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ALTERNATIVE VIBRATION PROTECTING SYSTEMS FOR MEN-OPERATORS OF TRANSPORT MACHINES: MODERN LEVEL AND PROSPECTS

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The up-to-date level and a few of the prospects are considered in transport biomechanical vibration protection systems. An experimental estimation of the maximum capabilities of traditional vibration protecting mechanisms (VPMs) used in driver seats is given. Some of the points of synthesis and research for the adaptive VPMs, called mechanisms of elastic links with small stiffness (ELSS-mechanisms) are presented. They contain a novel object of control: non-linear elastic elements with variable torsion "negative" stiffness (TNS). These TNS-elements help to optimize VPMs according to certain criteria and give them invariant structural and functional properties. Some experimental results are presented, and they correspond well with theoretical predictions. An approach is demonstrated for grade of quality of vibration protection of the men-operators of land unsuspended machines and pilots of helicopters.

1. INTRODUCTION

Transport biomechanical vibration protection system (transport bio-VPS) is understood here as a system which includes a vibration source [vibration on the workplace of the man-operator of a transport or automotive technological machine (TTM)], the protected object (the body of a sitting man) and a vibration protecting mechanism (VPM) as an elastic link (in the form of suspension, support, etc., for the seat) between the vibration source and the protected object. Traditional VPMs generally contain structural elements ("absolute" rigid in the studied frequency range), which form the path generating and damping mechanisms, etc., and also contain elastic elements in the form of metal and air spring, hydraulic cylinder and also combined types [1–5].

Transmissibility K_T is accepted as one of the main criteria of the quality of vibration protection using a VPM:

$$0 < K_T(\eta, \gamma) < 1. \tag{1}$$

Here, $\eta = f/f_0$ is the frequency ratio, where f is the frequency of external vibration, f_0 is the natural frequency of the VPS; γ is the relative damping coefficient.

Analysis shows that condition (1) cannot be satisfied in the infra-low-frequency band (first of all, if $f \in [1;\ 10]$ Hz, just where a human being is most vulnerable in terms of health, effectiveness of work and functional comfort) if the transport bio-VPS contains a traditional VPM of any kind. There are several reasons for it, and two main ones are: (1) The high stiffness of elastic elements along with the relatively small functional motions of the sitting man, which are limited by the dynamic anthropometrical parameters of the human body. (2) In addition, the redundant number of structural elements in the kinematic chain of traditional VPMs and, as a result, high damping decreases its transmissibility in these frequencies.

This prediction proves to be true by expert estimations made experimentally. The problem of vibration protection of the men-operators in most TTMs cannot be considered as satisfied in the frequency band $f \in [1;\ 10]$ Hz. The best of typical results are shown in Figure 1(a) and 1(b) [6–8]. This is true for traditional VPMs used in the passive as well as in the active modes of control, since passive and active VPM are formed from identical structural and elastic elements. In addition, the active ones have an even more complex structure as a result of using additional mechanical feedback.

