https://doi.org/10.15407/knit2023.05.003
UDC 629.7.02

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DEVELOPMENT OF VIBRATION PROTECTION SYSTEMS OF SPACECRAFT — STATE OF THE ART AND PERSPECTIVES

Vibration loads on the launch vehicle and spacecraft can reach a high level, leading to abnormal and emergency situations. Therefore, the spacecraft structure must not only support the payload and subsystems of the spacecraft but also have sufficient strength and rigidity to exclude any emergencies (damage, destruction, unwanted deformations of the structure, failure and failure of instruments and equipment) that may interfere with the success of the mission. The article aims to analyze the state of research on the design of vibration protection systems for spacecraft launched into working orbits by modern launch vehicles. The results of this analysis will contribute to the development of fundamental schemes of vibration protection systems and methods for effectively suppressing spacecraft spatial vibrations.

It is shown that the development of new promising vibration protection systems will take place in the following directions: increasing the frequency range and damping parameters of the dynamic coupled system of "spacecraft and vibration isolation system"; changing approach to vibration suppression of the entire spacecraft (as a whole unit) to setting up the system for damping individual (the most responsible and vibration-sensitive) spacecraft; the use the spacecraft active vibration suppression system in combination with a passive vibration protection system; use of schematic diagrams of spacecraft vibration protection systems with the introduction of hydraulic, electromagnetic and mechanical functional elements in order to increase the efficiency of vibration isolation systems; active suppression of random vibrations in outer space during the operation of various spacecraft systems (due to disturbances from engines of orbit correction systems, etc.); using the adapter structure to perform the functions of a passive vibration protection system of the spacecraft.

Keywords: *spacecraft safety; launch environment; vibration loads; launch vehicles; acoustics; random vibration; vibration isolation; control system algorithms; space flight, liquid rockets.*

Цитування: Pylypenko O. V., Khoroshylov S. V., Nikolayev D. O. Development of vibration protection systems of spacecraft — state of the art and perspectives. *Space Science and Technology.* 2023. **29**, № 5 (144). P. 3—19. https://doi.org/10.15407/knit2023.05.003

1. INTRODUCTION

The global space engineering field's operations were drastically altered with the beginning of the New Space paradigm. The New Space requires commercialization, which leads to changing the central driving role from government-funded organizations to privately owned ones. As SpaceX and many other private companies have proved, getting the commercial value to push more investment into the space sector requires more efficient and cheaper designing and development processes [29].

Higher mobile Internet speed or improvement in the harvest prediction quality has its own cost, which depends on the delivery cost of the satellite to orbit. Reducing the cost by launching multiple small satellites together is the way the space industry goes. More satellites per launch decrease the cost of spacecraft delivery to orbit. However, different factors block the progress here, and the satellites/spacecraft's structure and ability to handle dynamic loads during the launch phase is one of them.

The active phase of the flight of launch vehicles (LV) is characterized by the development of various kinds of vibrations of the LV structure, which are transmitted through its interface to the spacecraft (SC). Due to various reasons, these vibrations appear in the low and high-frequency ranges. Vibration is a harmful factor both for its source (i.e., mainly for the rocket propulsion system itself) and for the object of application of the force action — the launch vehicle body, which includes a spacecraft launched into working orbits with complex, expensive instruments and sensitive to vibrations by equipment [13]. Vibration loads on the structure of the launch vehicle and spacecraft can reach a high level and lead to abnormalities and emergencies [4, 13]. Therefore, the structure of a spacecraft with an adapter must not only support the payload and subsystems of the spacecraft but also have sufficient strength and rigidity to exclude any emergencies (damage, destruction, unwanted deformations of the structure, failure and failure of instruments, and equipment) that may interfere with success missions. Furthermore, the spacecraft must resist the actual action of all vibration loads. Therefore, its structure, components, and measuring instruments must be designed so that vibration indicators are minimal in a wide frequency range [12, 21, 27, 46, 47].

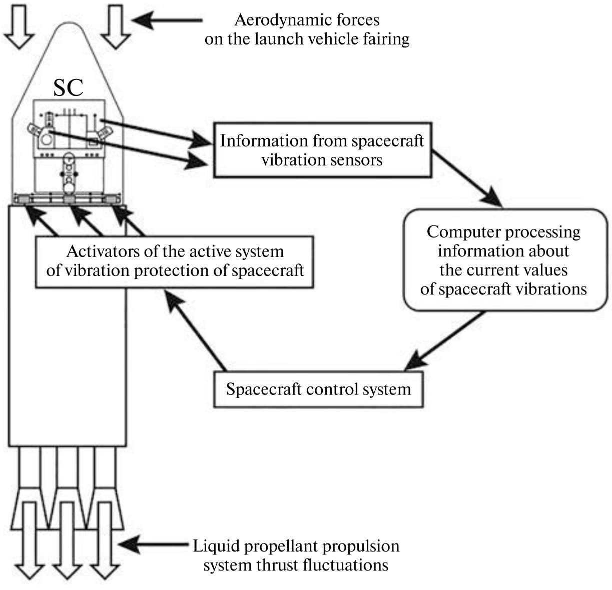


Figure 1. Interaction of functional modules of the spacecraft vibration isolation system with the launch vehicle control system

Maintaining the operability and operational characteristics of various spacecraft systems [15, 20, 30, 39, 48] during their launch into a working orbit and during their operation in orbit is no less difficult design task in comparison with the task of ensuring the integrity and strength of the spacecraft.

Moreover, when a spacecraft moves along an orbit in zero gravity (due to the low level of dissipative forces), disturbances from the operation of rocket systems (for example, from engines of spacecraft motion correction systems) can lead to the development of long-term oscillatory movements of optical cameras and spatial modules of solar batteries. When a satellite is in orbit, micro-vibration generated by its actuators (such as the launch and operation of orbit correction system engines, deployable mechanisms, and other factors) will affect the imaging quality of the camera [15]. Such oscillatory elements of the spacecraft are subject to damping by artificially introducing dissipation into the vibration isolation system. The isolation system active type KA can effectively reduce the reaction wheel micro-vibrations on the camera and subsequently increase the image quality [23].

Spacecraft vibration protection systems are undoubtedly necessary in a critical case when, based on the results of ground tests of the spacecraft (taking into account the forecasts of dynamic vibration accelerations of the rocket), the spacecraft designers concluded that it is impossible to meet the requirements for the spacecraft in terms of strength standards [1, 2, 26, 39].

In the theory of vibration protection systems (see, for example, [14, 19, 24, 42]), methods and means of protection against vibration are classified. By this classification, methods that reduce vibration transmission by using additional devices built into the structure of machines and building structures are divided according to the principle of their action: vibration isolation methods and vibration damping methods. Using an additional energy source, vibration isolation methods are divided into passive vibration isolation methods and active vibration isolation methods. According to the type of dynamic impact, they are divided into methods of power vibration isolation and kinematic vibration isolation [23]. Finally, according to the principle of operation, vibration dampers are classified into shock vibration dampers, dynamic vibration dampers, spring pendulum, eccentric, hydraulic, and others.

