient elements without compromising their damping properties. The presented design of the resilient element (Fig. 1, b) works as follows. The load applied to the pistons *3* causes them to enter the cut shell *1*, compressing the filler *2*. The filler *2* transforms the longitudinal movements of the pistons *3* in the radial deflections of the shell *1*. When unloading, the system returns to its initial position. Deformation of filler shape makes the main contribution to the flexibility of the system through the bending deformation of the cut shell (curvature of the open ring in cross-section decreases). At the cyclic loading of the resilient element of this type, there is the filler-shell frictional interaction. As a result, part of the energy supplied to the resilient element will be dissipated, mainly due to the phenomenon of structural hysteresis in the deformable system. Thus, the shell resilient elements have both shock absorption and damping properties.

To implement the described principle of operation and achieve the required performance characteristics of the vibration isolator, its components should have certain properties. The main energy storage (shell) should combine low rigidity with the required level of strength and durability. To provide the directional transformation of movements, the filler should easily change its shape (i.e. have a low shear modulus). From this point of view, the material of the filler should be soft compared to the material of the shell. On the other hand, the material of the filler should be low compressible (i.e. have a high modulus of volumetric compression) to cause the shell to deform in the conditions of contact interaction. The tribological properties of the filler-shell pair are selected for reasons of providing the required level of structural damping in a specific operational situation (hysteresis energy dissipation during dry friction).

3.1.1 Materials and methods for studying the contact interaction of the cut cylindrical shell with the resilient body

The laboratory samples were experimentally examined (Fig. 2), the schematic diagram Fig. 1, b shows the samples. The resilient cylinder (filler) with the radius of and the length of is placed in the shell with thickness of and length of , which is cut along its generatrix. The filler is compressed at the ends by rigid pistons with an external time-related monotonic or non-monotonic load . Dry positional friction is present on the filler-shell contact surface. It is necessary to evaluate the stress-strain state of the shell, the pliability of the resilient element, and to study the phenomenon of structural damping in this non-conservative system. The shell material was alloy steel AISI 4340 with yield strength of 900 MPa, Young's modulus of 210 GPa, shear modulus of 80 GPa, and Poisson's ratio of 0.31. The filler material was crude rubber mixture 7-3826 with high oil and gas resistance (Young's modulus was 20 MPa, shear modulus – 7 MPa, Poisson's ratio – 0.490).

Fig. 2. Laboratory samples of the resilient element with the cut shell

The geometric dimensions of the operational units used for the study were as follows: shell inner radius of $R = 0.08m$; wall thicknesses h ranged as follows: 0,01*m*; 0,015*m*; 0,02*m*; 0,025*m;* shell lengths –l_0: 0,2 *m*; 0,3 *m*; 0,4 *m*; 0,5 *m*; 0,6 *m*; 0,7*m*. The laboratory samples were made on serial equipment; a micrometer was used to check the accuracy of sample production. The loading process of samples was carried out on a universal test machine equipped with the automated measuring system ASTM-Digital. Loading on the piston of the resilient elements ranged from/to $Q = 0, \ldots, 150\ kN$. Paper-based wire strain gauges with the base of 10 mm and the nominal resistance of 100 Ohms were used in the study of the stress-strain state of the shell elastic elements. Gauges with strain ranged from 25 to 50 were selected from one batch to ensure a minimum deviation of resistance from the nominal; then they were glued to the shell. A digital strain gauge bridge was chosen as a recorder. To prevent temperature errors, the method of circuit compensation was used, i.e. compensating strain gauges were taken to the object of study and were in the same temperature conditions as the active sensors. 5% strain gages of the total number from each group were calibrated. The calibration results were applied to the whole group. A set of clock indicators “Dial Indicator 0.001” was used to determine the displacements. The least-squares method was used to process the obtained experimental data.

3.1.2 Research results and their analysis

The annular stresses σ_β on the outer surface of the cut shell were determined. These stresses were negative. Their biggest modulo values were observed in the longitudinal section of the shell with azimuth of $\beta=180°$. Radial displacements u_r of the shell outer surface were maximal at $\beta=90°$ and $\beta=270°$. Fig.

3 shows the pattern of distributions of annular stresses and radial displacements along the length of the shell generatrix (shell thickness 0.015 *m*; the load on the resilient element 100 *kN*).

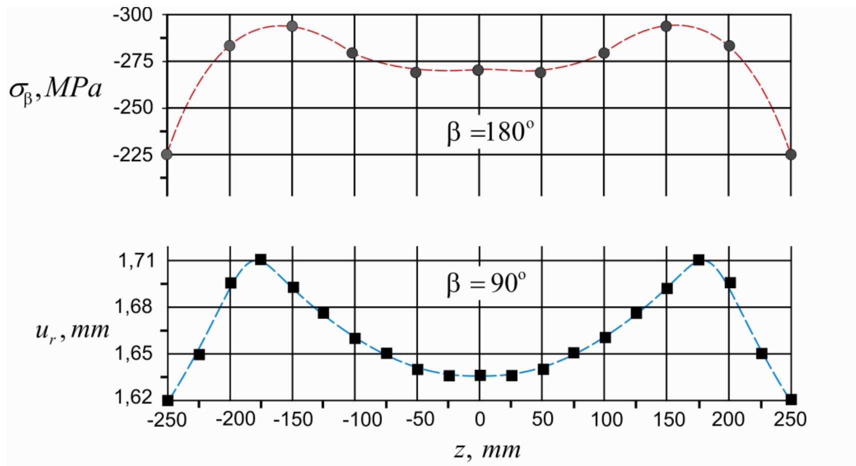


Fig. 3. **Distribution of maximum annular stresses and radial displacement in the cut shell**

Similar relations of annular stresses for many cross-sections of the shell have given us the general pattern of the resilient element bearing link stress state (Fig. 4).