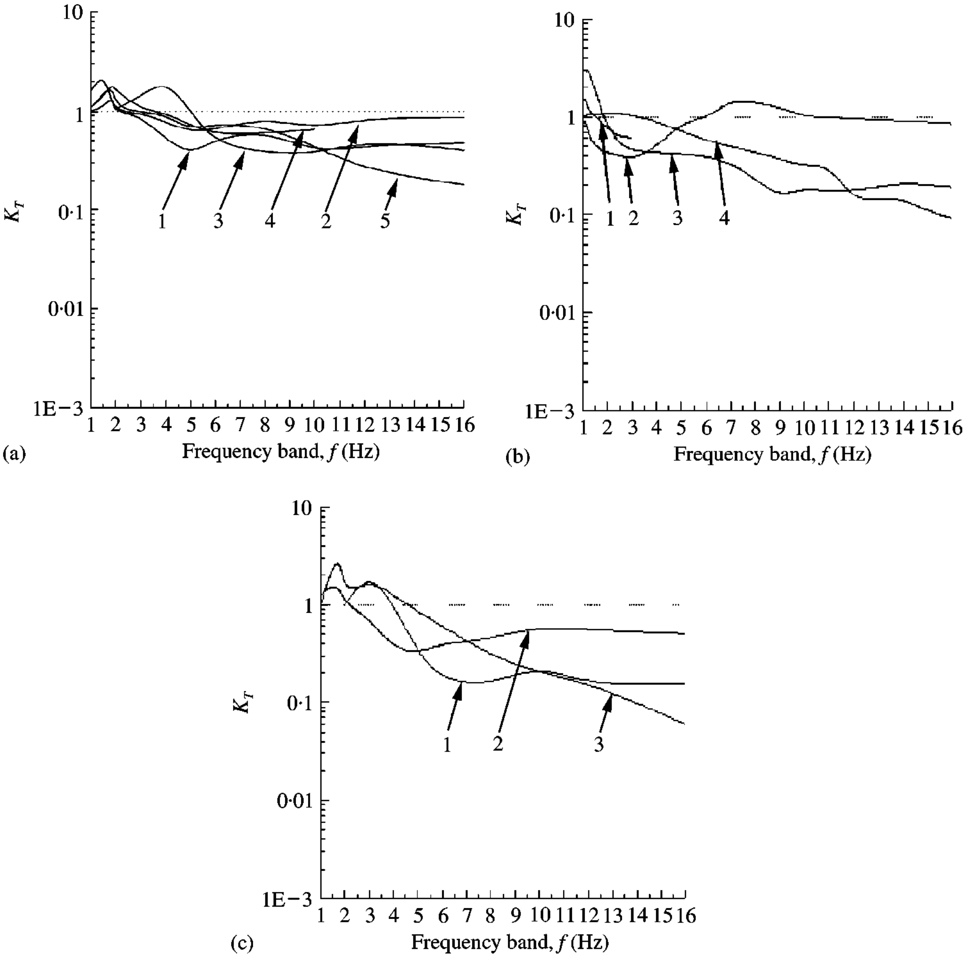

Figure 1. Transmissibility of transport bio-VPS with: (a) mechanical passive traditional VPM [6]; (b) hydro- and pneumo-mechanical active traditional VPM, incl. graph 1 by reference [7], graphs 2–3 by reference [8] and graph 4 by reference [4]; (c) mechanical passive VPM with quasi-zero stiffness [6].

This paper presents a few general points of the method of synthesis of VPMs called mechanisms of non-linear elastic links with small stiffness (ELSS-mechanisms). One approach based on this method is demonstrated for perfecting and optimizing a stock of traditional VPMs. Results of experimental tests are considered which compare ELSS-mechanisms with traditional VPMs used in land TTMs and helicopters. An evaluation of the conditions is given for obtaining any level of vibration protection quality using the ELSS-mechanisms.

2. SOME POINTS OF THE METHOD OF SYNTHESIS OF NON-LINEAR ELSE-MECHANISMS

2.1. THEORETICAL PREMISES

It is well known that the human body is sensitive to a wide vibration frequency spectrum. Therefore, vibration isolation is the most effective method of protection. Vibration isolation is attained by minimizing the natural frequency of the bio-VPS itself by reducing the stiffness of its elastic links.

Various elastic systems have been created to realize this method of protection. One of them is the elastic system with quasi-zero stiffness presented in many publications. Figure 1(c) demonstrates the vibration protection quality attained with the help of experimental VPMs, whose type diagrams are given in the monograph [9]. The known VPM with quasi-zero stiffness have long dimensions and small working stroke, where this physical effect is harnessed. In addition, their structure is more complex than that of traditional ones. Therefore, these VPM are not effective enough in transport bio-VPS.

In the work [10], a method is offered for synthesis of elastic systems with small stiffness. The synthesis goal is to be able to control the stiffness "vector" and to ensure the dynamic stability of elastic systems under optimal structural conditions. This is attained with the help of novel object of control: elastic elements with variable torsion "negative" stiffness (TNS). The idea of synthesis was confirmed experimentally and theoretically [6, 11–13]. The elastic elements with TNS should be non-uniform thin-walled structures. It could be, e.g., multi-layered sets of thin-walled bars or plates, not connected between themselves. In addition, their initial and work positions are obtained by consecutive super-critical deformations (buckling up to second form by longitudinal compression and post-bending by torsion) of the aggregate of the elastic elements on the two relative perpendicular axes.

A numerical synthesis has been developed for optimizing geometrical parameters for elastic elements with TNS. It is done using a method of the boundary problem's solution about non-linear deformation of a flexible bar by reference [14]. Figure 2 presents examples of dimensionless force $\bar{M}_2 = \bar{M}_2(\varphi)$ and stiffness $\bar{k}_2 = \pm\, \mathrm{d}\bar{M}_2/\mathrm{d}\varphi$ characteristics for elastic elements with TNS. They are synthesized according to the control ranges and criteria limits of their geometrical parameters in the ELSS-mechanism. The criteria limits are determined by the minimum of workspace for the ELSS-mechanism in a TTM compact driver's seat. As seen from the graphs in Figure 2(a), the theoretical model (solid graph 1) corresponds to the experimental results (symbol-graphs 2–2_2), obtained under various precompressions. The stiffness characteristic shown in Figure 2(b) has a wide range for control of the magnitude $|k_2|$, and without changing the structure of system of the elastic elements with TNS.

The conditions have been defined for joining a system of the elastic elements with TNS to an elastic link of a VPS. In particular, invariance in the number of structural degrees of freedom (d.o.f.) of the initial and synthesized elastic links:

$$W_{ELSS} = W_{init} + W_{TNS} = in\ var. \tag{2}$$

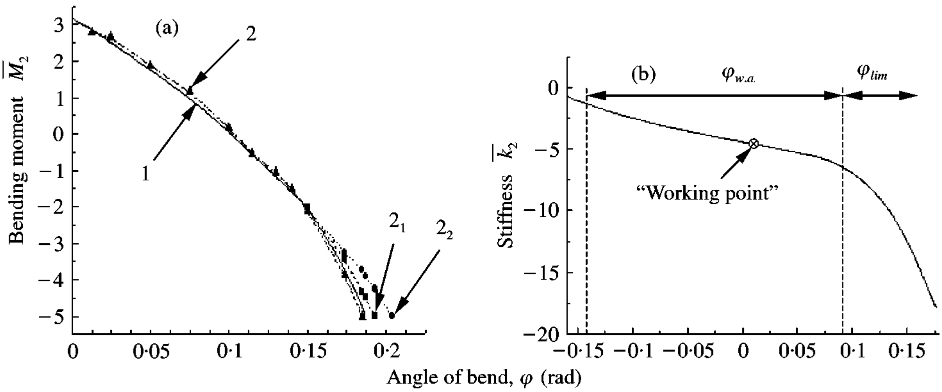

Figure 2. Theoretical static characteristics of a TNS-mechanism: (a) a fragment of force characteristic (graph 1) and its correlation to experiments (graphs 2–2_2); (*b*) range of "negative" stiffness.