Modern launch vehicles, as a rule, launch several dozen spacecraft of various types into working orbits (in particular, a record number of 149 low-mass spacecraft were simultaneously launched by the Indian launch vehicle PSLV [32]). Such spacecraft are attached to a specially designed adapter (dispenser). The vibration amplitudes of a particular spacecraft will also depend on the mechanical characteristics of the dispenser and the parameters of the fastening of the spacecraft. Thrust oscillations of launch vehicle engines, leading to spacecraft vibrations, can also often be difficult to predict in terms of amplitudes and frequencies of oscillations, depending on the launch conditions of the launch vehicle, and may differ from the experimental values recorded in bench tests [2, 3, 8, 33, 35].

Under these conditions, it is advisable to use active (or semi-active) means of suppressing vibrations of the spacecraft (for example, the active vibration isolation system of the Chinese launch vehicle [43], the vibration isolation system of the Arian-5 launch vehicle [37]), in which the vibration parameters of specific spacecraft during the flight of the launch vehicle are processed (analyzed using specially developed computer algorithms) in the launch vehicle control system and then transferred to the activators of the vibration isolation system of the spacecraft, i.e., the vibration isolation system is actively tuned to the parameters required at the moment. Fig. 1 shows a schematic diagram of the interaction of functional modules of such a vibration isolation system with spacecraft vehicle systems.

The article aims to analyze the state of research on the design of vibration protection systems for spacecraft launched into working orbits by modern launch vehicles. The results of this analysis will contribute to the development of fundamental schemes of vibration protection systems and methods for effectively suppressing spacecraft spatial vibrations.

2. FLIGHT DYNAMIC LOADS FROM THE SIDE OF THE MODERN LAUNCH VEHICLES FOR THE DESIGN AND EXPERIMENTAL TESTING OF SPACECRAFT

When choosing the parameters and developing the vibration protection system, they primarily rely on the data of flight tests of the launch vehicle, based on which the acting loads on the spacecraft are determined [1, 39] during the launch and flight of the launch vehicle, on the results of numerous vibration tests of the spacecraft on unique stands [13, 26, 29]. When processing the vibration protection system, it must be taken into account that during ground tests of the spacecraft, the dynamic characteristics of the system with the spacecraft are almost impossible to fully reproduce since the dissipative forces and surface tension forces realized in flight under microgravity conditions will be somewhat different than under the conditions of the earth gravity [3].

High levels of vibrations of the structure of the launch vehicle with the spacecraft are usually recorded during the launch of the launch vehicle, the start and stop of its engines, the separation of stages, the separation of the ejected compartments, tanks, and associated payloads, during transient processes associated with a change in the engine operating mode (Fig. 2 shows an example the longitudinal components of vibration accelerations of the launch vehicle).

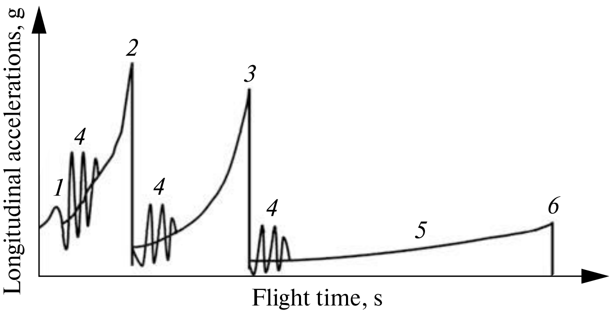


Figure 2. Representation of the dependence of the longitudinal accelerations of the spacecraft structure on the flight time of the launch vehicle, recorded in the low-frequency range in steady and transient modes during its launch by a three-stage launch vehicle with a rocket engine (*1, 2* — start and stop the propulsion system of the first stage of the launch vehicle, *3* — stop the operation of the propulsion system of the second stage of the launch vehicle, *4* — transient processes, *5* — site of active flight of a launch vehicle with a working propulsion system of the third stage)

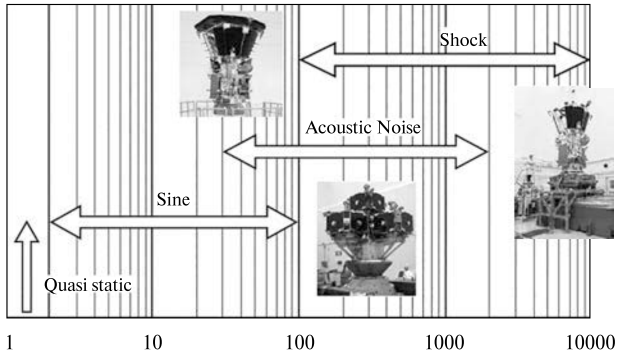


Figure 3. Quasi-static and dynamic loads acting on the spacecraft during its launch into an orbit in various frequency ranges and implemented during vibration testing of spacecraft of various types and masses

During the launch and flight of the launch vehicle, the following dynamic and static loads act on the spacecraft [12]:

- quasi-static overloads (during liftoff and launch into orbit),
- harmonic (quasi-harmonic) vibrations during transient processes (when launching into orbit),
- random vibrations caused by oscillations of an irregular nature (while launching into orbit),
- acoustic loads (when launching into orbit),
- shock loads (shocks) — impulsive vibration impacts caused by the effects of shock waves arising from the operation of pyrotechnic devices (during the separation of the fairing and the third stage, during the separation of the spacecraft from the launch vehicle).

The cause of spacecraft vibrations can also be longitudinal vibrations of a liquid launch vehicle (POGO) [33, 34] or pressure oscillations in a solid rocket engine [8], oscillations of the free surface of the liquid in the fuel tanks of a liquid launch vehicle [12], the action of pyrotechnic systems [17, 35], wind action, turbulent disturbances, and aerodynamic forces during the flight of a launch vehicle in dense layers of the atmosphere [13].

The vibration levels of a spacecraft during its launch into a working orbit [20, 39, 46] are mainly determined in several frequency ranges (Fig. 3):

a) vibrations of the launch vehicle structure during transient processes (with frequencies less than 80 Hz) due to changes in the parameters of the working processes in the rocket engine,

b) random vibrations and acoustic loads — with frequencies from 20 to 2000 Hz,

c) shock loads — vibrations with frequencies from 100 to 10000 Hz due to the pyrotechnic effects of shock waves.

Vibration loads during transient processes (during launch, a transition from one propulsion system (PS) thrust mode to another, engine shutdown, stage decoupling) are decisive for the design of the main power structures of the spacecraft: elements of the spacecraft to be withdrawn, supports, solar panels, and antennas, fixtures for measuring instruments and others. In addition, random vibration loads drive the design of lightweight spacecraft structures such as antennas and solar panels. Finally, the shock load impact amount is essential for the design of electronic components and instrumentation.

The basis for calculating the structure of the spacecraft [3, 20, 39] is the determination of the static and dynamic loads acting on the spacecraft during the flight of the launch vehicle, the design verification, and the experimental testing of strength. At the same time, optimizing the spacecraft should also reduce its size and cost.

