A NEW CONCEPT OF VIBRATION PROTECTION SYSTEMS WITH “QUASI-ZERO” STIFFNESS AND A NEW CHALLENGE TO USE SUCH SYSTEMS

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The systems with extremely small stiffness, in particular, with “quasi-zero” stiffness, are potentially one of the most effective for vibration protection of humans and engineering, especially in the infra frequency range. However, it is necessary to solve a number of new scientific problems for practical use of such systems. First, this is optimization of the design parameters to obtain compact springing elements and at the same time to extend the workspace with extremely small stiffness. Another problem is to increase the elastic limits of the elements and resistance to stress under post-buckling in large. A conceptual model of the element made of lightweight and high-strength non-metallic composites has been developed to solve these design problems. The study showed a possibility to increase the elastic limit of the elements made of composites up to 2700 MPa and over versus 1200 MPa for geometrically similar elements made of spring steels. Besides, the “quasi-zero” stiffness workspace can be increased from 20% (using a spring steel) to 60–70% (using the composites) of the system elastic response. In case of active position control, these systems are able to provide perfect vibration protection in a range including nearly zero frequencies. These advantages could drastically change the design philosophy of such systems and significantly expand their practical use. A concept of the system with "quasi-zero" stiffness with active control is discussed to protect extremely complex and expensive research and industrial machines such as future colliders that are highly sensitive to the vibrations in the infra frequency range, in particular of 0.1–0.2 to 3–5 Hz. Since there are no passive/active systems against such vibrations leading to significant offset of colliding beams at the interaction point, to a sharp emittance growth and other degradation and fail of the machines.

Keywords: infra-frequency vibration protection, springing element with extended workspace of “negative” or “quasi-zero” stiffness, future collider
1. Introduction and motivation

The systems with extremely small stiffness are one of the most effective for vibration protection in the low- and especially infra-frequency ranges. Such systems are designed, usually, as a certain combination of a carrying subsystem with “positive” stiffness and a corrective one with “negative” stiffness. A proper balance of stiffness values of these subsystems minimizes the aggregate stiffness of a vibration protection system named as a VPS with “quasi-zero” stiffness. The active control of the VPS makes it possible to reduce the input vibrations in a range, including the frequencies less than 1 Hz (see Fig. 1a). To an increasing extent, such systems are used for human and engineering vibration protection, e.g. in transport vehicles, in instrumentation for electronics, optics, etc [1–3]. However, the quality of “quasi-zero” stiffness degrades with time. The main reasons are: (a) very small workspace of the VPS, where the stiffness is minimal, (b) a certain deterioration of elastic properties due to a drift of the VPS beyond this workspace, (c) insufficient strength of springing elements under post-buckling deformation.

Figure 1: (a) Performance limits of a VPS in the infra-frequency range [3], (b) vibrations of the colliders [4].

Meanwhile, a base of equipment and machines requiring the infra frequency vibration protection of high quality is increasing. These are e.g. very complex and expensive research and industrial high-energy machines (future colliders, electron beam accelerators, synchrotrons). They generate the structural vibrations at the infra frequencies, in particular in 0.1–0.2 to 3–5 Hz. Besides, they are also sensitive to 1–100 Hz vibrations that are kinematically excited due to operation of supporting facilities for vacuuming, feeding and cooling of these machines (see Fig. 1b). This operating equipment can significantly increase the input vibrations in a distance from a few dozens of meters to 3 km. These vibrations lead to significant offset of colliding beams at the interaction point (I.P.), to a sharp emittance growth, and to other performance degradation and even to a fail of such machines [4–7].

