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Elastic, Frictional, Strength and Dynamic Characteristics of the Bell Shape Vibration Isolators Made of MR Wire Material

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Abstract: The results of the mechanical characteristic experimental studies are presented for the vibration isolators 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 inclusion into the material a reinforcing wire braid. 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 group field.

Key words: MR material, Elastic-Damping Element (EDE), DKU vibration isolator, similarity, Elastic Frictional Characteristics (EFC), dynamics, strength

INTRODUCTION

Mechanical characteristics of the MR vibration isolators (Ponomarev *et al.*, 2013) shall be based reasonably on the physical modeling of vibration isolators as the complex systems of structural damping (Jiang *et al.*, 2008; Xia *et al.*, 2005). 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 quasi-continuous media. However, the determination of elasticity modulus of 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) (Ao *et al.*, 2005; Ulanov and Ponomarev, 2009; Ponomarev and Ulanov, 2009; Ulanov and Ponomarev, 2008a, b).

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 (EFC) of MR material makes the design 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 into a body of MR material a High-Resistant Reinforcing Element (HRRE) which is made from a special wire braid. The braid is a strand wrapped with a spiral tension coil to coil (type 1) (Fig. 1) or filament wire (type 2).

The increased damping capacity of Elastic-Damping Elements (EDE) is ensured by the presence of additional energy dissipation at the HRRE boundaries with the MR material array and within HRRE. The high strength of vibration isolators is achieved by the braid coverage of all mounting holes in the EDE.

On the basis of the described method of UDE reinforcement the modification of the "Double Bell Reinforced" (DBR) vibration isolator is developed. This vibration isolator is shown in Fig. 2.

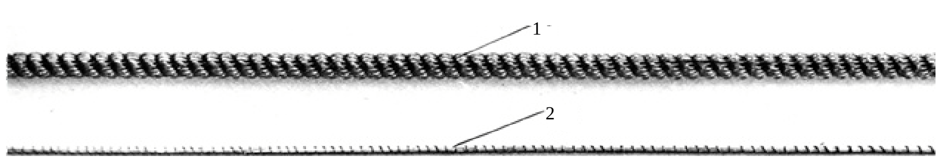

Fig. 1: Special braid types; 1: type 1; 2: type 2

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

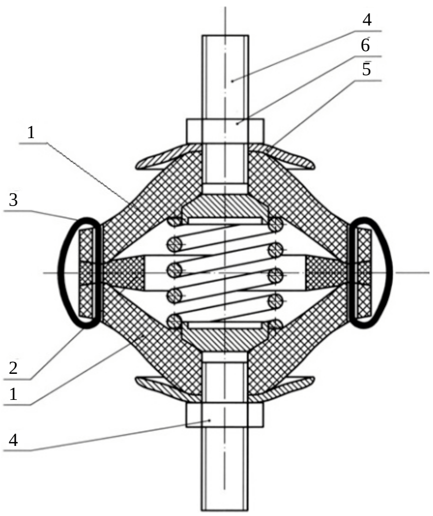

Fig. 2: DBR vibration isolator; 1: elastic-damping element; 2: spacer; 3: stitched wire; 4: mounting studs; 5: limiting washer; 6: nut

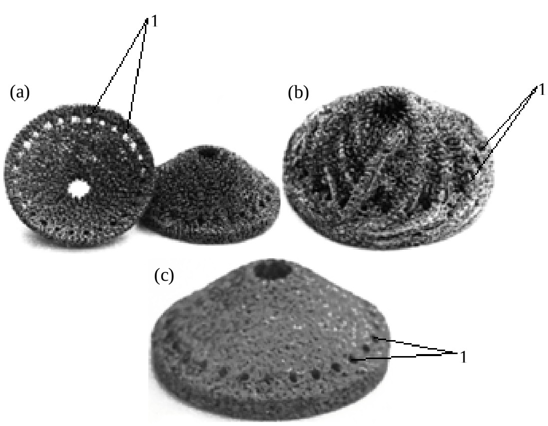

Fig. 3: Main stages of reinforced EDE production; a) EDE parts; b) HRRE; c) finished EDE; 1: fixing holes

METHODS

Determination method of generalized EFC: The most important parameters determining the properties of simplest DBR vibration isolator without relief springs and a spacer (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_{mo} and elasticity modulus E_u of the wire in EDE parts and within HRRE; brought to the sphere volume with the diameter D_K, HRRE density ρ_R and all parts ρ_p; δ_c diameter and the yield limit σ_{mc} of the stitched wire; diameter d_c brought along the stitch length and the number of stitching coils n_c.