Here, W_{ELSS}, W_{init}, W_{TNS} are the numbers of d.o.f. for the synthesized elastic link, the initial one and the system of the elastic elements with TNS respectively. In addition, the number q_{rc} of redundant constraints, at least, should not increase after attaching the new elements [12]:

$$q_{rc}^{(ELSS)} = 2 - 6n + \sum_{i=1}^{5} (6-i)p_{(6-i)} \leqslant q_{rc}^{(init)}. \tag{3}$$

Here, n, $p_{(6-i)}$ are the numbers of movable structural elements and their kinematic pairs of the ith mobility.

Joining elastic elements with TNS allows us to control the stiffness coefficient $k_1(q)$ of the elastic link of a VPS. The coefficient $k_1(q)$ is always "positive" as a result of the physical nature of deformation of the elements, which make it up. The stiffness coefficient $k(q)$ of the synthesized link can be "positive", "negative" or equal to zero after joining the elastic elements with TNS:

$$k(q) = k_1(q) + \Phi k_2(\varphi)\begin{cases} > 0, \\ = 0, \\ < 0. \end{cases} \tag{4}$$

Here, q is the generalized co-ordinate (linear or angular) of the elastic link of the VPS; $k_2(\varphi)$ is the stiffness coefficient of the elastic elements with TNS non-linearly involving the angle φ of bend; and Φ is the transmission function, whose form and dimensions are determined by the law of motion of a driving structural element of the elastic link and structural conditions of joining the system of the elements with TNS to it. A range of the elastic characteristics of ELSS-mechanisms can be expanded essentially by Φ control.

2.2. APPLYING THE METHOD

Fast and economical modernization of the stock of up-to-date traditional VPMs for TTM driver seats is one of the realistic applications of the method of synthesis presented. An approach has been created for improving and optimizing similar VPMs. Pursuant to

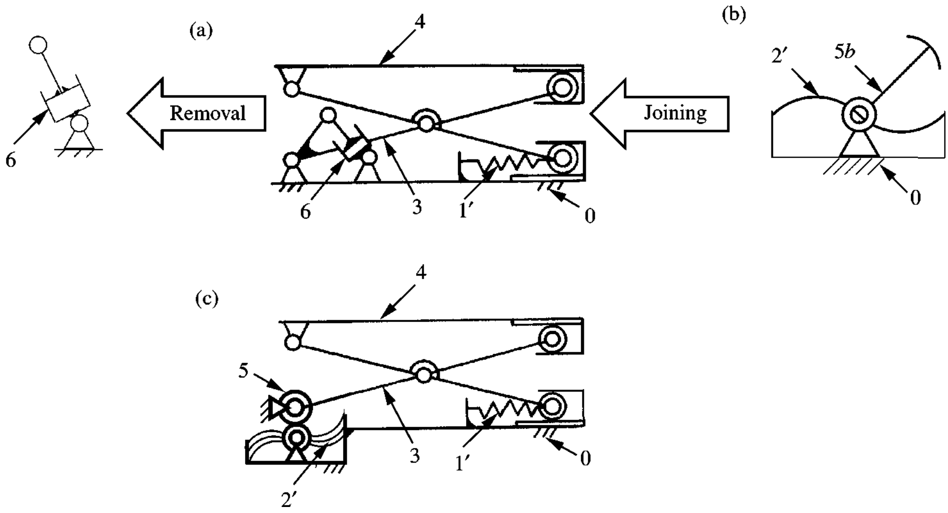

Figure 3. A scheme of type synthesis of the ELSS-mechanism: (a) initial VPM; (b) TNS-mechanism with a joining structural element; (c) ELSS-mechanism. Here a frame (position 0), a load bearing elastic element (1′), elastic element of TNS-mechanism (2′), intermediate structural elements (3), driving structural element (4), a drive for joining the TNS-mechanism (5), additional mechanism of damping (6) are shown.

this method, a system of elastic elements with variable TNS in the form of a module (TNS-mechanism) can be jointed into the basic kinematic chain of the initial VPM irrespective of its structure [13].

An example of the method's application is presented in Figure 3. The choice of the type diagram of initial VPM was made because at least 80% of VPM, used in TTM driver seats, have the same or analogous structure [13]. Using formulas (2) and (3), it can be shown that the structure of initial VPM does not become more complicated by the TNS-mechanism. In particular, the total numbers of structural elements and also redundant constraints are reduced due to the possibility of the elimination of the additional chain 6 of damping. It is easy to show that there are several combinations of structural numbers to obtain the condition $q_{rc}^{(ELSS)} = 0$. The stiffness of the elastic elements with TNS is determined by equation (4) under the condition $k(z) = 0$:

$$k_2(\varphi) = -\frac{k_1(z)}{\Phi\,\mu_k}. \tag{5}$$

Here, z is the co-ordinate of the vertical motions of the driving structural element 4 of ELSS-mechanism; $\mu_k \approx K_J l_1^2$ is the scale coefficient, where K_J is the dimensionless experimental coefficient; l_1 is the length of the intermediate structural elements 3. In the special case, Φ is the transmission ratio i of a gear or other drives. The ratio between the vertical motion z and angle φ of bend can be determined as

$$z \approx l_1\left(\frac{6i^2\varphi - \varphi^3}{6i^2}\right). \tag{6}$$

Here, i is the transmission ratio of the bevel gear 5 for joining the TNS-mechanism to the initial VPM.