This paper presents results of a study to increase the workspace, where the stiffness of the VPS can be extremely small, as well as the long-term durability of its springing elements by means of transition to fundamentally new structural materials. A concept of a VPS with “quasi-zero” stiffness is presented in a new possible application for such systems, namely, for the infra-frequency vibration protection of future colliders, which construction, use and service are time-consuming and expensive.
2. Developmental trends in the VPSs with “quasi-zero” stiffness

2.1 Optimal design of the mechanisms with “negative” and “quasi-zero” stiffness

The stress-strain state has been studied and an optimal designing of the mechanisms with “negative” and “quasi-zero” stiffness has been carried out. For these purposes, we developed, in addition to the methodology based on consistent theory of thin shells [2], the algorithms for on-line optimization of key and optional design parameters of such mechanisms [8]. The optimization is reduced the finding a minimum of a certain target function. Generally, this function is not smooth. Therefore, the gradient-based optimization algorithms provide too approximate results. To obtain a reliable procedure and solve the design problem, the nonlinear simplex methods can be used. For instance, we used Nelder-Mead method for designing the vector space of the parameters with dimensions up to six. However, the computation by the method can stop at a local extremum without finding a global one. Besides, there is no theory of convergence of the method. Therefore, we applied a new approach to determine the target function by searching an optimal error. We extended the method by taking into account the limits of the search algorithm. A novelty of the approach consists also in adding a verification if new vertices of the simplex meet the specified search range. Otherwise, the procedure is performed to obtain the vertices.

The adequacy of new algorithms was valid through the comparison of computed parameters and the geometry of a sample of the mechanisms for seat suspensions (a payload up to 1.5 kN), which were passed a long dynamic tests and operation [9]. Then, new approach made it possible to optimally design the geometrically and dynamically similar mechanisms for the VPSs of the equipment and machines that differ by several orders of magnitude of payload capacity. For instance, a compact mechanism has been designed, which dimensions exceed only 2.5 times the mechanism for a seat suspension, while the payload of a VPS using similar mechanism can reach 200–250 kN. The algorithms allow not taking into account the layout features of a VPS. This is very important when a multi-stage VPS is being designed with a set of similar mechanisms with “negative” or “quasi-zero” stiffness.

2.2 A progress in the system designing

A new generation of the mechanisms with “quasi-zero” stiffness for the infra-frequency VPSs is being developed. In a number of applications, such mechanisms can quite effectively perform the role of “self-reliant” VPSs under a small perturbation. These are e.g. compact vibration isolating platforms (tables) with payload capacities of 0.5 to 20 kN, which dimensions, however, are changed insignificantly. The stiffness of springing elements made of spring steels for such platforms (tables) can be varied in a wide range of "positive", "quasi-zero" and "negative" values.

Fig. 2a illustrates such a mini-platform with payload up to 0.6 kN in development testing. Fig. 2b shows the test results, where the input vibration (acceleration on the exciter table) was \( L_a \approx 60 \text{ dB} \). Such a concept of the VPS has shown effective in the frequency range of 0.9–100 Hz. Meanwhile, the quality of vibration isolation can be increased, and in a range including close to zero frequencies. However, for this purpose, the VPS must be supplied with an active positional control. In addition, it is necessary to minimize the system relative damping, at least to \( D \ll 0.06 \) [10]. This would allow to reduce the spectrum of the VPS natural frequencies to \( f_0 \approx 0.05-0.1 \text{ Hz} \).

Such VPSs can be nonresonance in a range including the infra- (0.1–10 Hz) and low (10–100 Hz) frequencies. For this purpose, it is necessary to keep (with the help of active positional control) the operating point of the VPS inside the workspace where the stiffness is small (“quasi-zero”). Fig. 3a illustrates a segment of 4 to 6.5 mm on the elastic response, where the VPS stiffness can be cut up, \( k \rightarrow +0 \). However, if the operating point is outside the workspace, then the quality of vibration protection will degrade. Fig. 2a illustrates such degradation when the operating point drifts to segments with higher stiffness (see segments 6–7, 7–8 and 8–9 mm in Fig. 3a). This results in worse infra-frequency vibration protection. To avoid this, it requires more extended workspace with “quasi-zero” stiffness.
Change of spring steels with the composites to design the springing elements

The studies have been carried out to increase the workspace and simultaneously the strength of springing elements with "negative" and "quasi-zero" stiffness, designed e.g. in the form of the plates or packages of thin plates made of various spring steels. The FEM analysis was performed in a dynamic formulation taking into account the plastic deformations of the material. Fig. 4 shows examples of computation of the stress intensity, as well as the plastic range in the elements under post-buckling.