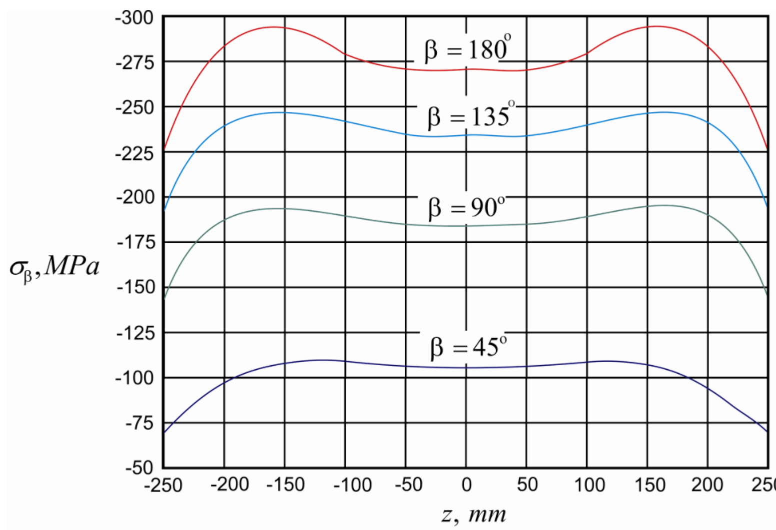


Fig. 4. Distribution of annular stresses on the outer surface of the bearing cut shell

Due to the contact interaction of the filler with the shell, the radial displacements and annular stresses along the generatrix are distributed unevenly. Additional analysis has shown that this unevenness increases if the filler-shell friction coefficient increases. At a fixed azimuth, the maximum radial displacements and annular stresses of the shell have been observed in the areas close to the piston end faces. With distance from the ends of the pistons, radial displacements and hoop stresses decrease. This indicates that an increase in the length of the shell and filler will not be accompanied by a constant increase in the flexibility of the structure (the authors were convinced of this by changing the length of the model). It should be noted that the axial displacements of the shell, in comparison with the radial ones, are rather small and do not significantly affect the performance characteristics of the elastic element. Therefore, the nature of the change in their values is not shown here.

Analysis of the shell material stress state indicates that the annular stresses are the decisive stresses in assessing the strength of the bearing link. The longitudinal section at $\beta=180°$ is the most dangerous, and the cross-sections located near the ends of the pistons are the most loaded. Fig. 5 shows the diagram of the relationship between piston draught δ of the resilient element and the shell length. For a constant shell-filler friction coefficient, the piston draught increases rapidly to the certain value of l_0 with shell length increasing. For further shell length increasing, the growth rate of piston draught slows down, or it remains almost constant, regardless of the increase in length. This phenomenon is observed relatively faster in elastic elements with a larger shell wall thickness. Obviously, this fact is associated with the decreasing slip zone length for the resilient element with the thicker wall of the shell.

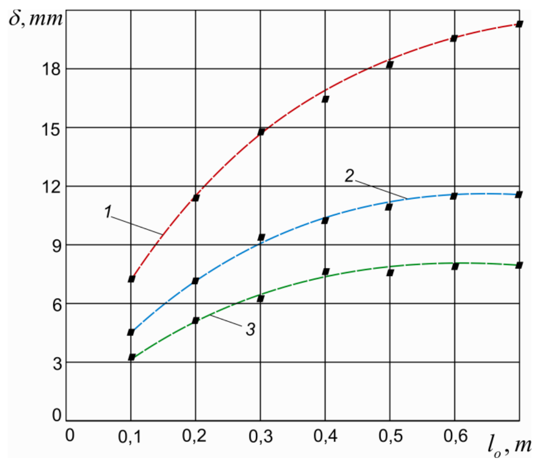


Fig. 5. Diagram of the relationship between piston draught δ of the resilient element and the shell length:
$1-Q=100\ kN,\ h=0.015\,m$; $2-Q=120\ kN,\ h=0.02\,m$; $3-Q=150\ kN,\ h=0.025\,m$

Fig.6 presents the diagram of the piston draught – loading relations for different thicknesses of the shells (here, $p=Q/\pi R^2$ is the pressure under the piston). They show that resilient elements with a smaller shell wall thickness expectedly provide more piston draught and are, therefore, more pliable. It should be noted that the change in the inclinations of the graphs to the coordinate axes depends nonlinearly on the thickness of the shell.

