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Elastic, Frictional, Strength and Dynamic Characteristics of the Bell Shape Shock Absorbers Made of MR Wire Material

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Abstract. The results of the mechanical characteristic experimental studies are presented for the shock absorbers of DKU type with the elastic elements of the bell shape made of MR material and obtained by the cold pressing of mutually crossing wire spirals with their inclusion in the array of reinforcing wire harnesses. The design analysis and the technology of MR production based on the methods of similarity theory and dimensional analysis revealed the dimensionless determined and determining parameters of elastic frictional, dynamic and strength characteristics under the static and dynamic loading of vibration isolators. The main similarity criteria of mechanical characteristics for vibration isolators and their graphical and analytical representation are determined, taking into account the coefficients of these (affine) transformations of the hysteresis loop family field..

1. Introduction

Mechanical characteristics of the MR shock absorbers [1] shall be based reasonably on the physical modeling of shock absorbers as the complex systems of structural damping [2, 3]. In this case, the interaction of all elastic frictional linkages in vibration isolators is considered and the problem of its deformation is solved in a closed form with the set of hypotheses and assumptions. However, this approach requires additional experimental confirmation of the proposed hypotheses and assumptions, the proof of which requires a lot of time and costs. At that the positive result may be not achieved.

Another approach is for the MR material presentation as a quasicontinuous environment. However, the determination of elasticity modulus non-linear characteristics and so on for MR material requires a large volume of experimental work, as well as for the case of geometric nonlinearity concerning the complex forms of MR products (e.g., bell-shaped ones) [4 -...8].

Therefore, one may consider an experimental method of the mechanical properties determination using the methods of similarity theory and dimensional analysis as the most relevant one.

The anisotropy of strength and elastic frictional characteristics (UFC) of MR material makes the provision of the aircraft engine isolation systems more difficult, especially under the influence of the spatial load. This disadvantage may be substantially eliminated by the inclusion of MR material in an array of high-resistant reinforcing element (HRRE), which is made from a special wire harness. The harness is a strand wrapped with a spiral tension coil to coil (type 1) (Fig. 1) or filament wire (type 2).

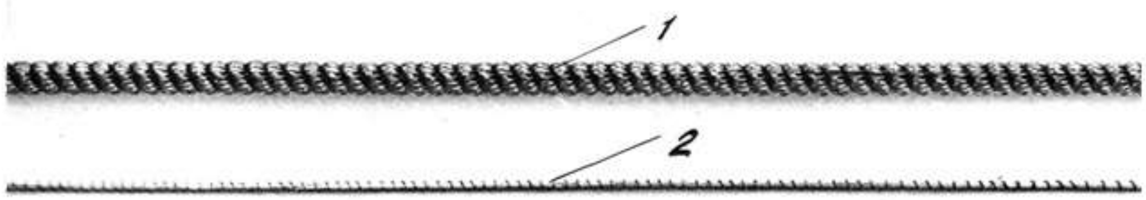

Figure 1. Special harness types: 1 - type 1; 2 - type 2

The increased damping capacity of elastic-damping elements (EDE) is ensured by the presence of additional energy dissipation at the AE boundaries of with the MR material array and within AE. The high strength of shock absorbers is achieved by the harness coverage of all mounting holes in the EDE.

On the basis of the described method MR UDE reinforcement method the modification of the "double bell reinforced" (DBR) shock absorbers is developed. This shock absorber is shown in Fig. 2.

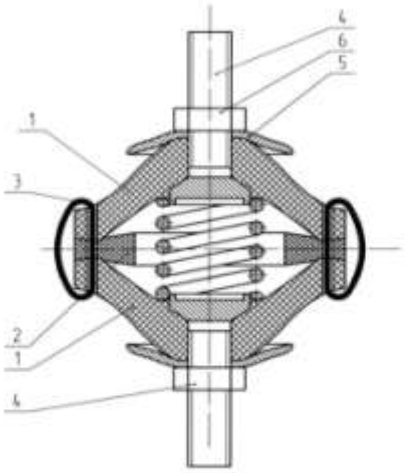

Figure 2. DBR shock absorber: 1- elastic-damping element; 2 - spacer; 3 - stitched wire; 4- mounting studs; 5 - limiting washer; 6- nut

The manufacturing process of the reinforced EDE consists of three main phases (Fig. 3 a, b, c). During the first step two bell-shaped EDE workpiece are made the spiral wire (see. Fig. 3a). During the second stage AE is produced from harness, which, if necessary, may be compressed according to the final product shape (see. Fig. 3b). During the third stage of AE is inserted in an array of spiral wire EDE blanks and wrapped over with a spiral wire. Then the final EDE shaping is performed by cold extrusion (see. Fig. 3c).