Inadequate strength of metal springing elements under post-buckling is another key reason for degradation of "quasi-zero" property and for a decrease in working life of such VPSs.

Experiments to increase the strength of the elements made of spring steels showed that the known methods of heat treatment give a slight increase in the elastic limit and resistance of such structures. This is reasonable when using the elements under post-buckling in small. However, these methods are not sufficient when the metal elements operate under post-buckling in large. Therefore, alternative springing elements have been developed made of various lightweight but high-strength composite materials such as the carbon plastics, graphene, kevlar, aramid, etc.

The study of new elements, made e.g. of carbon plastics, showed a significant increase in the elastic limit: up to 2700 MPa and more compared to 1200 MPa for the spring steel structures. Simultaneously, the workspace with "quasi-zero" was increased 3–5 times in comparison with the structures made of...
spring steels and having the same dimensions. Fig. 3b illustrates the elastic responses of various models of springing elements made of lightweight and high-strength composite materials. It can be seen that the dimensions of workspace with “quasi-zero” stiffness are increased 4–5 times, e.g. up to 9–12 mm compared to 2–2.5 mm when using the elements made of spring steels (please compare with the data in Fig. 3a). Thus, these composites seem to be more promising alternative for increasing the long-term strength and workspace of the VPSs with “quasi-zero” stiffness, however without an increase in dimensions of the springing elements. Besides, such composites allow reducing the VPS mass. For instance, the substitution of the metal elements with carbon plastic structures reduces the VPS mass 4 times, while its payload can be remain the same or even increased by 50%.

Figure 4: Analysis of deflected mode of metallic springing elements: (a) stress intensity, (b) plastic range.

3. A forecast of perfect infra-frequency vibration protection

3.1 Conditions for perfect vibration isolation using the VPSs with “quasi-zero” stiffness

In works [10, 11] we showed that, with active positional control, the spectrum of natural frequencies of a VPS with “quasi-zero” stiffness can be reduced to \( f_0 = 0.2–0.3 \) Hz even when the system relative damping is \( D \leq 0.09–0.1 \). Meantime taking into account the above, it is possible to formulate some basic conditions to shift the spectrum closer to \( f_0 \approx 0.05–0.1 \) Hz and thus to achieve an “ideal” infra-frequency vibration isolation. These are:

First condition. It is necessary to continuously hold the operating point of the VPS inside the workspace of "quasi-zero" stiffness. When using springing elements of new type (made of lightweight and high-strength composites), the solution of this problem seems to be quite simple (see elastic responses of the VPS models in Fig. 3b), in comparison with the geometric analogs of the elements made of spring steels (please compare the responses in Fig. 3a).

Second condition. It is necessary to minimize the system relative damping, at least to \( D \leq 0.06 \). This condition can be achieved e.g. by modifying the contact surfaces of movable joints in the VPS mechanisms by using the composites like “Al – Al2O3”- type which can be synthesized by microplasma oxidation of Al [10]. Fig. 5a illustrates an evaluation of the damping when using this design method in comparison with the methods used to design the bearings made of many other types of anti-friction materials. As seen, this method allows reducing the friction nearly to zero. Fig. 5b illustrates that, to shift the VPS workspace to the segment \( k \approx 0 \), one needs to run a certain lock-up behavior of such system. For this purpose, the damping is reduced from \( D_1 \approx 0.09 – 0.16 \) to \( D_2 \approx 0.06 – 0.065 \).
3.2 A concept of the VPS with “quasi-zero” stiffness for a future collider

The infra- and infra-low frequency vibrations continuously and seriously misalign the components of a collider. These result in the beams’ offsets at the I.P. (in a linear collider) and emittance growth (in a linear collider or a large hadron collider). The beam emittance growth can be compensated, however the beam offset cannot be corrected by a pulse-to-pulse feedback (see e.g. [6, 7]).