The research of these parameters influence on the elastic frictional and strength characteristics of vibration isolator was carried out using the methods of similarity theory and dimensional analysis. The similarity according to EFC at the tension and compression of vibration isolator was determined by an affine similarity of hysteresis loop groups 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 vibration isolator parameters. Boundary condition criterion:

$$\Pi_1 = \left(\frac{\sigma_{mu}}{E_u}\right)^{0.5} \left[\frac{\sigma_{mc}}{E_u}\left(\frac{\delta_c}{D_K}\right)^2 \frac{\delta_c}{d_c}\right]^{0.12} \left(\frac{d_{sn}}{d_c}\right)^{1.5}$$

Where:

$$d_{sn} = 0.7\, D_K\left(\frac{\rho_R}{\rho} + 0.16\right)$$

damping criterion:

$$\Pi_2 = \frac{d_u}{d_u}\left(1 - \frac{\rho_R}{\rho_p}\right) + 24.5\left(\frac{\sigma_{mc}}{\sigma_{mu}}\right)^{0.5}\left(\frac{\rho_R}{\rho_p}\right)$$

EDE buckling loss criterion:

$$\Pi_p = \frac{\rho_p}{\rho}$$

The ranges of value change determining the similarity criteria were as follows:

$$\xi \in [-3.45;3.45];\ \xi_A \in [0.14;3.45];\ \xi_q \in [-2.07;2.07];$$
$$\Pi_1 \in \left[0,75\cdot 10^{-2};\ 1,3\cdot 10^{-2}\right];\ \Pi_2 \in [8.5;24.4];\ \Pi_3 \in [0.05;1.32]$$

The research of the defining criteria effect for generalized EFC (Fig. 4) showed that the processes of DBR shock absorber deformation within the coordinates dimensionless load-dimensionless deformation are essentially nonlinear ones. The energy dissipation coefficient ψ dependency on the deformation amplitude ξ has its maximum (Fig. 4). At that the most intense increase of the dimensionless average stiffness $\bar{c}_{cp}$ is observed at $\xi_A<0.25$ (Fig. 5). At the large values of ($\xi_A>1.6$)

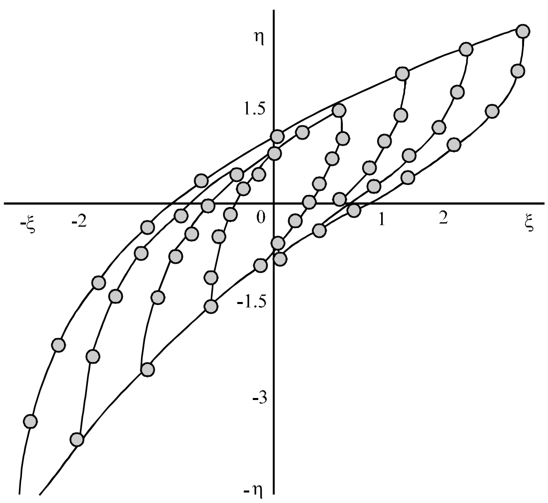

Fig. 4: Generalized group of hysteresis loops

$\bar{c}_{cp}$ is not changed almost. These circumstances are caused by the fact that during the amplitude of the vibration isolator deformation decreasing 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 stiffness $\bar{c}_{cp}$. With the strain amplitude increase ($\xi_A \in[0.1; 0.2]$) the most part of the contact wires interacts with slipping, causing a decreasing of stiffness $\bar{c}_{cp}$ and the friction force operation increasing. 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.