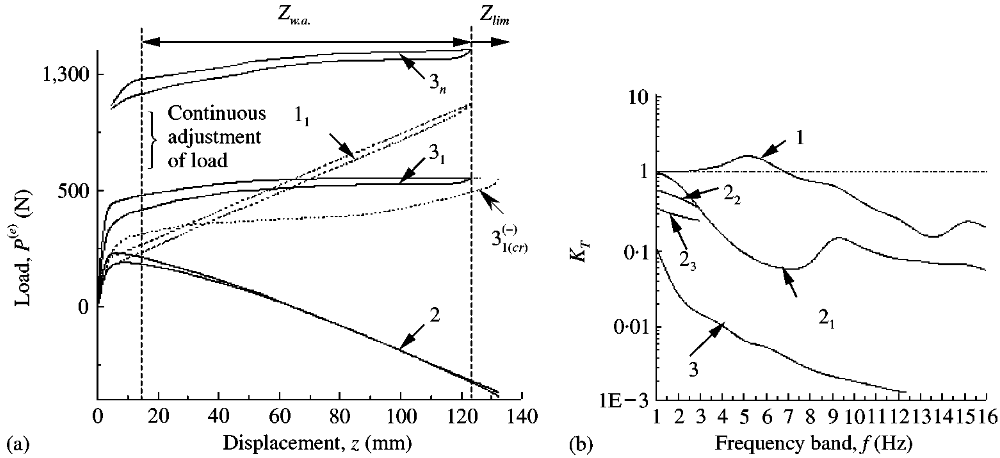

Figure 4. Experimental results of synthesis: (*a*) static characteristics of VPS-model containing initial VPM (graphs 1_1), TNS-mechanism (graphs 2) and ELSS-mechanism (graphs 3_1, 3_n); (b) transmissibility of VPS-model with initial VPM (graph 1) and ELSS-mechanism (graphs 2_1–2_3), a prediction of quality of a VPS with an ELSS-mechanism (graph 3).

A series of universal TNS-mechanisms has been developed. They are compact (the volume of TNS-mechanism for a driver's seat does not exceed 500 cm^3) and can be easily transformed depending on the limiting values k_1, l_1, i. Their elastic elements have the interval of angular motion of $\varphi = 0{\cdot}26$–$0{\cdot}4$ rad with "negative" stiffness. The values l_1 and i are determined by the configuration of the driver workspace, the dynamic anthropometrical and mass-inertial parameters of the human body. Based on the results of statistical analysis of known VPM kinematic diagrams, it is possible to generalize that $l_1 \in [285; 335]$ mm. In this case, the transmission ratio should be the following $i \in [1; 2)$, depending on elastic elements parameters of the initial VPM. Using formula (6), it is possible to obtain the working stroke $z_{w.a.} = 73$–130 mm for the driving structural element 4 of ELSS-mechanism, where effective control of stiffness is possible under the condition $i = 1$. This range is capable of laping over the working stroke of a driver's seat of any kind, which is usually $z_0 = 60$–75 mm.

The magnitude $|k_2|$ is formed in accordance with the value k_1. In Figure 4(a), elastic characteristics are presented for the initial VPM, the jointed TNS-mechanism and the synthesized ELSS-mechanism. As a result, the stiffness coefficient was decreased from $k_1 \in (5250; 10000]$ N/m (the typical level for the traditional VPMs) to $k \in [250; 750]$ N/m. The TNS-mechanism is also able to ensure a small stiffness of the elastic links of VPS independent of the variations in the static load $P^{(e)}$, and without changing its structure. Accordingly, the natural frequency of the bio-VPS model was reduced from $f_0 \in (2; 3]$ Hz (with the traditional VPM) to $f_0 \in [0{\cdot}4; 0{\cdot}7)$ Hz (with the ELSS-mechanism).

Figure 4(b) shows the behavior in the dynamics of the bio-VPS model as a result of transforming the initial VPM into the ELSS-mechanism. Transmissibility K_T was used to independently evaluate the quality of the vibration protection with the help of initial VPM and ELSS-mechanism:

$$K_T = 10^{(L_{out} - L_{in})/20}. \tag{7}$$

Here, L_{out} and L_{in} are the output vibration accelerations (on the driving structural element) and the input ones (on the vibrating table of an exciter) of the bio-VPS model, measured in decibels. Effectiveness factor $\bar{K}_T$ was introduced for a comparative evaluation of the vibration protection quality:

$$\bar{K}_T = \frac{1}{10^{(L_{out}^{(ELSS)} - L_{out}^{(init)})/20}}. \tag{8}$$

Here, $L_{out}^{(ELSS)}$ $L_{out}^{(init)}$ are the vibration accelerations on the driving structural elements of ELSS-mechanism and initial VPM respectively. As it follows from Figure 4(b), the advantage of ELSS-mechanism reaches $\bar{K}_T = 20$ and higher in the frequency band $f \in [1; 10]$ Hz.

