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The problem of ensuring and controlling microaccelerations in the internal environment of a small technological spacecraft

A. V. Sedelnikov, E. V. Eskina, A. S. Taneeva*, E. S. Khnyryova, and M. E. Bratkova

Samara National Research University, 34, Moskovskoye shosse, Samara, 443086, Russia

*Corresponding author; E-mail: nastya-gorozhankina@yandex.ru

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Abstract

This paper gives reviews approaches to reduce microaccelerations in the internal environment of a small spacecraft and provides quantitative estimation of the level of microaccelerations. These approaches involve the reduction of microaccelerations in the entire internal environment of the spacecraft or the creation of a protected zone using vibration-isolating devices. In the latter case, gravity-sensitive processes can be performed only inside this zone. Various vibration-isolating devices based on various operating principles are considered. These anti-vibration devices have been experimentally tested under space flight conditions on various spacecraft. In this study, they are considered as ready-made solutions for the creation of a small technological spacecraft. A small technological spacecraft design was developed, and the issues of ensuring the quality of the obtained results of gravity-sensitive processes by controlling the level of microaccelerations were considered. The results can be used in the design and operation of small technological spacecraft.

Keywords: *gravity-sensitive process; internal environment; microacceleration; operating principles; small spacecraft.*

1. Introduction

For conducting gravity-sensitive processes on board a small spacecraft, it is necessary to comply with the requirements for microaccelerations (Lyubimova, Zubova, & Shevtsova, 2019; Sharifulin, & Lyubimova, 2021; Belousov, & Sedelnikov, 2013). These requirements are the most important in developing a design of a small technological spacecraft. Many researchers have noted the prospects of using small spacecraft in the space technology field (Orlov, 2021; Taneeva, Lukyanchik, & Khnyryova, 2021; Sedelnikov, 2022; Sedelnikov, & Orlov, 2020). The clear advantages of small spacecraft are:

- the low cost of development, manufacture, and launch of a small spacecraft;
- the short project implementation time;
- the maximum ability to meet the requirements of creating a small spacecraft for performing a specific gravity-sensitive process.

The first advantage makes experiments under real conditions of near-Earth space generally accessible (Belousova, & Serdakova, 2020; Snell, & Helliwell, 2005). At the same time, the launch of a small spacecraft as a hosted payload allows more efficient use of the launch vehicle capabilities without increasing the number of launches (Abrashkin et al., 2017; Salmin, & Chetverikov, 2017).

The short project implementation time allows us to perform complex experimental development of gravity-sensitive processes, adjust the requirements for their implementation by taking into account accumulated experience, and identify new factors that affect the process and its results (Perminov, Lyubimova, & Nikulina, 2021; Huang, Li, Huang, & Liu, 2018). This is a prerequisite for making breakthroughs in both scientific and technological aspects.

Finally, a small technological spacecraft can be created specifically for the implementation of certain gravity-sensitive processes. At the same time, its design and layout will maximally take into account the features of the process being implemented. This cannot be imagined for spacecraft of other classes, where many processes are implemented and a whole range of target tasks are solved.

In the future, all the above-mentioned advantages will allow us to develop space materials science using small technological spacecraft.

Of note, the difficulties with the implementation of gravity-sensitive processes are partially associated with the multifunctionality of the spacecraft. This has become clear since the launch of the American space laboratory "Skylab" (1973). By controlling the telescope, the researchers disturbed the favorable conditions inside the Skylab laboratory module. Currently, owing to the high cost, it is difficult to imagine launching a medium-class spacecraft or a laboratory module to implement a single gravity-sensitive process. However, a small technological spacecraft would allow this unique opportunity.

2. Objectives

Currently, no fully implemented technological projects use small spacecraft. There are separate attempts to test the capabilities of certain small spacecraft platforms for their use as small technological spacecraft. Therefore, it is necessary to classify the requirements for microaccelerations for various types of processes by dividing them into three categories:

- category A implies requirements for microaccelerations up to 1 μm/s^2;
- category B implies requirements for microaccelerations of 1–10 μm/s^2;
- category C implies requirements for microaccelerations of 10–100 μm/s^2;
- category D does not imply explicit requirements for microaccelerations; however, microaccelerations may affect achieving the objectives.