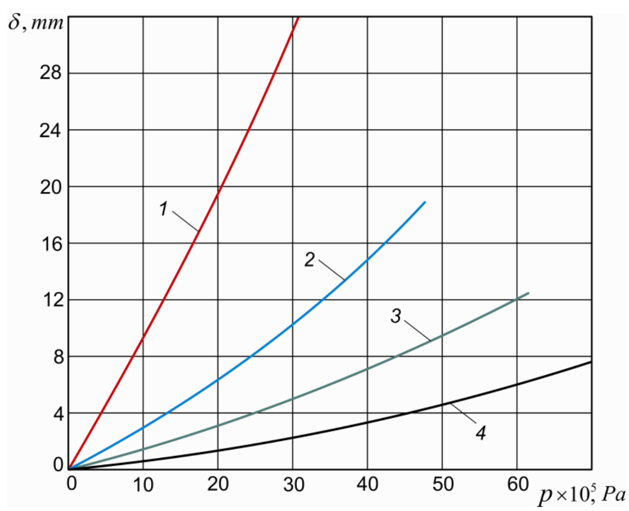


Fig. 6. Diagram of the relationship between piston draught δ of the resilient element and p (for $l=0.5\ m$):
$1-h=0.01\,m$; $2-h=0.015\,m$; $3-h=0.02\,m$; $4-h=0.025\,m$

Fig.7 shows the damping loops of the resilient element with the cut shell for different values of the shell-filler friction coefficient f. The dashed line indicates the curves corresponding to the reload stage. The presented diagrams characterize the history of reloading by a load cycle asymmetry factor of 0.4.

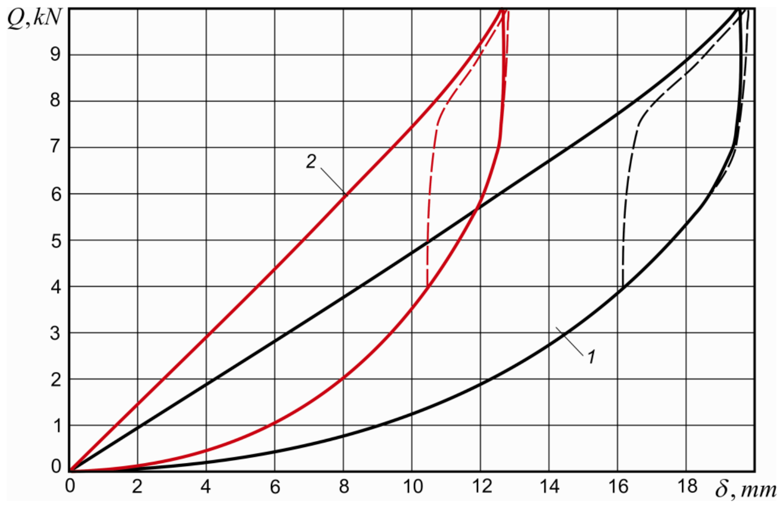


Fig. 7. Experimental damping loops (cut shell):
$h = 0.015\ m$; $l = 0.5\ m$; $1 -\ f = 0.5$; $2 -\ f = 0.8$

Fig. 8 illustrates the effect of the changing of the filler – cut shell friction coefficient on the form of the resilient element deformation diagrams. The loss of energy supplied to the resilient element during the load cycle is numerically equal to the area of the damping loop. The diagram clearly shows the expected effect of increasing the shell resilient element pliability when filler – cut shell friction coefficient reduces. However, we observe an unexpected and at first glance even paradoxical effect in Fig. 8. For the fixed amplitude of the load cycle, the energy dissipated per cycle gradually decreases when the filler – shell friction coefficient increases (for example, the area of the damping loop for $f = 0.8$ visually is clearly smaller than for $f = 0.3$).