The quality of vibration protection in the studied frequency band can be controlled by adaptive stabilization of ELSS-mechanism. The tuning of the variable parameter $\bar{k}_2$ is achieved by choosing the optimal initial deformed condition of the elastic elements of the TNS-mechanism. As a result, the transmissibility was reduced, e.g., from $K_T \in [0{\cdot}9; 0{\cdot}3)$ to $K_T \in [0{\cdot}3; 0{\cdot}2]$ under constant damping ($\gamma = 0{\cdot}065$) in the frequency band $f \in [1; 3]$ Hz (see graphs 2_1–2_3 in Figure 4(b)).

3. COMPARATIVE EVALUATION OF VIBRATION PROTECTION IN FIELD CONDITIONS

3.1. A FEW GENERAL POINTS OF MEASUREMENT PROCEDURES

A man-operator is subject to the most intense vibrations in unsuspended land TTMs: constructional equipment, agricultural machines, etc. Helicopter pilots are under similar conditions in terms of the level of vibration accelerations as well as their frequency range. So, a helicopter can be categorized (conventionally) with the unsuspended TTM, since a helicopter fuselage does not have any special means of vibration isolation in the infra-low frequency band [15].

Therefore, the methodology and equipment for tests were, mainly, identical for testing bio-VPS for land TTM and helicopters. In Figure 5, the effectiveness factor of vibration protection of bio-VPSs in some of the most typical groups of land TTMs and helicopters [11] is presented. Measurements were carried out in the discrete frequency band with center values $f = 1, 2, 4, 8, 16$ Hz (and also 10 Hz for helicopters). The ordinate axis is the factor $\bar{K}_T$ calculated by formula (8). Here, $L_{out}^{(ELSS)}$ $L_{out}^{(init)}$ are the vibration accelerations on the cushions of the driver seats containing the ELSS-mechanism and the traditional VPM respectively. All tested seats were classified into three groups: commercial seats with traditional VPMs (graphs 1); experimental seats with novel traditional VPMs (graphs 2); experimental seats with ELSS-mechanisms and commercial cushions (graphs 3). In field tests, traditional VPMs as well as experimental ELSS-mechanisms, or identical devices tested previously on vibration exciter (see Figures 1(a) and 4(b)) were used.

3.2. EXPERIMENTS IN UNSUSPENDED LAND TTMs

Suspended seats are the main means of vibration protection for the men-operators of the grain combines, short-chassis automotive cranes and other similar low-speed unsuspended land TTMs. Cabins of four commercial combines were equipped with commercial seats, and the fifth one—with a seat containing an experimental ELSS-mechanism. The field conditions of all five combines were identical. One crane was used during the tests, and various seats were mounted consecutively into its cabin.