Typical technical requirements for the spacecraft structure relate to the following items [46]:

— structural strength,
— stiffness,
— mass properties,
— dynamic characteristics of the structure,
— the range of vibration accelerations and displacements of spacecraft structural elements in the longitudinal and transverse directions (dynamic envelope [42]),
— damping,
— interface (connection of the spacecraft with the launch vehicle).

The strength of the spacecraft structure is confirmed by the conclusion on static strength, made based on the results of static tests, and the conclusion on vibration strength, based on the results of dynamic tests [4, 7, 9].

According to [4, 13], the development of the spacecraft vibration strength is carried out by its dynamic tests at various levels of filling the tanks with propellants (or its simulators), as well as admissible (in terms of testing safety) pressurization. Vibration tests are carried out on the complete spacecraft or its compartments and units, equipped with standard onboard systems, instruments, and units (or their overall mass models). As a margin of safety, it is advisable to test the spacecraft for a combination of maximum loads [45].

Vibro-strength tests of the spacecraft for flight loading cases are carried out for harmonic vibration (in the frequency range from 5 to 20 Hz) and random vibration (in the frequency range from 20 to 2000 Hz) [13, 46]. Equivalent harmonic vibration tests may replace random vibration tests. If spacecraft acoustic tests are provided, vibration strength tests are carried out only for harmonic vibration at frequencies up to 100 Hz.

In order to determine the resonant frequencies of the spacecraft and its components, as well as to confirm the safety of the structure during vibration strength tests (an essential criterion for safety is the absence of a shift in the resonant frequencies of the spacecraft structure relative to their original position), before and after vibration strength tests, tests are carried out to determine the amplitude-frequency characteristics spacecraft (i.e., the SC is loaded with harmonic vibration of a trim level). These resonant frequencies (natural frequencies of the spacecraft) must be within the appropriate frequency range to prevent dynamic coupling with main excitation frequencies.

The spacecraft's rigidity, dissipative and mass characteristics determine its natural oscillation frequencies. The values of these parameters are interrelated: giving the structure additional rigidity increases its strength but, at the same time, increases its weight and natural frequencies. In this regard, the choice of the values of these parameters results from a complex compromise solution: the rigidity of the spacecraft structure must be sufficient to provide the necessary strength but not too high to not lead to a significant increase in the mass of the spacecraft. At the same time, the rigidity of the spacecraft must ensure a particular localization of the dominant natural frequencies of the spacecraft, such that these frequencies are outside the ranges in which the main excitation frequencies are located (in particular, the frequencies of POGO oscillations of a liquid launch vehicle). As for the damping parameters of the spacecraft structure, their values are determined based on the results of experimental studies of the developed spacecraft or its prototypes. In the absence of experimental data, the relative damping is assumed to be equal to the level of weakly damped systems, i.e., from 0.01 to 0.02 (or 1—2 % of a critical value of the damping factor).

3. THE STATE OF DEVELOPMENT OF VIBRATION PROTECTION SYSTEMS FOR SPACECRAFT LAUNCHED INTO WORKING ORBITS BY MODERN LAUNCH VEHICLES

For spacecraft vibration isolation, several developed vibration protection systems (for example, [6, 37, 43, 47, 48]) are currently designed and offered in the space services market. They use various workflow management systems in vibration protection systems. Let us consider the primarily developed spacecraft vibration isolation systems, which are interesting for their design solutions and have characteristics verified by experimental data.

3.1. ***Active vibration isolation systems.*** The papers [43, 44] present an active vibration isolation system WSVI of a spacecraft, which is installed between the adapter and the spacecraft to prevent damage to the spacecraft during the launch of the spacecraft into orbit. The WSVI system consists of support leaf springs (Fig. 4), coil motors (VCM), and actuator supports

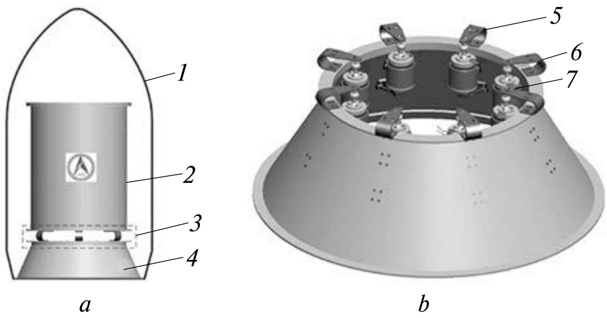


Figure 4. The layout diagram of the WSVI system (*a*: *1* — fairing, *2* — spacecraft, *3* — WSVI system, *4* — adaptor) and the layout of the supporting leaf springs on the KA adapter (*b*: *5* — supporting leaf spring, *6* — VCM, *7* — support)

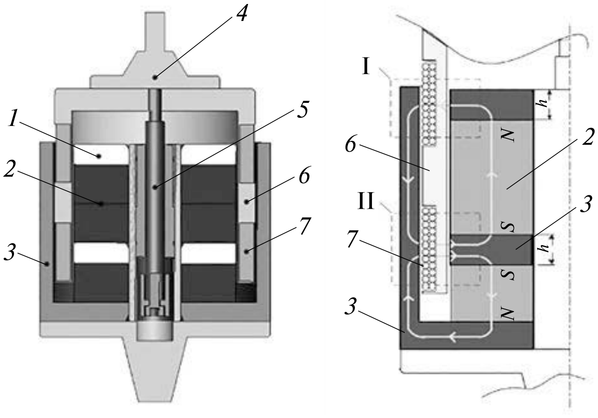


Figure 5. Schematic diagram of solenoid coil motors (VCM) and actuator supports of the WSVI system (*1* — soft iron, *2*— magnet, *3* — steel, *4* — mover, *5* — liner bearing, *6* — coil support, *7* — coil)

(Fig. 5). Based on the electromagnetism theorem, the VCM electromagnetic drive was converted into a viscous damper (Fig. 5). In the actuator, the particular shape and configuration of the permanent steel magnet contribute to the formation of a regular magnetic field, where the magnetic field line mainly passes through sections I and II (Fig. 5) when crossing the air gap. Furthermore, magnetic steel with high magnetic permeability restrains the magnetic field line's spread, preventing its divergence.

The insulation performance of the WSVI system has been verified through simulation and experiment. The authors created a dynamic WSVI device model to evaluate system performance. The dynamic characteristics and responses to external excitation of a spacecraft with a WSVI installed on it are studied.

On an experimental device, frequency-varying sinusoidal vibration tests were carried out in both transverse and longitudinal directions to determine the insulation performance of the proposed WSVI system. As a result of the experimental study, it was determined that in the case of a lateral experiment, the amplitude at the resonance peak significantly decreased from 29.15 to 11.23 m/s^2. On the other hand, in the case of a longitudinal experiment, the response at the system's resonant frequency decreases from 88.88 to 27.46 m/s^2 due to the contribution of electromagnetic damping.

The designed WSVI device takes up little space, is light in weight, and also satisfies the design requirements for vibration isolation without changing the design of the payload adapter fitting. In addition, the test results show that the new WSVI device can significantly reduce the amplitude of the spacecraft vibration response, which is suitable for suppressing spacecraft vibration.