a)	b)	c)

Figure 3. Main stages of reinforced EDE production: a – EDE blanks; б - AE; в – finished EDE; 1 – fixing holes

2. Methods

2.1. Determination method of generalized UFH

The most important parameters determining the properties of simplest DBR shock absorbers without relief springs and a spacer (see. Fig. 2) are as follows: EDE diameter; the average density of EDE material ρ; the wire material density ρ_u and its diameter δ_u; spiral diameter d_u; fluidity limits σ_{mu}, σ_{m0} and elasticity modulus E_u of the wire in EDE blanks and within AE; brought to the sphere volume with the diameter D_K , AE density $\rho_{Ж}$ and all blanks $\rho_{з}$; δ_c diameter and the fluidity limit σ_{mc} of the stitched wire; diameter d_c brought along the stitch length and the number of stitching coils $n_{в}$.

The research of these parameters influence on the elastic frictional and strength characteristics of shock absorbers was carried out using the methods of similarity theory and dimensional analysis. The similarity according to UFH at the tension and compression of shock absorbers was determined by an affine similarity of hysteresis loop families with different A amplitudes and q tightness. The coefficients of these transformations were chosen as the sections cut off with congruent processes of loading and unloading from the coordinate axes (T_n - according to the load R, a_n - according to the deformation X).

In this case, the determined similarity criterion is the dimensionless load $\eta = R/T_n$. The determining criteria are the dimensionless strain $\xi = X/a_n$, the amplitude $\xi_A = A/a_n$ and the tension $\xi = q/a_n$. The experiments also showed that the similarity criteria are presented by the values composed of the shock absorber parameters:

Boundary condition criterion

$$\Pi_1 = \left(\frac{\sigma_{mu}}{E_u}\right)^{0,5} \left[\frac{\sigma_{mc}}{E_u}\left(\frac{\delta_c}{D_K}\right)^2 \frac{\delta_c}{d_c}\right]^{0,12} \left(\frac{d_{сн}}{d_c}\right)^{1,5}, \tag{1}$$

Where

$$d_{сн} = 0,7 D_K\left(\frac{\rho_з}{\rho} + 0,16\right); \tag{2}$$

damping criterion

$$\Pi_2 = \frac{d_u}{\delta_u}\left(1 - \frac{\rho_{жс}}{\rho_з}\right) + 24,5\left(\frac{\sigma_{mc}}{\sigma_{mu}}\right)^{0,5}\left(\frac{\rho_{жс}}{\rho_з}\right); \tag{3}$$

EDE buckling loss criterion

$$\Pi_3 = \frac{\rho_з}{\rho}. \tag{4}$$

The ranges of value change determining the similarity criteria were as follows: $\xi \in [-3,45;3,45]$; $\xi_A \in [0,14;3,45]$; $\xi_q \in [-2,07;2,07]$; $\Pi_1 \in [0,75\cdot 10^{-2};1,3\cdot 10^{-2}]$; $\Pi_2 \in [8,5;24,4]$; $\Pi_3 \in [0,05;1,32]$

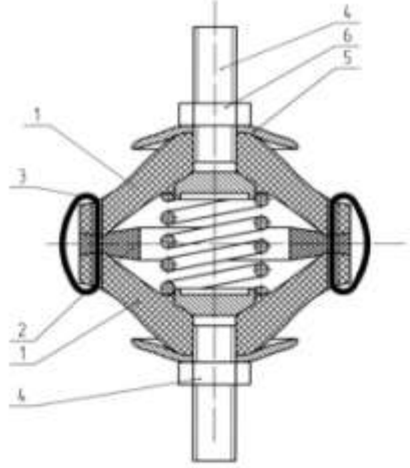

Figure 4. Generalized field of hysteresis loops

The research of the defining criteria effect for generalized UFH (Fig. 4) showed that the processes of DBR shock absorber deformation within the coordinates dimensionless load - dimensionless deformation are essentially nonlinear ones. The absorption coefficients ψ depending on the deformation amplitude ξ has its maximum (fig. 4). At that the most intense increase of the dimensionless average rigidity $\bar{C}_{cp}$ is observed at $\xi_A < 0,25$ (fig. 5). At the large values of ($\xi_A > 1,6$) $\bar{C}_{cp}$ is not changed almost. These circumstances are caused by the fact that during the amplitude decrease the shock absorber deformation most of the contact wires in the MR material as in the structural damping system (e.g., of a multi-layer cantilever beam) interact with each other elastically without slipping. This leads to a sharp decrease of the friction forces operation and increases the rigidity $\bar{C}_{cp}$. With the strain amplitude increase ($\xi_A \in [0,1;0,2]$)the most part of the contact wires interacts with slipping, causing a stiffness decrease $\bar{C}_{cp}$ and the friction force operation increase. However, at the further increase of $\xi_A > 0,25$ the increment of the friction forces is smaller than the increment of the elastic forces, making the reduction of ψ.