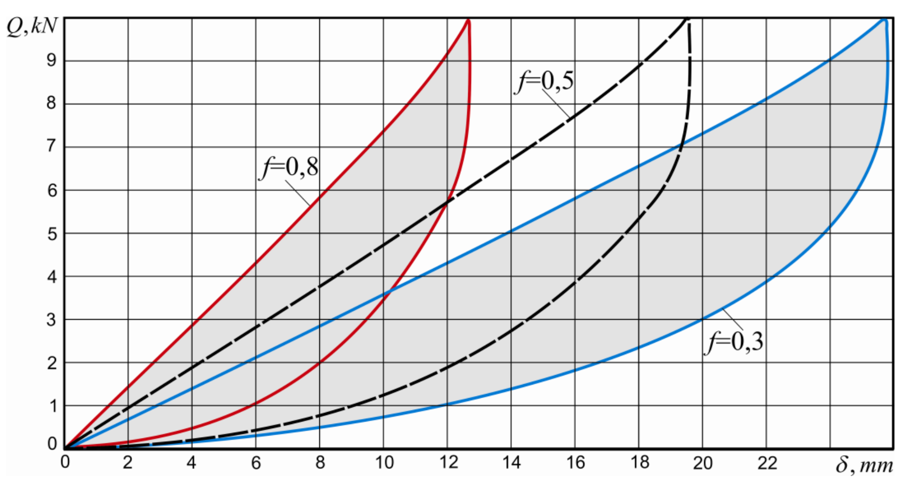
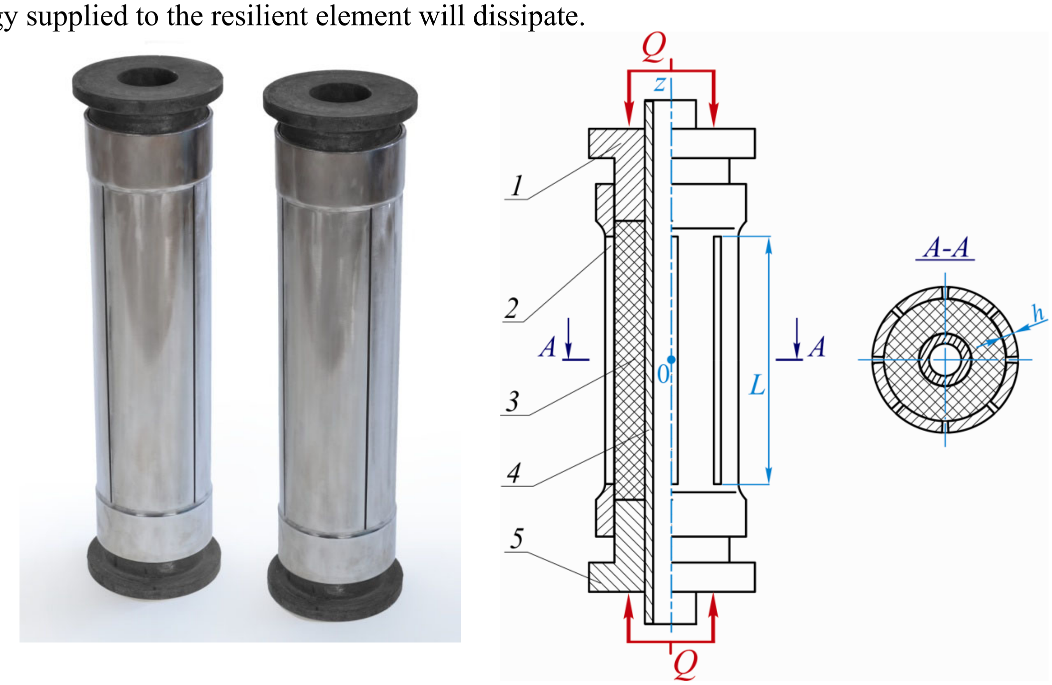


Fig. 8. Diagrams of the resilient element deformation for different friction coefficients of the contact pair

In our opinion, this effect is explained by the fact that in systems with dry positional friction the distribution of friction forces depends on the contact element deformations (here they are a shell and a filler). However, the magnitude of the system deformation depends on the frictional forces. This close relationship between deformation and frictional forces determines the specific, often intuitively unpredictable features of the behavior of such structures. In this situation, increasing friction coefficient leads to decrease in the area of shell-filter mutual slip, and, consequently, to decrease in structural energy dissipation which occurs only in this area. The idea to optimize the shell vibration control devices by determining the required tribological properties of contacting pairs looks promising.

3.2 Slotted shell resilient element

Globally, the idea of using the bending deformation of the bearing thin-walled links to ensure the necessary flexibility of the shell resilient elements has proven to be quite fruitful. This idea underlines the technical solution resulting in the slotted shell resilient element (Fig. 9). The main bearing link of this resilient element is the thin-walled cylindrical shell with several incomplete slots. The external load applied to the pistons *1* and *5* forces them to go inside the shell *2*, compressing the filler *3*. In fact, a slotted shell consists of a set of panels that, as a result of contact with a deformable filler, experience a flat bend in the radial planes. The internal entire cylindrical shell (barrel *4*) is necessary for technological needs only. For example, drilling mud is moved along the barrel of the resilient elements of drilling shock absorbers; in other cases, the barrel is used to cool the vibration isolator, to put the cable in it, etc. It is clear that the barrel is much harder than the outer slotted shell. The main contribution to the flexibility of the system is made by the change in filler shape due to bending deformations of the slotted shell panel. At the cyclic loading of this resilient element, there is a shell-filler frictional interaction. As a result, part of the energy supplied to the resilient element will dissipate.



a b

Fig. 9. Slotted shell elastic element: industrial design (a); schematic diagram (b); 1, 5 – pistons; 2 – slotted shell; 3 – deformable filler; 4 – barrel

3.2.1 Statement of the problem of studying the contact interaction between the slotted cylindrical shell and deformable filler

Let us consider a resilient hollow cylinder – filler that separates coaxially installed slotted and entire cylindrical shells (Fig. 9, b). The external load is applied to the end of the cylinder (deformable filler) through rigid pistons. The research aims to determine the stress state and radial displacements of the slotted shell, the axial pliability of the resilient element, and to evaluate the energy dissipation in the contact system. The objects of research were full-scale samples of resilient elements of drilling shock absorbers and laboratory models with the bearing link in the form of the slotted cylindrical shell (Fig. 10). For the experimental research, we have selected the resilient elements with the following geometric dimensions of the bearing links: inner diameter of $d = 0.142 \ m$, wall thickness of the slotted cylindrical shell of $h = 5 \ mm$; length of shells ranged as L: 0.2 m; 0.3 m; 0.4 m; 0.5 m; 0.6 m. The shell and barrel are made of alloy steel AISI 4340. The filler is made of crude rubber mixture with high oil and petrol resistance. The bench studies were static and quasi-static by the nature of the applied load. The experimental samples have been loaded along the axis of the resilient elements through massive metal plates according to the loading-unloading principle with recording the measured data at each stage.