It should be noted that even in the last century, the concept of using magnetohydrodynamic (MHD) effects [36] was proposed in the problems of orientation and stabilization of rotating spacecraft with elastic elements such as whip antennas and solar batteries and with tanks partially filled with propellant components. The proposed MHD element in the form of a torus with a highly electrically conductive magnetized fluid, being included in the spacecraft attitude control loop, opens up the possibility of creating hingeless (unlike flywheel systems and gyrodines) systems of uniaxial orientation that do not require the expenditure of a working fluid. Fundamentally close to those described above are the design solutions proposed by the author of this direction for suppressing spacecraft vibrations caused by POGO vibrations of a liquid rocket.

In the work (Fei et al. [10]), the authors explored an active technology for vibration isolation of an entire spacecraft based on predictive control during a launch vehicle flight. Fig. 6 is a schematic diagram of the active control of the system. Considering the rocket design's special conditions, a pneumatic-type vibration isolation system is used here. Furthermore, to improve the dynamic performance of the isolation

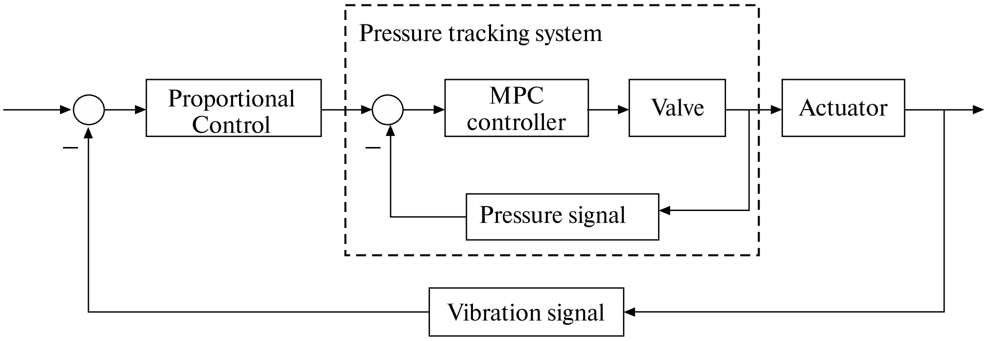
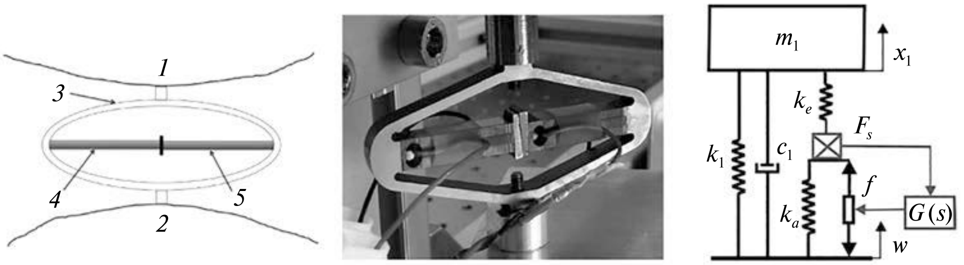


Figure 6. Schematic diagram of the active control of the spacecraft vibration isolation system



a *b* *c*

Figure 7. From left to right: *a* — the concept of an active isolator (*1* — payload, *2* — launcher, *3* — metallic suspension, *4* — force transducer, *5* — piezoelectric actuator); *b* — image of an APA 100 M linear piezoelectric actuator from Cedrat Technologies used for experiments (one piezoelectric unit is used as a force sensor and the other as an actuator); *c* — simplified model of one degree of freedom payload mounted on such an insulator

system, a cascade control with a two-loop structure and a predictive control algorithm for monitoring the pressure in the internal loop of the system are proposed. The developed pneumatic servo system demonstrated strong non-linearity. Moreover, to solve this problem, this paper proposes and applies the method of multi-model control in combination with the MPC (model predictive control) model, where the piecewise linear models on which the controllers are built are obtained by integrating models with data at operating points. Furthermore, a strategy for switching to the lead is proposed to increase the tracking speed, the feasibility and effectiveness of which have been proven experimentally. In addition, by “resetting” the forecast horizon and weight matrices of the MPC algorithm, the impact of a significant time delay caused by a long pipeline on the performance of the control system is effectively suppressed. These recently proposed approaches significantly improve pressure-tracking performance. Thus, with this design, real-time monitoring of system pressure can be guaranteed, and, therefore, the authors believe that the active control system can operate in a higher frequency range.

In [41], A. Souleille et al. showed that installing passive spacecraft vibration isolators could harm the amplification of the spacecraft’s low-frequency oscillatory movements due to suspension resonances. This paper introduces a new concept of active attachment for aerospace cargo (see Fig. 7 for an active insulator concept). Although the mount is easy to install on the launch vehicle for spacecraft vibration isolation, it serves two purposes.

The first goal is a high level of damping of both suspension dynamics resonances and system elasticity resonances without compromising the isolation

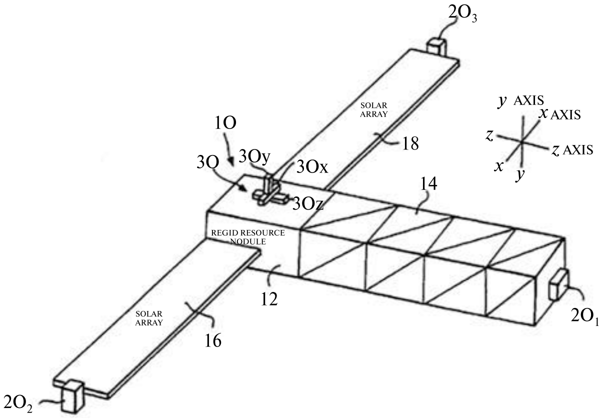


Figure 8. Schematic diagram of the active vibration damping system of the space platform

and large stability margins of the closed-loop system due to the co-location of the actuator and sensor. The second is a broadband reduction in the dynamic force transmitted to the payload, achieved at 16 dB. The presented concept was investigated numerically and experimentally on an insulator with one degree of freedom. A commercial insulator was chosen for the demonstration. Experimental testing on test benches with multiple degrees of freedom has shown that force feedback can dampen both suspended and elastic modes (the first and second modes, respectively) and significantly reduce the transmitted force in some wide frequency ranges.

A space platform's active vibration damping system, presented by Joseph V. Fedor in a US patent [9], is proposed for oscillatory movements while bending in two orthogonal directions. During torsion of flexible ends of the platform in each of three mutually perpendicular axes (the principle diagram of the active system operation is presented in Fig. 8). The system components for each axis include an accelerometer, a signal filtering and processing device, and a DC motor.

The torque of the motor, when driven by a voltage proportional to the relative speed of the vibrating tip, generates a reactive torque to counteract and, therefore, damp vibration at a certain modal velocity. Thus, with a single sensor/actuator pair, it is intended to damp several vibration modes. Furthermore, when a three-axis damper is located on each of the main platform ledges, all kinds of vibrations of the system can be effectively damped.