ξ_q criterion influences rather weakly on the nonlinear EFC nature. The strongest influence of ξ_q is performed on ψ and $\bar{c}_{cp}$. At the compaction of the vibration isolator 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 $\mathbf{\Pi}_1$ criterion is especially evident at the vibration isolator extension: while $\mathbf{\Pi}_1$ is increased $\bar{c}_{cp}$ is increased. This is due to the compressive loads increase at EDE periphery, preventing the HRRE

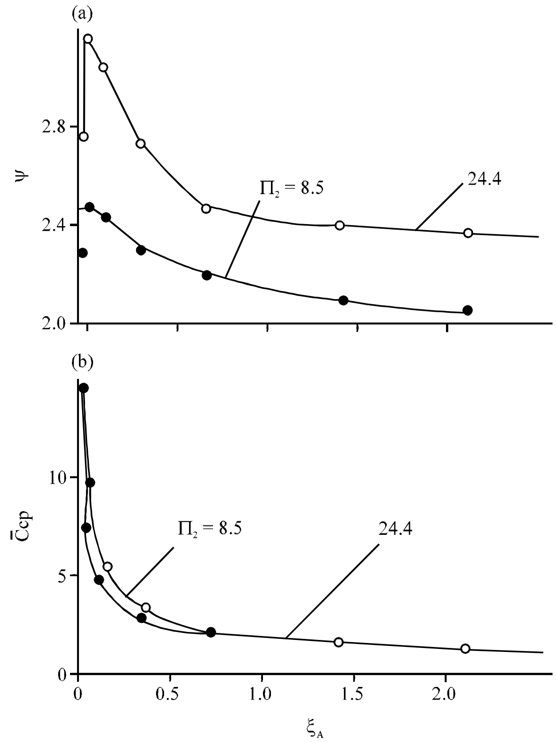

Fig. 5: Dependencies: a) of absorption coefficient and b) average stiffness on the dimensionless amplitude and damping criterion

displacement relative wire spiral arrays. With the reduction of $\mathbf{\Pi}_2$ criterion ψ is decreased. The EFC nonlinearity grade is decreased, estimated by the intensity of $\bar{c}_{cp}$ changes according to the amplitude ξ_A. $\mathbf{\Pi}_3$ criterion physically characterizes the degree of MR material crimping and determines the EDE profile width. At a small profile width and large vibration isolator 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 $\mathbf{\Pi}_1$, $\mathbf{\Pi}_2$, $\mathbf{\Pi}_3$ influence degree on the EFC, the functional connections were established experimentally of such transformation coefficients with the dimensionless complexes composed of the vibration isolator parameters according to the first part of the P-theorem:

$$\frac{T_n}{E_u D_K^2} = 0.066\Pi_1^{2.2}\left(\frac{\rho_p}{\rho_u}\right)^{1.2}\left[\left(1-\frac{\rho_R}{\rho_p}\right)+3.9\frac{\sigma_{m0}}{\sigma_{mu}}\frac{\rho_R}{\rho_p}\left(0.8-\frac{\rho_R}{\rho_p}\right)\right]$$

$$\frac{a_n}{D_K} = 0.195\Pi_1\Pi_2$$

The relations obtained in the aggregate with the data presented in Fig. 4, allow you to define any EFC of any DBR vibration isolator 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 EFC, define the characteristics of the vibration protection system with the dynamic action for example, the resonance frequency of the system, the dynamic transfer ratio, the allowable free-running and others.

Generalized dynamic characteristics determination method: Let's consider the harmonic kinematic excitation of a Vibration Protection System (VPS) with one degree of freedom. The differential equation of the mass motion in the absolute coordinate system has the following Equation:

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

Where:

- x_1 = An absolute VPS displacement
- 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:

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

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 $\bar{Q}$.

Figure 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 ($\mu_p = f(\xi_0)$) has a pronounced minimum, located at the area of ξ_0 = 0.15-0.2. One may also note that while Π_2 criterion increases μ_p criterion decreases.

The method of strength characteristic research: The research of the DBR vibration isolator strength characteristics was carried out under the static, vibration and shock loading.