Fig. 10. The bearing link of the resilient element
(thin-walled slotted shell with slots)

3.2.2 The obtained results and their discussion

As a result of the experiments, the relations between the controlled characteristics of the contact bodies and the device in general have been developed. Diagrams of system deformation have been obtained. Let us consider the results.

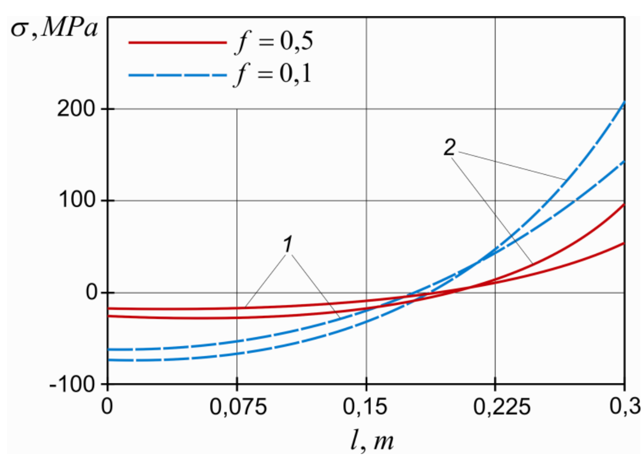


Fig. 11. Distribution of normal axial stresses on the outer surface
of the shell along its length

Fig. 11 shows the distribution of normal axial stresses on the outer surface of the slotted shell along its length (along the generatrix) under the external static load of $100 \ kN$ (numbers of curves 1 and 2 correspond to the number of slots $N = 4, \ 6$, shell length – $L = 0.6 \ m$). Dashed lines indicate the cases when the coefficient of friction between the shell and the filler $f = 0.1$, and solid lines – $f = 0.5$. As far as the resilient element has a symmetrical design, the obtained data has turned out to be symmetrical and are presented for the shell half-length. It was found that normal axial stresses are maximum in absolute value at the edges of the slotted shell (in the end sections). With an increase in the number of cuts in the shell and a decrease in the coefficient of friction in the contact pair, normal axial stresses increase in modulus. In order to determine a relation between maximum normal stresses σ and the shell length, we performed a number of experiments. The magnitude of the stresses on the outer surface for different shell lengths in the area of the slot beginning under the load on the device of $100\ kN$ has been determined. Fig.12 shows the diagram of maximum normal axial stresses in the slotted shell related to its length. Numbers of curves 1 and 2 correspond to the number of slots *N=4, 6*; *l=L/2*– shell half-length. The diagram shows that the normal stresses increase to a certain value when shell working part length increases. Further, if shell length increases, the value of normal stresses remains almost constant, regardless of the increase in length.

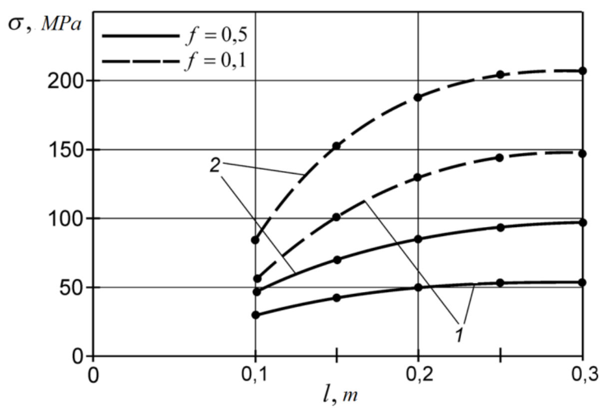


Fig. 12. Diagram of maximum normal axial stresses in the slotted shell related to its length

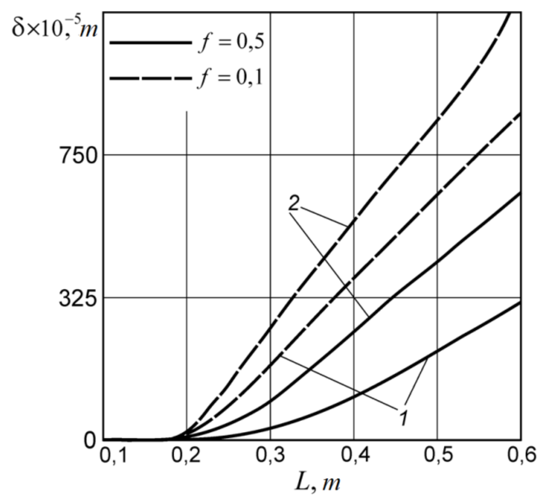


Fig. 13. Diagram of filler end axial movements related to the shell length

An important characteristic of the shell resilient elements is their rigidity. To determine the stiffness of the shock absorber, the axial displacements of the pistons from the compressive load were determined. At this stage of the work, the dependence of the elastic element compliance on the length of the working part of the bearing link, the number of shell cuts and the coefficient of friction between the shell and the filler was investigated. Fig. 13 shows the results of the study. An increase in the number of slots in the shell and its length, a decrease in the coefficient of friction between the filler and the shell lead to an increase in the axial movement of the pistons.