Samuel W. Sirlin [40] notes that the guidance requirements for space science payloads will become increasingly stringent. However, for cost-effectiveness reasons, the trend will move away from free-flying single payload spacecraft towards large multipurpose spacecraft. In the face of such a demanding dynamic environment, future space stations will host attached payloads, some of whose guidance requirements approach those of free-flying space telescopes. This publication describes the developed finite element model of the active soft attachment of the spacecraft, which is controlled based on a piezoelectric polymer polyvinylidene fluoride. The model includes geometric nonlinearities associated with the possibility of a large deflection of the soft mount. This model is combined with a simple space station model, and then simulations are performed in both linear frequency and time domains. The possibilities of broadband interference suppression are demonstrated in the frequency domain and the nominal mode.

The study [49] presents a new active variable vibration isolator (AVS-VI) used as a vibration isolation device to reduce excessive vibration of the entire spacecraft isolation system. The AVS-VI consists of a horizontal spring, a positive spring, a parallelogram linkage, a piezoelectric actuator, an acceleration sensor, viscoelastic damping, and an active PID controller. Based on AVS-VI, the generalized vibration transmissibility, determined by the non-linear output frequency characteristics and energy absorption coefficient, is applied to analyze the isolation characteristics of the entire spacecraft system using AVS-VI. AVS-VI can perform variable severity adaptive vibration suppression for the entire spacecraft system, and the analysis results show that AVS-VI effectively reduces the extravagant vibration of the entire spacecraft system, where vibration isolation is reduced to more than 65 % under various acceleration excitations. Finally, various AVS-VI parameters are considered to optimize the entire spacecraft system based on the generalized vibration transfer and energy absorption rate.

The right software for active vibration control is crucial as it affects the system's overall performance, including sensors and actuators' optimal utilization, without compromising any other mechanical or structural parameters. Modern software platforms are essential in designing and implementing active vibration control systems. The main functions of these software platforms are simulation and modeling, controller design, real-time control and system monitoring [28].

3.2. ***Semi-active vibration isolation systems.*** A study by Behzad Jafari [18] aims to analyze the feasibility of implementing a semi-active system instead of a passive one and compare its potential benefits in attenuating the transmission to sensitive spacecraft components during the launch phase.

First, a passive system was studied, and a technique for optimizing the design in the frequency and time domains was formulated. The optimized passive system is then used as the basis for comparing the performance of the active system.

Semi-active control strategies based on Skyhook (SH) and combined damping control (Skyhook and Acceleration Driven Damping, SH-ADD) have been used to control the damping of the insulator between the spacecraft and launch vehicle to dampen vibration. The results showed that the semi-active system has a significant advantage over the passive system in attenuating vibrations when the excitations are harmonic or narrowband. However, the results were not as promising with random broadband excitation (which is a realistic model of the excitations a spacecraft experiences during launch). This calls into question the practical effectiveness of using a semi-active system in the entire spacecraft vibration isolation system. Further research work with experimental tests is needed to test whether semi-active systems can have practical applications in the entire spacecraft insulation system.

R. G. Cobb [7] describes the design and field testing of a Vibration Isolation and Suppression System (VISS) that can be used to isolate precision payloads from spacecraft interference.

VISS uses six hybrid isolation struts in a hexapod configuration. The centerpiece of this concept is a new hybrid drive concept that provides both passive isolation and active damping (Fig. 9). Passive isolation is provided by the flight-proven D-shaped design. An active voice coil system complements the passive design. The active system is used to improve the performance of the passive isolation system at lower frequencies and provide payload control capability.

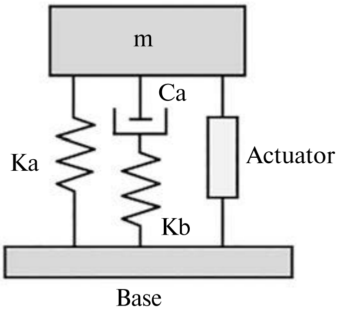


Figure 9. Schematic diagram of the Semi-Active Isolation and Vibration Suppression System (VISS)

3.3. ***Passive (without feedback from the launch vehicle control system) spacecraft vibration protection systems.*** The passive vibration isolating system includes the pneumatic vibration protection system of the spacecraft [30, 31]. The pneumatic system protects the spacecraft from longitudinal vibration loads during its launch into working orbits. The main component of the vibration protection system is the elastic-dissipative module. In addition, guide elements are used to ensure one-dimensional movement of the vibration protection system structure along the longitudinal axis of the launch vehicle.

Mathematical modeling of the low-frequency dynamics of the vibration protection system with spacecraft has been performed. It is shown that the installation of a vibration protection system between the upper stage of the launch vehicle and the spacecraft provides a reduction in the level of longitudinal vibration loads on the spacecraft in the frequency range from 5 to 100 Hz by a factor of two or more, which meets the requirements set by the spacecraft developers. Fig.10 contains the results of mathematical modeling of longitudinal vibration accelerations of spacecraft of various masses during launch and flight of the launch vehicle (during the operation of the propulsion system of the first stage), obtained using experimentally confirmed models of the dynamics of vibration protection modules of the spacecraft (where z is the amplitude of the coordinate of the center of mass of the spacecraft, q is the amplitude of the base coordinate vibration protection module during its harmonic excitation). As follows from the figure, installing this spacecraft vibration protection system on this launch

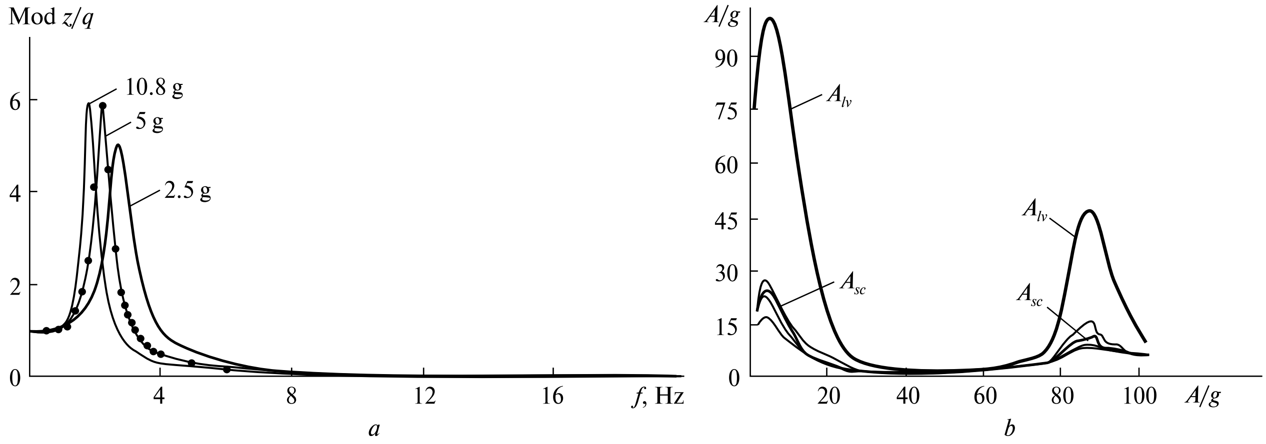


Figure 10. Gain coefficients (*a*) of the elastic-dissipative module of the vibration protection system in terms of displacement *z/q* at various static overloads of the spacecraft (10.8*g*, 5.0*g*, 2.5*g*) and the results (*b*) of determining the calculated maximum level of spacecraft vibration loads during launch and LV flight (A_{lv} is the upper envelope of vibration accelerations in the section of the upper frame of the LV structure, A_{sc} is the upper envelope of vibration accelerations in the section of the center of mass of the spacecraft for spacecraft masses of 4000, 2500, 1200, 400 kg)

vehicle reduces the maximum level of spacecraft vibration loads by three or more times.