The static strength of vibration isolator 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 HRRE work pieces. It is easy

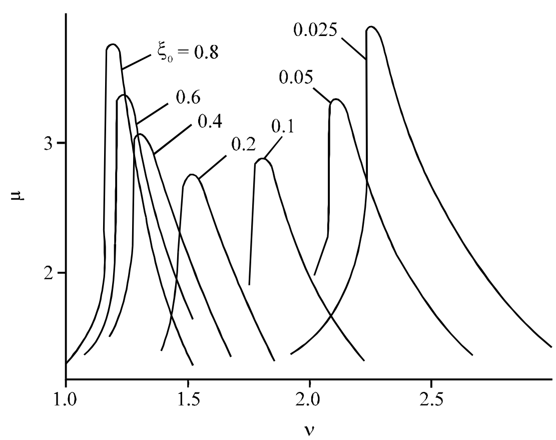

Fig. 6: Generalized amplitude-frequency characteristics at Q = 0.9

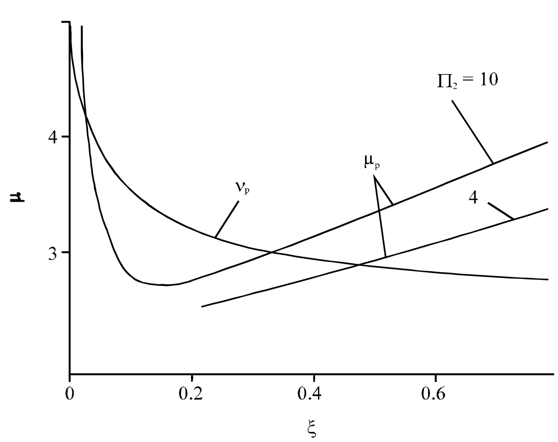

Fig. 7: Resonance characteristics of vibration isolator

to show that the HRRE theoretical breaking strength is proportional to the complex $P_R/P_p\ \sigma_{B0}/E_u$ where σ_{B0} is the strength limit. The strength of MR material array made of coils may be determined experimentally on DK vibration isolator without HRRE. However, the actual working conditions of the vibration isolator require the consideration of such factors as the uneven loading of the braid in HRRE, 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:

$$\frac{P_P}{E_u D_K^2} = K\frac{\rho_R}{\rho_u}\frac{\sigma_{c0}}{E_u} + 0.76\cdot 10^{-5}\frac{\rho_P}{\rho_u}\left(1-\frac{\rho_R}{\rho_u}\right)\left(\frac{D_K}{d_u}\right)^{0.5}$$

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 vibration isolator may be changed 7-10 times without any noticeable changes in other characteristics. Three types of destruction take place at the vibration isolator vibration loading:

- The emerging of cracks along the EDE periphery developing in the radial direction
- The breaking of stitching coils
- 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 EDE 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 HRRE areas located on the EDE periphery at $\varepsilon_A > 0.05$, $T_n > 2.10^{-7} E_u D_k^2$ and the loading frequency of >20 Hz. The smaller the temperature (up to 473 K) is observed on the EDE surface. The DBR vibration isolator 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 $N_C = 10^6$ operation cycles. With the increase of Π_1 criterion the vibration isolator resistance may be decreased in several times at that the most characteristic

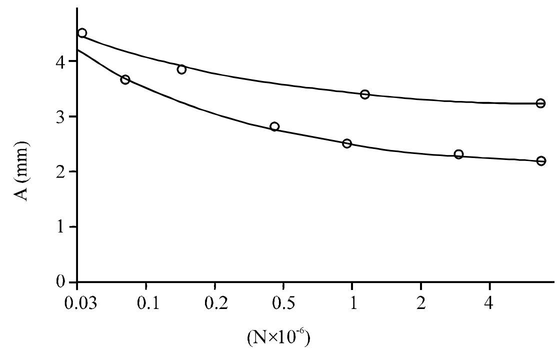

Fig. 8: Dependence of vibration isolators life-time; DK-38-2/18 and DBR (model DKU-38-0.6/40)

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 yield stress 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 vibration isolator 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.

CONCLUSION

Thus, DBR vibration 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 load. It should be noted that there may be a mathematical description of the loop groups 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 vibration isolators 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 of problems requires a more detailed study of the load and unloads 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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