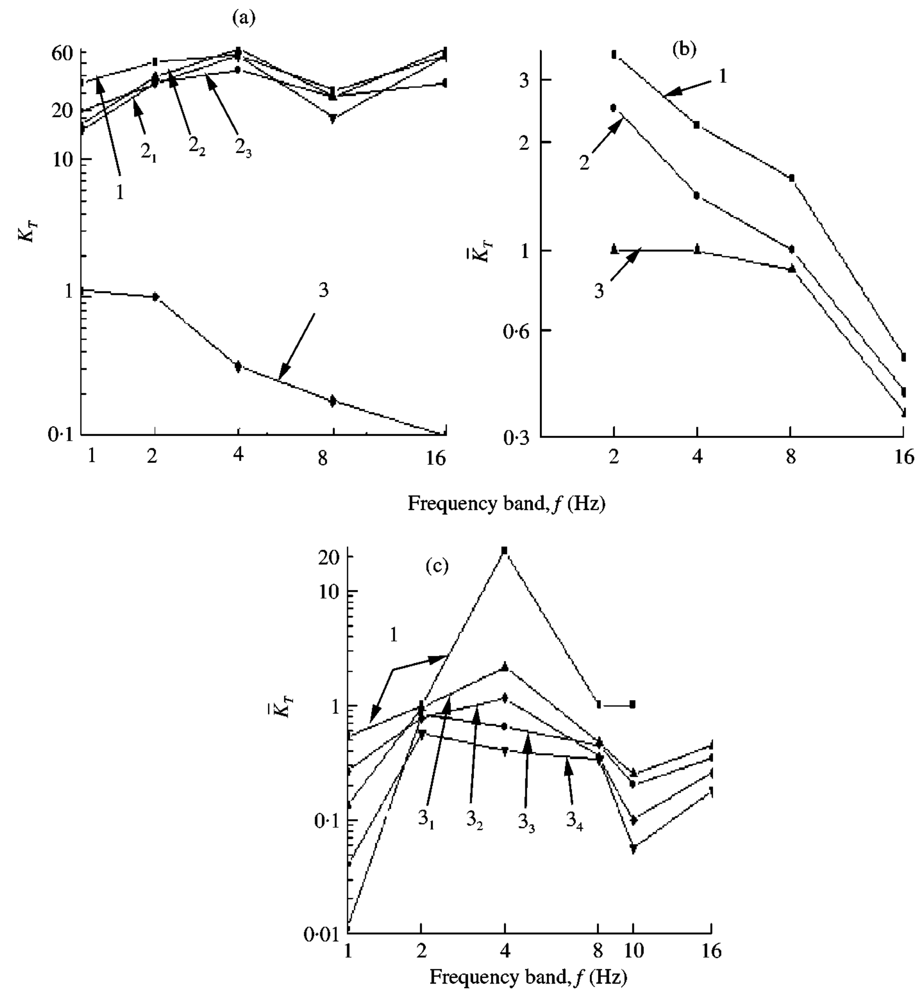

Figure 5. Field comparative tests of transport bio-VPS in: (a) grain harvester combines; (b) short-chassis automotive crane; (c) civil cargo-passenger and multi-purpose helicopters.

As seen in Figure 5(a), the advantage of the seat with the ELSS-mechanism is $\bar{K}_T \in (15;\ 300]$ in comparison to the commercial seats tested in the combines. This advantage is somewhat less in the seats tested in the crane (see Figure 5(b)), as a result of the low-power input vibration signal.

3.3. TESTS IN HELICOPTERS

Helicopter manufacturing companies are designing various passive and active controlled means for protecting the fuselage from vibrations, mainly, of the rotor, main reducer and tail rotor [11, 15–17]. One of them is the dynamic anti-vibration isolator (DAVI) for the central hub of the rotor. The maximum quality of vibration protection is $K_T \in (0{\cdot}5;\ 0{\cdot}25)$, and in the narrow frequency band (usually, $f \in (16;\ 25]$ Hz).

Attempts to design a VPM, similar to DAVI, or use the VPMs, applied in the driver seats of land TTMs, have not been very effective. Therefore, graphs 2 are absent in Figure 5(c). It practically means the absence of standard seats with special VPMs for vibration protection of pilots in the infra-low frequency band.

A few standard and experimental seats were tested in flights. Experimental seats were equipped with ELSS-mechanisms and standard cushions. Standard seats were mounted for the captains, and the experimental ones for the copilots [11].

As shown in Figure 5(c), the advantage of the experimental seat is $\bar{K}_T \in (3;\ 30]$. In addition, this was true in helicopters equipped with DAVI on the central hub of the rotor (graphs 3_2 and 3_4), as well as those without DAVI (graphs 3_1 and 3_3). The vibration protection quality is minimal on frequency $f = 2$ Hz for all helicopters used in the flight tests. This is due to the disabling of the tested traditional VPMs and ELSS-mechanisms by friction forces with the low-power input vibration signal ($L_{in} < 45$ dB, in the case given).

4. A FEW PERSPECTIVES FOR IMPROVING THE QUALITY OF VIBRATION PROTECTION

In Figure 4, the characteristics of an ELSS-mechanism are shown, developed on the basis of a traditional VPM having an optimal structure and dynamic characteristics similar to one another. As seen in graphs 2_1–2_3 [Figure 4(b)], the vibration protection quality corresponds, at least, to the criteria "Reduced comfort boundary" recommended in reference [18]. At the same time, a principally higher level of quality (see, e.g., graph 3) can be attained under the following ELSS-mechanism parameters: $f_0 \leqslant 0{\cdot}3$ Hz, $\gamma \approx 0{\cdot}025$. Some approaches are considered below for attaining these parameters with the help of TNS-mechanism. Experimental results are also given demonstrating the possibility of realizing these approaches.

4.1. DOWN IN DAMPING IN THE ELSS-MECHANISMS

The problem of friction is solved in a diametrically opposite manner in traditional VPMs and ELSS-mechanisms in the frequency band $f \in [1;\ 10]$ Hz. In a traditional VPM, it has to be such that the damping is $\gamma \in [0{\cdot}2;\ 0{\cdot}25]$. On the other hand, the Q-factor of an ELSS-mechanism must be high enough in these frequencies. Kinematic and structural friction can be reduced by optimization of the structure of elastic links. As a result, the parameter of damping is reduced from $\gamma \in (0{\cdot}2;\ 0{\cdot}25]$ to $\gamma \in [0{\cdot}05;\ 0{\cdot}065]$ by removing the additional damping chain from the structure of any VPM (see, e.g., graphs 1_1 in Figure 4(a)). This approach enables to increase the Q-factor of ELSS-mechanism and, accordingly, the quality of protection in the case of low-power input vibration signal. Thus, a traditional VPM will be stopped to protect vibration to remove the additional damping chain from its structure.

The increase of the Q-factor of an ELSS-mechanism in the infra-low frequency band improves the quality of vibration protection also in the low and middle frequency range. It is visible well from experimental data. As shown in Figure 6(a), the input vibration signal is not reduced by the driver's seat containing the traditional VPM, and the constructional resonances of this bio-VPS (50 and 80 Hz) are amplified by the given VPM. The ELSS-mechanism protects the same object completely [see Figure 6(b)].