Given the efficiency of this passive vibration protection system, its use will significantly expand the possibilities of launching spacecraft for various purposes into working orbits and increase the competitiveness of launch vehicles with a vibration protection system in the global space services market.

Based on research by Park et al. [29], a triaxial passive launch vibration isolation system based on shape memory alloy (SMA) technology was developed to significantly attenuate launch dynamic loads transmitted to small-weight spacecraft. This provides excellent damping performance with super-elastic SMA blades reinforced with multi-layered thin plates with viscous lamellar adhesive layers of acrylic tape (Fig. 11).

The main characteristics of the proposed insulation system with different amounts of viscoelastic laminates were obtained from a static load test. In addition, the performance of the design has been validated under start-up conditions simulating sine and random vibration tests.

The design of systems with passive isolation is often carried out “on one axis”, while the performance requirements have several degrees of freedom for most applications. [16] performed a six-by-six channel gain optimization that required a deep understanding of the underlying system perturbations, payload performance needs, envelope constraints, and mass/cost weighting. It is shown that the analysis of singular values of the noise transfer function matrix in the frequency domain is effective in constructing a single curve for multiaxial isolation. Various passive isolation limitations are listed as limitations on the optimization process. The results of the design analysis and optimization of the kinematic hexagonal (six support) installation of a hypothetical commercial payload of a laser communication terminal are presented.

CSA Engineering, Inc. [25] performed analysis, design, and testing for the Los Alamos National Laboratory as part of the FORTE spacecraft vibration reduction program. The technical goal of the work was to reduce the response to the location of payload elements when exposed to the dynamic load associated with launch and proto-qualification tests. The end product of the work was a set of viscoelastic struts that were fabricated, tested, and installed in the FORTE design. CSA developed the Nastran finite element model of the FORTE design, worked with LANL to select the best approach to implement passive damping, performed analytical trade studies using the system FE model and the strut FE model to determine the best viscoelastic strut design configu-

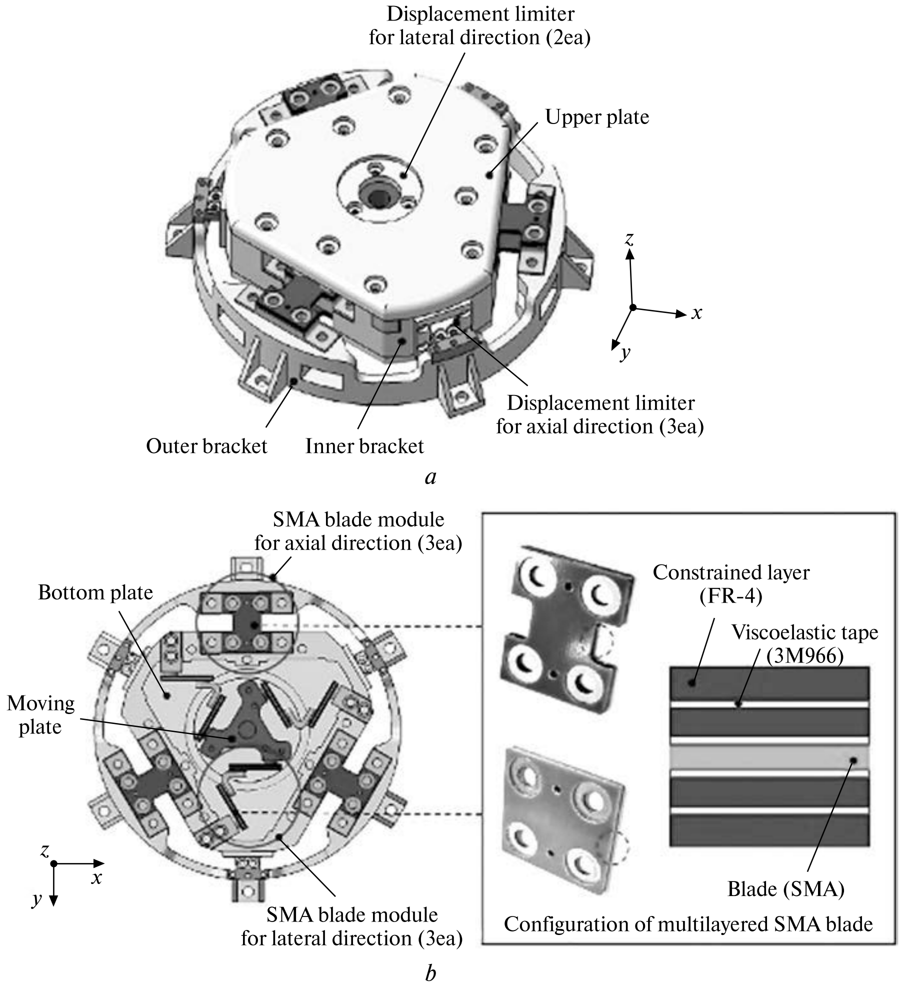
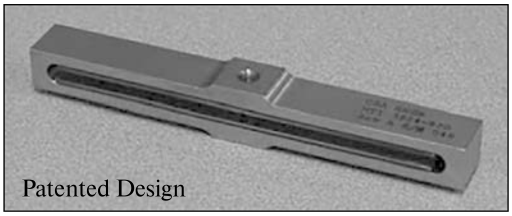


Figure 11. Configuration of the Proposed WSVI (*a* — Isometric View, *b* — Inside View)

ration, performed material testing, fabrication assistance struts, perform direct comprehensive strut stiffness tests, and help evaluate strut performance based on random vibration test measurements. The addition of viscoelastic struts bogged down the dynamics of the decks, and shearing the viscoelastic material dissipated vibrational energy in a critical frequency band and reduced the vibrational response on key spacecraft components.

Viscoelastic struts were used with force-limited vibration testing, special brackets modified to provide isolation, and altered system mass distribution to successfully reduce FORTE vibration.