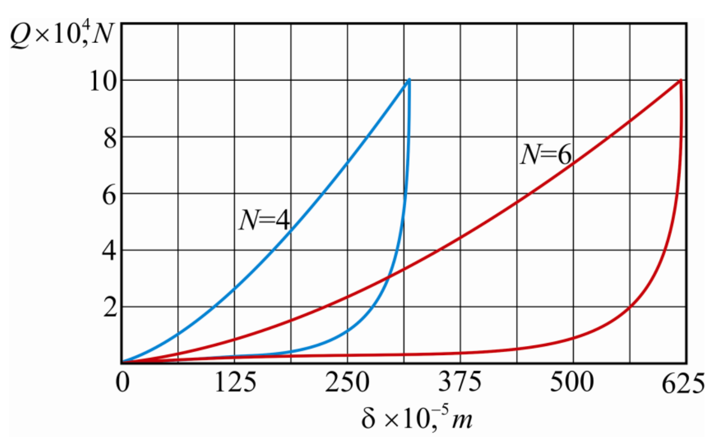


Fig. 14. Damping loops of the slotted shell resilient element

The relation is mainly linear for the considered range of slot numbers and shell lengths. At the final stage of the research, experimental damping loops have been obtained. Fig. 14 presents the diagrams describing the loading/ unloading process of the shell resilient with a different number of slots in the shell (length of $L = 0.6\,m$; shell – filler friction coefficient of $f = 0.5$). The area of each damping loop is numerically equal to the loss of the energy supplied to the resilient element during the load cycle. Analysis of the obtained experimental data shows that as the number of shell slots increases, the scattered energy increases during the loading-unloading cycle.

4. Conclusions

Experimental studies have made it possible to determine the influence of shell length and thickness, the number of cuts, and the tribological properties of the contact bodies on stiffness, strength and damping capacity of the shell resilient elements. Two different configurations of contact systems have been considered. Thus, the conclusions are divided into two parts.

Shell resilient element with the cut along its generatrix (Fig. 1)

This study covers the influence of main structural and technological factors on the pliability of the cut shell resilient elements, in particular shell length, thickness, the shell-filler friction coefficient. It has been determined that the draught of the pistons increases intensively with an increase in shell length to a certain limit with a subsequent slight increase. Besides, the draught of the pistons decreases with the increase of shell thickness and the shell-filler friction coefficient. In addition, the experimental hysteresis loops of resilient elements under nonmonotonic loading have been obtained. An interesting, intuitively unexpected effect in the study of the cut shell-filler friction coefficient influence has been recorded. At a fixed amplitude of the load cycle, energy dissipated per cycle gradually decreases when the shell-filler friction coefficient increases. Our explanation for this interesting effect is as follows. Obviously, in systems with dry positional friction, the distribution of friction forces depends on the deformations of the contact elements (here they are the deformable filler and the cut shell), but the deformations, in turn, depend on the friction forces. This close relationship between deformation and friction forces determines the specific, often intuitively unpredictable features of the behavior of such structures.

Shell resilient element with several slots (Fig. 9)

Increasing the number of slots in the shell and its length, as well as reducing the filler-cut shell friction coefficient, lead to decreasing of resilient element stiffness. The pattern of normal axial stress distribution along the generatrix has been obtained. The occurrence of maximum normal axial stresses in the shell at the edges of the slots (cuts) has been experimentally confirmed. The magnitude of these stresses can be used to assess the structure strength. The energy dissipated per cycle of loading – unloading increases if the number of slots in the shell increases and the damping properties of the device improves.

In general, the results of the experimental studies make it possible to understand the features of shell resilient element behavior, to assess the performance of these structures and can serve as a basis for choosing rational parameters in the design of resilient elements.

References

Bedzir, O. O., & Shopa, V. M. (2010). Contact interaction of a slotted cylindrical shell and a deformable filler with regard for dry friction. *Journal of Mathematical Sciences, 168*(5), 665–672.

Bedzir, A. A., Shatskii, I. P., & Shopa, V. M. (1995). Nonideal contact in a composite shell structure with a deformable filler. *International Applied Mechanics, 31*(5), 351–354.

Bulbuk, O., Velychkovych, A., Mazurenko, V., Ropyak, L., & Pryhorovska, T. (2019). Analytical estimation of tooth strength, restored by direct or indirect restorations. *Engineering Solid Mechanics, 7*(3), 193–204.

Chudyk, I., Raiter, P., Grydzhuk, Y., & Yurych, L. (2020). Mathematical model of oscillations of a drill tool with a drill bit of cutting-scraping type. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, 1, 52–57.

Dalyak, T. (2019). Investigation of the interaction of two parallel shifted cracks in plate bending adjusted for their closure. *Theoretical and Applied Mechanics, 46*(2), 147–155.