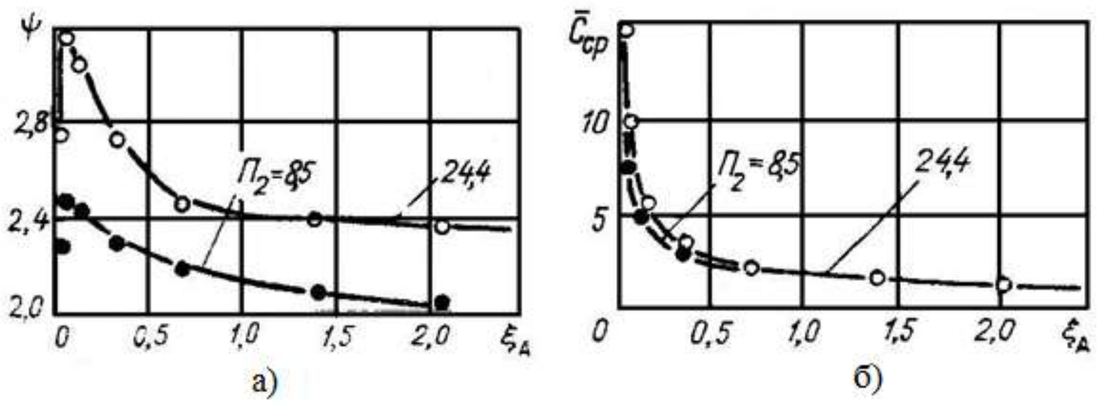

Figure 5. Dependencies: a – of absorption coefficient, б - average rigidity on the dimensionless amplitude and damping criterion

ξ_q criterion influences rather weakly on the nonlinear UFH nature. The strongest influence of ξ_q is performed on ψ and $\bar{C}_{cp}$. At the compaction of the shock absorber ψ is increased for fixed ξ_A, and is decreased at $\bar{C}_{cp}$. $\bar{C}_{cp}$ is increased during the extension, and ψ is decreased.

The influence of Π_1 criterion is especially evident at the shock absorber extension: while Π_1 is increased $\bar{C}_{cp}$ is increased. This is due to the compressive loads increase at EDE periphery, preventing the AE displacement relative wire spiral arrays. With the reduction of Π_2 criterion ψ is decreased. The UFH nonlinearity grade is decreased, estimated by the intensity of $\bar{C}_{cp}$ changes according to the amplitude ξ_A. Π_3 criterion physically characterizes the degree of MR material crimping and determines the EDE profile width. At a small profile width and large shock absorber deformations the load processes have flat areas and the period of EDE resistance loss may occur.

Along with the determination of the approximate similarity criteria Π_1, Π_2, Π_3 influence degree on the UFH, the functional connections were established experimentally of such transformation coefficients with the dimensionless complexes composed of the shock absorber parameters according to the first part of the P-theorem:

$$\frac{T_n}{E_u D_K^2} = 0{,}066\Pi_1^{2,2}\left(\frac{\rho_з}{\rho_u}\right)^{1,2}\left[\left(1-\frac{\rho_{ж}}{\rho_з}\right)+3{,}9\frac{\sigma_{m0}}{\sigma_{mu}}\frac{\rho_{ж}}{\rho_з}\left(0{,}8-\frac{\rho_{ж}}{\rho_з}\right)\right]; \quad (5)$$

$$\frac{a_n}{D_K} = 0{,}195\Pi_1\Pi_2. \quad (6)$$

The relations obtained in the aggregate with the data presented in Fig. 4, allow you to define any UFH of any DBR shock absorber at its cyclic loading, including the newly designed one, provided that the geometric similarity of its elements and tooling components is kept (profiles of punches and matrices, the scheme of harness stacking, etc.).

The requirements imposed on UFH, define the characteristics of the vibration-proof system with the dynamic action, for example, the resonance frequency of the system, the dynamic gain ratio, the allowable free-running and others.