The paper [47] demonstrates the possibility of protecting a spacecraft from dynamic loads using vibration and shock isolation systems for the entire spacecraft. The basic concept of isolating the entire spacecraft is to isolate the entire spacecraft from the dynamics of the launch vehicle. Two different systems are considered here: the SoftRide system, a low-frequency (10—50 Hz) isolation system, and the ShockRing system, designed to attenuate high-frequency loads (70 Hz and above), including shock loads. All seven flights of the CSA SoftRide systems (the layout of the vibration isolation system can be judged from the photo in Fig. 12) demonstrated excellent load reduction when analyzed by coupled loads and confirmed by flight telemetry data. In particular, Fig. 13 shows the flight data of vibration accelerations before and after the SoftRide vibration



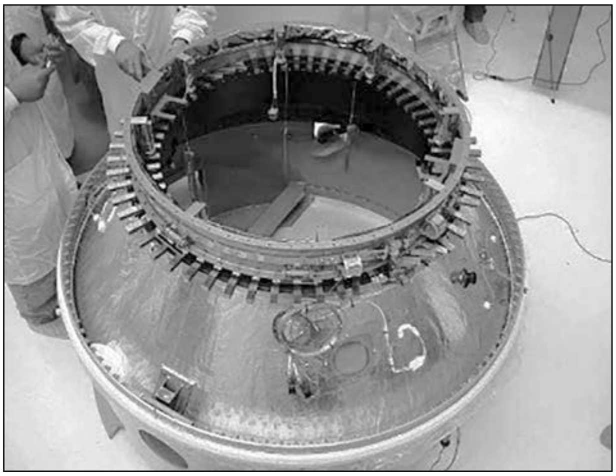


Figure 12. Element of the SoftRide vibration isolation system and the arrangement of these elements on the KA adapter

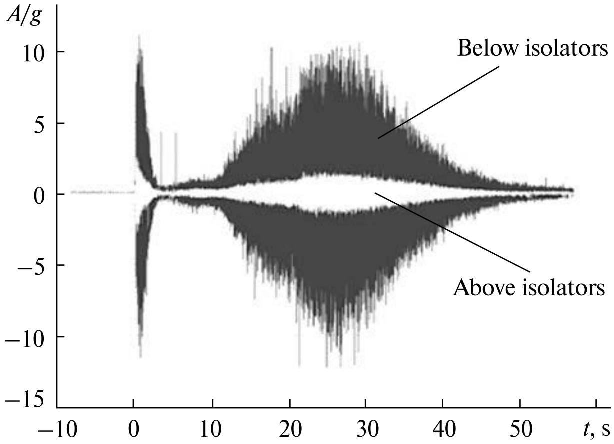


Figure 13. STEX flight data — below and above isolators for the Taurus/STEX SoftRide isolation system

isolators during the launch of the STEX spacecraft by the Taurus launch vehicle.

Component testing was performed on the Shock-Ring using a specially designed air gun that can generate 10000 g on the test item. These tests demonstrate a significant reduction in the shock load transferred to the payload. Next, the results of system tests, consisting of a spacecraft simulator, payload attachments, an avionics section, and a shock plate, are discussed. The system tests used pyrotechnic devices to achieve high test impact levels. Finally, the flight data of the first flight will be discussed.

Article [5] reviews the latest vibration defense systems of spacecraft payload for further possible use in suborbital missions of reusable launch vehicles. A brief description of the vibroacoustic environment of the Orbital Science and Kistler Aerospace small launch vehicles indicates the deep level of random vibrations, shocks, and acoustics that the payload must withstand. The same random oscillations were found in the entire family of sounding rockets: Black Brant, Orion, Nike-Orion, Taurus-Orion, and Terrier-Orion. This review also presents recent flight experiments designed to test isolation systems at launch or in orbit. While in-orbit vibration isolation systems have been active-passive systems that have recently used bright designs and new control algorithms, including those based on adaptive neural networks, launch isolation systems have evolved from passive to active-passive systems, which have recently been tested during the VALPE-2 experiment. Active-passive launch systems provided a 10-fold reduction in vibration versus the 5 to 1 provided by passive systems. In addition, active-passive systems in orbit reduced vibration by about ten times.

The paper [50] explores a method for evaluating the characteristics of vibration isolation of discrete vibration isolation of flexible spacecraft. First, a dynamic model of a discrete integral spacecraft system has been constructed, and a reduction of the model has been proposed. The analysis of the vibration isolation method of vibration transmission from the vibration isolator to the satellite is discussed. The estimation method is then studied from the perspective of simulation and experiment, and the results show that the theoretical analysis is correct. Next, a method for estimating the power flow of a discrete integral spacecraft of a flexible spacecraft is presented. Based on the study of the power flow of vibration isolation, it is shown that the proposed method complements the shortcomings of vibration transmission. Finally, it is proposed to evaluate vibration isolation performance by combining the vibration transmission at some key points in the satellite and the power flow of the vibration isolator.

Dynamic launch loads are the driving force behind the structure of any spacecraft, but they can be especially significant for small spacecraft on solid rocket launchers [11]. In this case, we often have an unenviable combination of demanding launch loads and sensitive spacecraft components in the form of unique scientific or remote sensing instruments. Passive vibration isolation of the entire spacecraft has proven to be a valuable tool in reducing these dynamic loads, thus reducing the overall risk of mission success. The NASA Orbiting Carbon Observatory (OCO) mission will use the flight-tested CSA Engineering SoftRide passive containment system during the launch.

Hamilton Sundstrand Sensor Systems made the payload for scientific instruments. NASA's Kennedy Space Center managed the acquisition of the Taurus launch vehicle built by Orbital Sciences Corporation and the SoftRide vibration isolation system built by CSA Engineering. The OCO spacecraft was dynamically tested on the SoftRide UniFlex insulation system under the "test in flight" philosophy. A few of the 12 satellites that used SoftRide on the Pegasus, Taurus, Minotaur, and Atlas V launch spacecraft included the SoftRide isolation system in the spacecraft level vibration tests. Testing at the spacecraft level with an isolation system presents unique challenges that do not arise during conventional vibration tests at the level of an uninsulated spacecraft. Therefore, the development of the OCO vibration test has been done, focusing on how the inclusion of the Soft-ride system has influenced this development. Test results show how the spacecraft/SoftRide system responded during testing. During the vibration tests, unique problems arose with the control of the low-frequency vibration-isolated system.

The SoftRide entire spacecraft isolation system was selected for implementation on the OSTM/Jason 2 mission based on the likelihood of meeting load reduction criteria and cost and timing considerations. Reference [22] provides a) an overview of the study that resulted in the selection of SoftRide, b) the process of designing, analyzing, and testing the SoftRide system, as well as some of the design problems and their solutions, and c) a summary of the KSC/JPL independent risk assessment-associated with the SoftRide program. The SoftRide solution for OSTM/Jason 2 demonstrated the adequacy of the legacy qualification for the launch configuration. Along with some design problems and their solutions, and c) a summary of KSC/JPL's independent assessment of the risks associated with the SoftRide program. The SoftRide solution for OSTM/Jason 2 made it possible to demonstrate the adequacy of the legacy launch qualifications for the launch configuration. Along with some design problems and their solutions, and c) a summary of KSC/JPL's independent assessment of the risks associated with the SoftRide program. The SoftRide solution for OSTM/Jason 2 demonstrated the adequacy of the legacy qualification for the launch configuration.