Dalyak, T. M. (2004). Bending of a plate containing a periodic system of shifted parallel cracks whose lips are in contact. *Materials Science, 40*(1), 139–143.

Dutkiewicz, M., Gołębiowska, I., Shatskyi, I., Shopa, V., & Velychkovych, A. (2018). Some aspects of design and application of inertial dampers. *MATEC Web of Conferences, 178*, 06010.

Grydzhuk, J., Chudyk, I., Velychkovych, A., & Andrusyak, A. (2019). Analytical estimation of inertial properties of the curved rotating section in a drill string. *Eastern-European Journal of Enterprise Technologies, 1*(7–97), 6–14.

Kolesov, V. S., Vlasov, N. M., Tisovskii, L. O., & Shatskii, I. P. (1992). The stress-deformation state of an elastic half-space with a spheroidal thermal inclusion. *International Applied Mechanics, 28*(7), 426–434.

Kolesov, V. S., Vlasov, N. M., Tisovskii, L. O., & Shatskii, I. P. (1993). The stress concentration in an elastic ball with nonconcentric spherical cavity. *Journal of Soviet Mathematics, 63*(3), 335–339.

Kravchuk A. S., Neittaanmäki P. J. Variational and Quasi-Variational Inequalities in Mechanics. – Springer-Verlag Berlin, 2007. – 338 P.

Kryzhanivs'kyi, E. I., Rudko, V. P., & Shats'kyi, I. P. (2004). Estimation of admissible loads upon a pipeline in the zone of sliding ground. *Materials Science, 40*(4), 547–551.

Levchuk, K. G. (2017). Investigation of the vibration transfer process to a stuck drill string. *In SOCAR Proceedings, 2*, 23–33.

Levchuk, K. G. (2018). Diagnosis of catches of metal drill pipes by their stress-strain state in a sloping well. *Metallofizika i Noveishie Tekhnologii, 40*(5), 701–712.

Li, X., Yang, Y. & Shi, W. (2019). Study on the Damping Effect of Particle Dampers considering Different Surface Properties. *Shock and Vibration, 2019*, Article ID 8293654.

Martynyak, R. M., Prokopyshyn, I. A., & Prokopyshyn, I. I. (2015). Contact of Elastic Bodies with Nonlinear Winkler Surface Layers. *Journal of Mathematical Sciences, 205*(4), 535–553.

Panevnik, D. A., & Velichkovich, A. S. (2017). Assessment of the stressed state of the casing of the above-bit hydroelevator. *Neftyanoe Khozyaystvo – Oil Industry, 1*, 70–73.

Popadyuk, I. Yo., Shats'kyi I. P., Shopa V. M., & Velychkovych A. S. (2016). Frictional interaction of a cylindrical shell with deformable filler under nonmonotonic loading. *Journal of Mathematical Sciences, 215*(2), 243–253.

Pryhorovska, T. (2018). Rock heterogeneity numerical simulation as a factor of drill bit instability. *Engineering Solid Mechanics, 6*(4), 315–330.

Pryhorovska, T. A., & Chaplinskiy, S. S. (2018). Finite element modeling of rock mass cutting by cutters for PDC drill bits. *Neftyanoe Khozyaystvo - Oil Industry, 1*, 38–41.

Pryhorovska, T., & Ropyak, L. (2019). Machining Error Influnce on Stress State of Conical Thread Joint Details. *In Proceedings of the International Conference on Advanced Optoelectronics and Lasers, CAOL, 2019*, 493–497.

Ropyak, L. Y., Shatskyi, I. P., & Makoviichuk, M. V. (2019). Analysis of interaction of thin coating with an abrasive using one-dimensional model. *Metallofizika i Noveishie Tekhnologii, 41*(5), 647–654.

Saakiyan, L. S., Efremov, A. P., & Ropyak, L. Y. (1989). Effect of stress on the microelectrochemical heterogeneity of steel. *Protection of Metals (English Translation of Zaschita Metallov), 25*(2), 185–189.

Saakiyan, L. S., Efremov, A. P., Ropyak, L. Y., & Gorbatskii, A. V. (1987). A method of microelectrochemical investigations. *Soviet Materials Science, 23*(3), 267–269.

Sarwar, W., & Sarwar, R. (2019). Vibration Control Devices for Building Structures and Installation Approach: A Review. *Civil and Environmental Engineering Reports, 29*, 74–100.

Shats'kyi, I. P., & Struk, A. B. (2009). Stressed state of pipeline in zones of soil local fracture. *Strength of Materials, 41*(5), 548–553.

Shats'kyi, P. (2015). Limiting Equilibrium of a Plate with Partially Healed Crack. *Materials Science, 51*(3), 322–330.

Shats'kyi, I. P., & Makoviichuk, M. V. (2005). Contact interaction of crack lips in shallow shells in bending with tension. *Materials Science, 41*(4), 486–494.

Shats'kyi, I. P., & Makoviichuk, M. V. (2009). Analysis of the limiting state of cylindrical shells with cracks with regard for the contact of crack lips. *Strength of Materials, 41*(5), 560–565.