2.2. Generalized dynamic characteristics determination method

Let's consider the harmonic kinematic excitation of a vibration-proof system (VPS) with one degree of freedom. The differential equation of the mass motion in the absolute coordinate system has the following formula:

$$m\frac{d^2x_1}{dt^2} + \Phi'\left[(r+x), x_k, sign\dot{x}, z_1, \ldots, z_m\right] = Q, \quad (7)$$

where x_1 is an absolute VPS transition; $x_1 = (x+r) + a_0 \sin\omega t$; m – system mass; r - the offset of dynamic equilibrium center; Q - constant force equal to the system weight; a_0 - exciting oscillation amplitude; ω - forced oscillations frequency; t - time.

Using the values of $\omega_q = \sqrt{\frac{T_q}{a_q m}}$ and a_q as such transformation coefficients of the variables t and x_1, x, r, x_k respectively, we obtain the generalized differential equation of motion

$$\frac{d^2\xi_1}{d\theta^2} + \Phi''\left[(\xi_r+\xi), \xi_k, \Pi_1, \Pi_2, \Pi_3\right] = \bar{Q}. \quad (8)$$

Here $\xi_1 = \xi_r + \xi + \xi_0 \sin\upsilon\theta$; $\xi_r = \frac{r}{a_q}$; $\xi_0 = \frac{a_0}{a_q}$; $\upsilon = \frac{\omega}{\omega_q}$; $\theta = \omega_q t$; $\bar{Q} = \frac{Q}{T_q}$.

The generalized amplitude-frequency characteristics (AFC) of the DBR shock absorbers were defined as the dependencies of the dynamic coefficient μ_q on the frequency υ of disturbing oscillations by varying the parameters ξ_0, Π_2 and $\bar{Q}$.

Fig. 6 shows the results of the AFC research, and Fig. 7 shows the results of the study. As can be seen from Fig. 7, the dimensionless natural frequency υ_p and the dynamic amplification factor at the resonance μ_p depend strongly on the excitation amplitude; at that the function ($\mu_p = f\left(\xi_0\right)$)has a pronounced minimum, located at the area of $\xi_0 = 0{,}15 \ldots 0{,}2$. One may also note, that while Π_2 criterion increases μ_p criterion decreases.

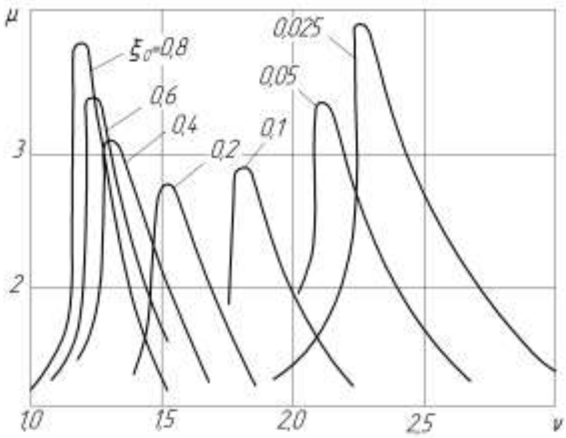

Figure 6. Generalized amplitude-frequency characteristics at Q=0,9

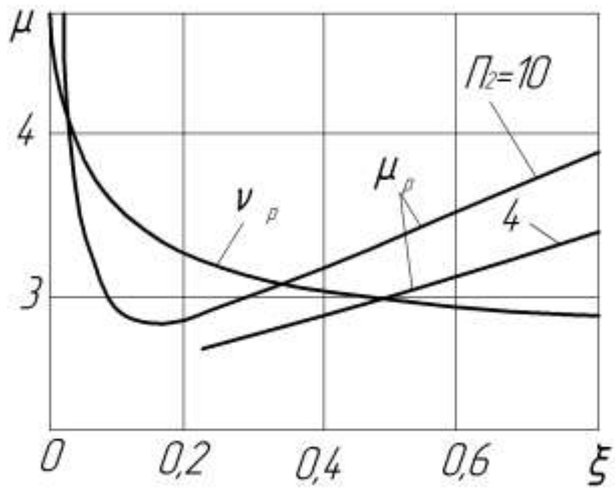

Figure 7. Resonance characteristics of shock absorbers

2.3. The method of strength characteristic research

The research of the DBR schock absorber strength characteristics was carried out under the static, vibration and shock loading.

The static strength of shock absorbers was determined by the P_P load value, causing EDE destruction. In this case, the EDE strength at break may be regarded as a total strength of EDE and AE workpieces. It is easy to show that the AE theoretical breaking strength is proportional to the complex $\frac{\rho_{ж}}{\rho_{з}} \frac{\sigma_{в0}}{E_{и}}$, where $\sigma_{в0}$ is the strength limit. The strength of MR material array made of coils may be determined experimentally on DK shock absorbers without AE. However, the actual working conditions of the schock absorber require the consideration of such factors as the uneven loading of the harness in AE, its interaction with an array of coils, the presence of stress raisers at the intersections of the strands. This may be accounted by using the experimental K coefficient:

$$\frac{P_P}{E_u D_K^2} = K \frac{\rho_{ж}}{\rho_u} \frac{\sigma_{в0}}{E_u} + 0,76 \cdot 10^{-5} \frac{\rho_з}{\rho_u} \left(1 - \frac{\rho_{ж}}{\rho_u}\right) \left(\frac{D_K}{d_u}\right)^{0,5}, \quad (9)$$

where K=0,058 for type 1 strand and K=0,098 for type 2 strand.