It is known that the traditional payload attachment (PAF) fitting does not provide any vibration isolation due to its high rigidity. The paper [3] theoretically investigates the vibration isolation of the entire spacecraft as a direct and practical approach to ensuring the successful launch and orbital placement of a spacecraft. Given the stiffness and vibration isolation design issues that most concern designers, the Spacecraft Vibration Isolator (WSVI) study consists of two parts. The stiffness characteristic is studied with reliability analysis and experimental data in the first part. Concerning WSVI, a study was made on the function of ribs to impart rigidity and damping to vibration isolators. The second part discusses the problems caused by stiffness changes. Simulated and experimental data show that the transmission coefficients combined with the stiffness can be reduced by installing a vibration isolator between the spacecraft and the launch vehicle.

4. DISCUSSION

The considered examples of active and passive suppression of spacecraft vibrations in the active part of the Launch Vehicle flight trajectory showed the need to take into account, when designing vibration isolating systems, the requirements for their performance during oscillatory movements of the spacecraft in several degrees of freedom (such requirements are set out, for example, in [41]).

As follows from the analysis of the above works on the dynamics of vibration-isolated spacecraft systems, when designing a spacecraft as a mechanical system, circumstances and phenomena may not be completely determined, leading in some cases to a loss of strength and performance of both the entire spacecraft and during the operation of its tools on orbit. The uncertainty of the dynamic characteristics of the spacecraft exists in the case of launching numerous spacecraft of different customers. In this case, active means of suppressing spacecraft vibrations should be developed, considering possible resonance phenomena in the dynamic system "adapter-spacecraft" that were not detected during ground tests.

Some problems of physical and mathematical modeling of working processes in vibration protection systems remain unresolved. In particular, in the conditions of airless space and weightlessness, spatial oscillations of the spacecraft can be carried out with vibration damping different from the work of damping forces under conditions of ground vibration tests [38]. Therefore, this phenomenon must be considered when analyzing and generalizing the results of the experimental determination of the characteristics of the vibration protection system [1].

Problems remain in designing a vibration protection system to achieve the required quality of passive vibration suppression with a minimum spacecraft weight. At the same time, in the case of suppression of high-frequency vibrations of the spacecraft [44] using electromagnetic activators (active vibration isolating systems), the need to introduce additional elastic forces into the system (i.e., elements of passive vibration damping) is shown [29].

When designing spacecraft vibration isolation systems, the notable increase in the spacecraft overload during the spacecraft launch into the working orbit is often not considered. This can significantly change the efficiency of a passive vibration protection system [30] since with a significant increase in the longitudinal acceleration of the launch vehicle in flight, and hence the weight of the spacecraft, the elasticity and the lowest natural frequency of the dynamic system "vibration protection system — spacecraft" change.

When launching up to several dozen autonomous spacecraft into working orbits, an adapter (dispenser) is made, usually of an original design, having a complex spatial configuration for the sound installation of individual spacecraft, which, as a rule, have different masses and natural frequencies. In this case, the task of vibration protection is promising not for the spacecraft as a whole but for the active "tuning" of vibration protection systems to actively suppress the vibration of each spacecraft or the most sensitive to vibrations of the spacecraft.

5. CONCLUSIONS

The analysis of the current state of development of vibration protection systems for spacecraft launched into orbits by modern launch vehicles is carried out. Such analysis is instrumental in choosing the direction of practical design of spacecraft vibration protection systems and in determining fundamentally new means and schemes of vibration isolating systems and methods for effectively suppressing spatial vibrations of spacecraft.

The development of spacecraft vibration protection systems has a history of more than 20 years. At the present stage of the development of space launch vehicles, some space vehicles have been developed jointly by vibration protection systems and tested on special vibration stands. Moreover, different launch vehicles used SC vibration protection systems in some missions. In particular, 19 vibration protection devices and systems of the SoftRide family, starting from 1998, have been used for vibration protection of spacecraft put in orbit by the Taurus, Taurus XL, Minotaur I, Pegasus, Delta II, Delta 4-H, Falcon I launch vehicles. At the same time, for the spacecraft for modern launch vehicles, many problems of creating advanced vibration isolation systems remain relevant, the solution of which will increase the efficiency of means for suppressing spacecraft vibrations while reducing the requirements for the strength of their design.

Thus, developing spacecraft vibration isolation systems is a persistent global trend. For future research in Ukraine's rocket and space industry, the introduction of advanced vibration isolation systems for modern spacecraft is promising. The research will be carried out in the following areas:

- use of an active spacecraft vibration suppression system in combination with a passive vibration protection system;

- increasing the frequency range and damping parameters of the spacecraft;
- changes in the approach to vibration suppression of the entire spacecraft (as a whole) to an approach with system tuning for damping individual (the most critical and vibration-sensitive) spacecraft;
- application of schematic diagrams of spacecraft vibration protection systems with the introduction of hydraulic, electromagnetic, and mechanical functional elements in order to increase the efficiency of vibration isolation systems;
- active suppression of random vibrations during the operation of various spacecraft systems in outer space (during disturbances from engines of orbit correction systems and others);
- use of the adapter (dispenser) design to perform the functions of a passive vibration protection system of the spacecraft.

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Стаття надійшла до редакції 26.03.2023
Після доопрацювання 26.05.2023
Прийнято до друку 29.05.2023

Received 26.03.2023
Revised 26.05.2023
Accepted 29.05.2023

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РОЗРОБКА СИСТЕМ ВІБРОЗАХИСТУ КОСМІЧНИХ АПАРАТІВ — СТАН ТА ПЕРСПЕКТИВИ

Вібраційні навантаження на ракету-носій і космічний апарат (КА) можуть досягати високого рівня і призводити до нештатних і аварійних ситуацій. Конструкція космічного апарата повинна не тільки підтримувати корисне навантаження і підсистеми КА, але і мати достатню міцність і жорсткість, щоб виключити будь-які аварійні ситуації (пошкодження, руйнування, небажані деформації конструкції, вихід з ладу і вихід з ладу приладів і обладнання), які можуть перешкодити успіх місії. Основною метою статті є аналіз стану досліджень динаміки систем віброзахисту космічних апаратів, що виводяться на робочі орбіти сучасними ракетами-носіями. Результати цього аналізу сприятимуть розробці принципових схем систем віброзахисту та методів ефективного демпфування просторових коливань космічних апаратів.

Показано, що розвиток перспективних систем віброізоляції відбуватиметься у напрямку: збільшення частотного діапазону та показників демпфування КА; переходу від демпфування вібрацій КА (в цілому) до настроювання системи на демпфування окремих (найбільш відповідальних та чутливих до вібрації) КА; використання системи активного демпфування вібрацій КА у поєднанні з пасивною системою віброзахисту; використання принципових схем віброзахисних систем КА із введенням гідравлічних, електромагнітних та механічних функціональних елементів з метою підвищення ефективності віброізолювальних систем; активного пригнічення випадкових вібрацій у відкритому космосі під час роботи різних систем космічного корабля (при збуреннях від двигунів систем корекції орбіти тощо); використання конструкції адаптера для виконання функцій пасивної віброзахисної системи КА.

Ключові слова: безпека космічного апарата, середовище запуску, вібраційне навантаження, космічний апарат, акустика, випадкова вібрація, віброізоляція, алгоритми системи керування, космічні польоти, рідинні ракети.