A greater reduction in the damping (as low as $\gamma \leqslant 0{\cdot}025$) is possible by reducing the friction in the basic kinematic chain. With this purpose in mind, a number of experiments have been performed using traditional and new anti-friction materials for the contact surfaces of kinematically joined structural elements of ELSS-mechanism. Some results are

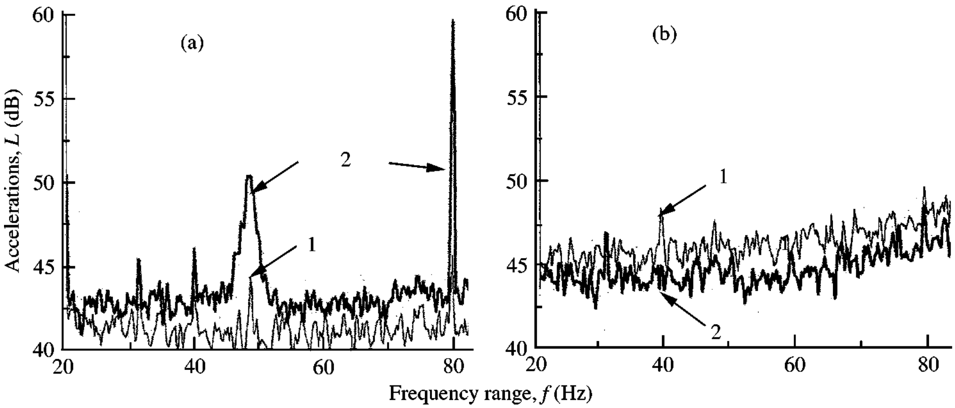

Figure 6. A vibration spectrum in transport bio-VPS containing: (a) traditional VPM; (b) ELSS-mechanism. Here, levels are shown in the vibration source (graphs 1) and on protected object (graphs 2).

Table 1

Experimental values of the coefficient of relative damping [12]

No.	Material name	Parameter γ_1
1	Brass and bronze	0·09
2	Aluminum alloy (raw)	0·08–0·09
3	Aluminum alloy (standard hardened)	0·06–0·065
4	Aluminum alloy with micro-plasma hardening	0·045–0·05
5	Aluminum alloy with micro-plasma hardening and lubricated with fluorine film	0·03–0·035
6	Fluorine compound (standard)	0·06
7	Fluorine self-lubricating compound	0·015–0·02, $\gamma_{1max} = 0{\cdot}025$

presented in Table 1. All materials are classified into a few groups: alloys including copper, aluminum alloys, fluorine-containing self-lubricating solid and liquid compounds with the general chemical formula $(CF_2\text{–}CF_2)_n$, etc.

All values of parameter γ in Table 1 were obtained with the TNS-mechanism disconnected from the basic kinematic chain: $\gamma = \gamma_1$. As seen in graphs 3_1, 3_n [Figure 4(a)], friction in the given example of ELSS-mechanism practically does not increase after joining the TNS-mechanism: $\gamma = \gamma_1 + \gamma_2 \approx \gamma_1$. Here, γ_2 is the relative damping in the TNS-mechanism (see graphs 2).

Use of thin (thickness approximately 2–3 μm) protective liquid perfluoro-films can be effective in reducing the kinematic as well as structural friction. These films have a number of new properties, different from usual lubricating materials. In particular, the film is incompressible; it is dielectric. The film is kept on the contact surface by the forces of acceptor interaction of fluorine molecules with the surface. Covering the adjoining surfaces of the elastic elements (thin plates) with the film additionally reduces the structural friction in the TNS-mechanism. This film results in an increase in the flexibility of the thin plate sets, and, accordingly, in a widening of the working section with $\gamma_2 \approx 0$, in an additional 20–25% [12].

4.2. USING AN ELSS-MECHANISM AS AN UNIMPACT ELASTIC STOPPER

As known, output signal (on the protected object) increases several times during transient vibrations of a transport bio-VPS. This is due to a high "positive" stiffness of the elastic elements of a traditional VPM. The stiffness increases in the peripheral sections of a working stroke and it comes several times in contact of the VPM with additional elastic stoppers, having, as a rule, a force characteristic as shown by graph 4 in Figure 7. More over, the jump in stiffness is already in the start moment of this contact (see graph 1_1).

This influence can be reduced if the elastic properties of TNS-mechanism are used. For example, the value k_2 of "negative" stiffness can be increased by 2–3 times or more in the section φ_{lim} [see Figure 2(b)]. Then, the increment of elastic forces is minimized: $\Delta P_{3\mathrm{k}} \to \min$. It can be done through construction approaches, e.g., with the "floating" boundary of working stroke $z_{w.a.}$ by the partial use of peripheral sections z_{lim} (see Figure 4(a)). In addition, the increment ΔP_{3k} can be "positive" as well as "negative", as shown in Figure 7:

$$\Delta P_{3k} = P_{3\{k+1\}} - P_{3k} = 0. \tag{9}$$

An event ($\Delta P_{3\mathrm{k}} < 0$) is possible with a drift of k_2 limited on time. It is a sufficient condition to quickly increase the damping to $\gamma \geqslant 0{\cdot}2$ on the boundary of working stroke, as shown in Figure 4(a) (graph $3_{1cr}^{(-)}$).