Various passive and active VPSs are designed, used or planned to be used for the infra- and infra-low vibration protection of the main machinery and supporting equipment of future colliders. For instance, this can be a set of single stiff isotropic elastomers or a set of more soft metal springs providing the passive vibration isolation in the frequency range over 7–28 Hz. For active vibration control, the sensors measure the input vibration (e.g. on the base) below the elastomers and deliver voltage proportional to the velocity of vibration motion. Such active VPSs with a set of single stiff isotropic elastomers can be effective in the range of 0.8 to 1 Hz (see e.g. [12]). The capabilities of known passive and active VPSs are sufficient for the low-frequency vibration protection of the colliders and similar high-energy machines in a range of 10 to 100 Hz. At the same time, even in active control, such VPSs will operate at the limit of capabilities or even useless for vibration isolation in a range of 0.1 to 1 Hz. However, these vibrations are critical for the colliders because they result in structural resonances of the main machinery and may lead to degradation of the functional parameters and motion of colliding beams.

The capabilities of the VPSs with “quasi-zero” stiffness and extremely small damping are sufficient to provide perfect vibration isolation in the frequency range starting from 0.7–10 Hz even in passive control. With active control, such VPSs are able to provide the vibration isolation in a range including the frequencies of 0.4–0.7 Hz and lower. Fig. 6a illustrates a structure of a future linear collider, which could be supplied with a built-in active VPS of “quasi-zero” stiffness between the rigid base and each final focusing e/magnet of the collider. This can reduce the infra- and low frequency vibrations impacting due to dwell, seismic nature and human activities. An algorithm of certain law of programmable motion can be implemented to set the VPS operation modes by using e.g. the pneumatic control system (see Fig. 6b). Such a discrete-continuous control system supposes one of the states for a j-th actuator of N ≥ 2 [11]. The control system provides the positioning relatively to the reference point $z_0$. This control system is equipped with the feedbacks of displacement, $z_2(t)−z_i(t)$, and velocity, $\dot{z}_2(t)−\dot{z}_i(t)$, in the relative motion of fixed and output structural elements of the actuators. The pressure feedback controls the pressure $p(t)$ inside the chambers of rodless air-springs. In the steady-state vibration motion, the algorithm is mostly based on the estimating the deviation of instantaneous position $(z_2−z_i)$ relative to $z_0$ and correcting the position of the output element within the limits of pre-given $\xi$-drift inside the workspace.

Figure 5: An approach to shift the VPS natural frequencies as close to zero as possible: (a) minimization of damping by using the antifriction composites of close to no damping, (b) a result of the approach use.
where the VPS stiffness is minimal, i.e. where \( k \rightarrow +0 \). Thus, the control strategy we propose essentially differs from well-known concepts of the active vibration control based on the attenuation of extraneous resonant responses by using controlled dampers. In the VPS with extremely small stiffness one should not know the input signal data but focus attention on the VPS self-stabilizing to prevent degradation of the “quasi-zero” stiffness quality.

Figure 6: A concept of the active VPS with “quasi-zero” stiffness for a future collider module: (a) simplified layout of the modules, (b) an algorithm of position control of the VPS.

4. Conclusions

Drastic changes are presented in the vibration protection systems with “quasi-zero” stiffness due to transition from the springing elements made of spring steels to lightweight and high-strength composites. First, this is an increase at least twice in the strength of the elements, what is imperative in operating under post-buckling deformation. The testing showed the stability of the system elastic response within a sustained loading of the elements. Next, the dimensions of the VPS workspace with “quasi-zero” stiffness were increased 4–5 times compared to the VPS-models designed by using the metal springing elements, however with the same geometry. This can fundamentally change the design philosophy of the mechanisms with "negative" and "quasi-zero" stiffness for the systems of broadband infra- and low frequency vibration protection. Further study will aim an analysis of non-linear effects, as well as searching the approaches to design the springing elements with 3D-“quasi-zero” stiffness property. Such a qualitative leap in the systems with "quasi-zero" stiffness can make them out of competition in providing the requirements of perfect vibration protection in a range starting from nearly zero frequencies for a variety of existing or promising machinery and equipment, e.g. of future colliders. These requirements are very challenging and never achieved in the past by using known passive/active vibration protection systems.

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