The practiced expression analysis shows that the static strength of DBR shock absorbers may be changed 7-10 times without any noticeable changes in other characteristics.

Three types of destruction take place at the shock absorber vibration loading:
1) The emerging of cracks along the EDE periphery developing in the radial direction;
2) The breaking of stiching coils;
3) The emerging of radial cracks on EDE.

The last type of damage is typical for large relative deformation amplitudes ($\varepsilon_A = \frac{A}{D_K}; \xi_A > 0,12$) and it is the most dangerous one, as it causes a catastrophic reduction in the static strength of the vibration isolator. The long-term cyclic loading of the vibration isolator is accompanied by UDE vibration heating and the wire element wear in MR material. The intensity of these processes largely determines the vibration isolator resistance. The significant temperature of vibration heating (up to 673 K) is observed within AE areas located on the EDE periphery at $\varepsilon_A > 0,05$, $T_n > 2 \cdot 10^{-7} E_u D_K^2$ and the loading frequency of more than 20 Hz. The smaller the temperature (up to 473 K) is observed on the EDE surface. The DBR shock absorbers resistance is largely dependent on the relative amplitudes ε_A and Π_1 and Π_2 criteria. At the increase of Π_2 criterion from 8,5 to 15,0...18,0 at ceteris paribus the vibration isolator resistance increases 5-10 times and makes more than $N_Ц = 10^6$ operation cycles. With the increase of Π_1 criterion the vibration isolator resistance may be decreased in several times, at that the most characteristic is the first type of fracture that occurs due to the stress concentration increase around the stitched holes. With the small diameters of stitched wire and the low fluidity limit σ_{mc} the strength of the stitched wire is insufficient and leads to the second type of fracture. It should be noted that in comparison with the existing DK modification the DBR shock absorbers have a significantly higher vibration resistance (Fig. 8). Moreover, there is a reduction of the DBR damping capacity to 50% and the stiffness increase up to 60% during the operation time.

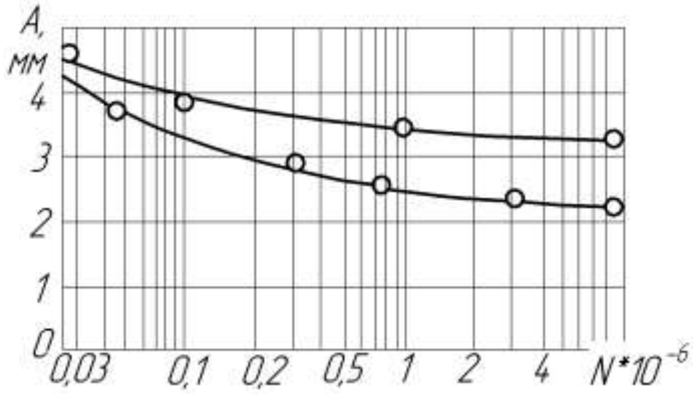

Figure 8. Dependence of vibration isolators endurance: 1 - DK-38-2/18; 2 - DBR -38-0,6/40

3. Conclusion

Thus, DBR isolators have the increased strength and damping properties. The performed studies confirm the possibility of DBR use within the vibration protection systems, operated under intense mechanic loadings.

The obtained results may serve as the basis for the design of various DBR vibration isolator sizes for a wide range of their mass loads and the intensity of vibration exposure. It should be noted that there may be a mathematical description of the loop field families, for example, by orthogonal polynomials and also by deformation processes at an arbitrary loading. This, together with the known approximate analytical methods of nonlinear differential equations solutions concerning the motion vibration isolation systems reveals broad prospects for the dynamic characteristics of the shock absorbers study at shock and random vibration loading, various laws of harmonic excitation from the frequency, the complex effect of static and dynamic loads, etc.

The solution of this type problems requires a more detailed study of the load and unload processes behavior at the arbitrary loading of the vibration isolator. Furthermore, due to the substantial non-linearity not only elastic, but also non-elastic forces in the MR material it is necessary to test the known approximate analytical methods concerning the possibility of their use during the solution of a wide class of dynamic problems.

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