4.3. ADAPTIVE CONTROL OF "NEGATIVE" STIFFNESS

It has been experimentally established [11, 13], that the stiffness of elastic elements of an ELSS-mechanism can be reduced to $k = 87$–100 N/m and lower, without the loss of their load bearing capacity. This is achieved by choosing the initial deformed condition of the elastic elements of TNS-mechanism in accordance with the changes in the "positive" stiffness of the load bearing elastic elements. In the example given (see Figure 4(a)), the small stiffness was attained in the section $z_{w.a.} \in [50; 123]$ mm. As a result, the natural frequencies of transport bio-VPS model were reduced up to $f_0 \approx 0{\cdot}15$–$0{\cdot}2$ Hz.

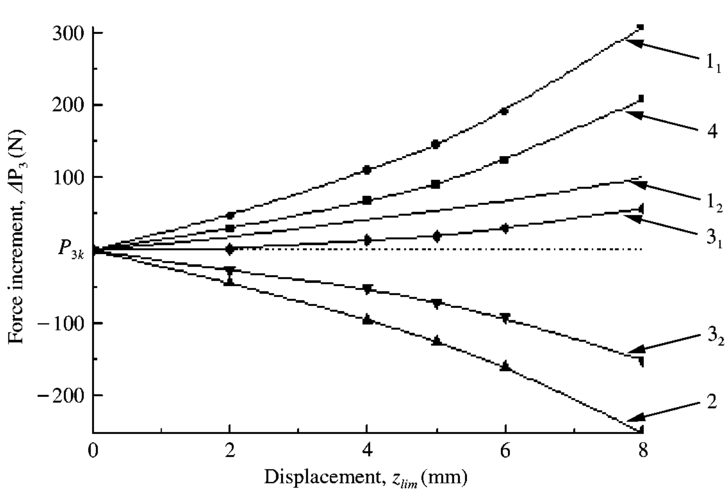

Figure 7. Force increments on boundaries of working stroke: of an initial VPM with an elastic stopper (graph 1_1) and without one (graph 1_2); of TNS-mechanism (graph 2); of ELSS-mechanism with elastic stopper (graph 3_1) and without one (graph 3_2); force characteristic of an elastic stopper (graph 4).

In a real transport bio-VPS, such characteristics can be obtained in the automatic control over the stiffness of ELSS-mechanism. The control is necessary to keep the drift of the "working point" (see Figure 2(a)) within a section, in order to make the magnitude $|k| \to \min$ available. However, the automatic controlled adaptive ELSS-mechanism differs from the traditional active VPM in function as well as in construction, in particular:

(1) In an ELSS-mechanism, a paradoxical but local control problem is solved: keep the dynamic system stability as a whole (ELSS-mechanism) by initializing instability in one of its unload bearing subsystems (TNS-mechanism). In addition, in the event of a loss, the control system, the vibration protection quality will be the same, with the exception of frequencies $f \leqslant 0{\cdot}3$ Hz.

(2) A compensation mechanism is immanently in mechanical feedback of an ELSS-mechanism: it is the TNS-mechanism.

(3) For adaptive control of an ELSS-mechanism, a low-power external source is needed to keep the elastic elements with TNS in a position of unstable equilibrium. For a seat's ELSS-mechanism, the compensation forces do not exceed $\Delta P \in (125; 150]$ N independent of static load in the range $P^{(e)} \in (500; 1300]$ N.

5. CONCLUSIONS

In this paper, it is shown that a man-operator cannot be protected from vibration in the infra-low frequency band using passive traditional VPMs, regardless of their technical characteristics. VPM, called ELSS-mechanisms, are presented as a possible alternative for use in transport bio-VPSs.

Non-linear elastic elements with variable TNS have been created to control the stiffness in magnitude and in sign, in accordance with an algorithm set beforehand. In addition, they give the ELSS-mechanisms invariant structural and functional properties. TNS-mechanisms can be jointed into the structure of any VPM and optimize its parameters in accordance with the desired level of vibration protection quality.

An economical approach, demonstrated in this paper, has been proposed for optimizing the structure and dynamic characteristics of a stock of up-to-date traditional VPMs.

The experimental results of testing ELSS-mechanisms are presented. They were obtained through comparative laboratory, as well as field tests with the most effective traditional VPMs in some types of land TTM and helicopters. These results show a good correlation with the theoretical predictions.

The ELSS-mechanisms can be used in transport bio-VPSs, first of all, where the vibration protection is necessary, but not effective or impossible with the help of traditional VPMs:

(1) Agricultural machines, constructional equipment and similar low-speed unsuspended TTMs must be equipped with seats with special VPMs in the ELSS-mechanism type.

(2) Through flight tests, it was confirmed that one of the urgent challenges is designing special VPMs for vibration protection of helicopter pilots in the infra-low frequency band.

(3) The mini-TTM and TTM with a very small workspace for a driver's seat are the fields of application of ELSS-mechanisms also [6, 11, 13].

(4) Automatic controlled adaptive ELSS-mechanisms can be applied in the driver seats of suspended TTMs (urban buses, trucks) [11, 13] and passenger off-road cars [6].

(5) The TNS-mechanisms can be applied to improve vibration protection also of technical objects in TTMs (engine, cabin, etc.), especially in combination with constructional methods [19]. For example, several TNS-mechanisms, used in driver seats, can be mounted under a cabin. Because they are compact, and each one has the parameters

for interaction with load bearing elastic elements designed for load upto 1500 N. In addition, the range of parameter control of TNS-mechanism can be increased without change of its structure.

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