Shats'kyi, I. P., Lyskanych, O. M. & Kornuta, V. A. (2016). Combined Deformation Conditions for Fatigue Damage Indicator and Well-Drilling Tool Joint. *Strength of Materials, 48*, 469–472.
Shatskii, I. P., & Perepichka, V. V. (2013). Shock-wave propagation in an elastic rod with a viscoplastic external resistance. *Journal of Applied Mechanics and Technical Physics, 54*(6), 1016–1020.
Shatskii, I. P., & Makoviichuk, N. V. (2011). Effect of closure of collinear cracks on the stress-strain state and the limiting equilibrium of bent shallow shells. *Journal of Applied Mechanics and Technical Physics, 52*(3), 464–470.
Shatskyi, I. P., Perepichka, V. V., & Ropyak, L. Y. (2020). On the influence of facing on strength of solids with surface defects. *Metallofizika i Noveishie Tekhnologii, 42*(1), 69–76.
Shatskyi, I., Ropyak, L., & Velychkovych, A. (2020). Model of contact interaction in threaded joint equipped with spring-loaded collet. *Engineering Solid Mechanics, 8*(4), 301–312.
Shatskyi, I., & Velychkovych, A. (2019). Increase of compliance of shock absorbers with cut shells. *In IOP Conference Series: Materials Science and Engineering, 564*, 012072.
Shatskyi, I., Popadyuk, I., & Velychkovych, A. (2018). *Hysteretic Properties of Shell Dampers. In: Awrejcewicz J. (eds) Dynamical Systems in Applications. DSTA 2017*. Springer Proceedings in Mathematics & Statistics, 249. Springer, Cham, 343–350.
Shatskyi, I., Velychkovych, A., Vytvytskyi, I., & Seniushkovych, M. (2019). Analytical models of contact interaction of casing centralizers with well wall. *Engineering Solid Mechanics, 7*(4), 355–366.
Shopa, V. M., Shatskii, I. P., & Popadyuk, I. I. (1989). Elementary calculation of structural damping in shell springs. *Soviet Engineering Research, 9*(3), 42–44.
Sol-Sánchez, M., Moreno-Navarro, F., & Rubio-Gámez, C. (2015). The use of elastic elements in railway tracks: A state of the art review. *Construction and Building Materials, 75*, 293–305.
Tatsiy, R. M., Pazen, O. Y., Vovk, S. Y., Ropyak, L. Y., & Pryhorovska, T. O. (2019). Numerical study on heat transfer in multilayered structures of main geometric forms made of different materials. *Journal of the Serbian Society for Computational Mechanics, 13*(2), 36–55.
Valeev, A., Zotov, A., & Kharisov, Sh. (2015). Application of Disk Springs for Manufacturing Vibration Isolators with Quasi-Zero Stiffness. *Chemical and Petroleum Engineering, 51*(3), 194–200.
Velichkovich, A. S. (2007). Design features of shell springs for drilling dampers. *Chemical and Petroleum Engineering, 43*(7–8), 458–461.
Velichkovich, A. S., & Velichkovich, S. V. (2001). Vibration-impact damper for controlling the dynamic drillstring conditions. *Chemical and Petroleum Engineering, 37*(3–4), 213–215.
Velichkovich, A., Dalyak, T., & Petryk, I. (2018). Slotted shell resilient elements for drilling shock absorbers. *Oil and Gas Science and Technology, 73* (34).
Velichkovich, S. V., Popadyuk, I. I., Shatskii, I. P. & Shopa, V. M. (1991). Structural hysteresis in a shell-type vibration damper with distributed friction. *Strength of Materials, 23*(3), 279–281.
Velychkovych, A. S., Andrusyak, A. V., Pryhorovska, T. O., & Ropyak, L. Y. (2019). Analytical model of oil pipeline overground transitions, laid in mountain areas. *Oil and Gas Science and Technology, 74*, article number 65.
Velychkovych, A., Petryk, I., & Ropyak, L. (2020). Analytical study of operational properties of a plate shock absorber of a sucker-rod string. *Shock and Vibration, 2020*, article ID 3292713.
Vytvytskyi, I. I., Seniushkovych, M. V., & Shatskyi, I. P. (2017). Calculation of distance between elastic-rigid centralizers of casing. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, 5*, 28–35.
Weixing, Sh., Liangkun, W., Zheng, L., & Hongtao, W. (2019). Experimental and numerical study on adaptive-passive variable mass tuned mass damper. *Journal of Sound and Vibration, 452*, 97–111.
Yuan, X., Tian, T., Ling, H., Qiu, T., & He, H. (2019). A Review on Structural Development of Magnetorheological Fluid Damper. *Shock and Vibration, 2019*, Article ID 1498962.
Zhanwen, W., Tianming, Z., Zutao, Z., Yanping, Y., & Yujie, L. (2020). A high-efficiency regenerative shock absorber considering twin ball screws transmissions for application in range-extended electric vehicles, *Energy and Built Environment, 1*(1), 36–49.
Zheng, L., Zixin W., Ying Z., & Xilin, L. (2018). Nonlinear dissipative devices in structural vibration control: A review. *Journal of Sound and Vibration, 423*, 18–49.