The first and second categories of requirements are related to the developed and promising technological gravity-sensitive processes, e.g., technologies of directed crystallization (Perminov et al., 2022; McPherson, & DeLucas, 2015), obtaining ultrapure materials (Sedelnikov, & Serpukhova, 2009; Li, Anken, Liu, Wang, & Liu, 2017), and the study of fluid behavior and combustion processes (Ruff, 2001; Li, Guo, Zhao, Li, & Hu, 2022). In terms of the feasibility of the requirements at the current stage of development, the category B requirements are practically achievable in a specialized technological spacecraft, if additional means of vibration protection are used (Wu, Liu, Cui, & Zhao, 2019; Liu, Gao, Dong, & Li, 2018). For category A, currently, no technical means or space technology can meet these requirements. However, this developmental direction is necessary to achieve progress in space technology.

Category C meets the requirements for biomedical experiments (Hu et al., 2014; Sedelnikov, & Potienko, 2017). At the same time, it should be taken into account that living organisms during their life can create additional microaccelerations (Abrashkin et al., 2015; Sedelnikov, 2015). Thus, frequently, the requirements for microaccelerations in biomedical experiments are not as stringent compared to those in technological experiments.

Category D involves the solution of target problems not directly related to gravitational sensitivity. However, uncontrolled microaccelerations are also undesirable. An example of such a problem is the Earth's remote sensing. Here, restrictions on the accuracy of pointing and the angular velocity when imaging the target object are important (Abrashkin et al., 2019; Li, Wang, Wang, Liu, & Jin, 2020). However, the limitation on the angular velocity is an indirect limitation on microaccelerations. On the other hand, for example, natural oscillations of large elastic elements can cause the target object to be "blurred". Moreover, these oscillations are one of the main sources of microaccelerations (Sedelnikov, 2016; Yang, Liu, Liu, & Li, 2021). Therefore, the connection between microaccelerations and the quality of solving target problems in this case is clear.

The objective of this work was to ensure modern requirements for microaccelerations by effectively using a developed means of vibration protection.

3. Materials and methods

Let us consider two of the most well-known methods currently used. Subsequently, they allow us to develop a combined approach to effectively solve the problem of ensuring the required level of microaccelerations. The idea of a combined approach as a method for creating favorable conditions for microaccelerations is not new. However, its practical implementation is currently absent. Therefore, we can talk about new techniques that include a specific design of a small technological spacecraft. Additionally, the composition of vibration-proof equipment and the elements of the motion control system, which allow the reduction of microacceleration in the entire internal environment of a small technological spacecraft, are also specified.

This approach maximizes the use of the entire internal volume of the spacecraft. However, the highest requirements for microaccelerations are imposed in this case because at each point of the internal environment, where the equipment for the implementation of gravity-sensitive processes is located, the requirements for microaccelerations must be met. Moreover, these requirements must be met through the motion control system executors' operation. Let us separately consider the translational and rotational parts of the spacecraft motion. For the translational part, we apply the theorem on the motion of the center of mass:

$$m_0\vec{w}_C+\sum_{i=1}^{n}\int_0^{m_i}\vec{w}_i dm_i=\vec{F}^e+\vec{F}_{con}, \tag{1}$$

where m_0 is the mass of the spacecraft, including the mass of elastic elements; $\vec{w}_C$ is the acceleration of the center of mass of the spacecraft body; m_i is the mass of the i-th elastic element; $\vec{w}_i$ refers to the relative accelerations of the points of the i-th elastic element; $\vec{F}^e$ is the main vector of external forces acting on the spacecraft; and $\vec{F}_{con}$ is the main vector of forces of the spacecraft motion control system executors; n is the number of large elastic elements.

For the rotational part of the spacecraft motion, we can write the theorem on the change in the angular momentum in the main fixed coordinate system:

$$\hat{I}_0\cdot\dot{\vec{\omega}}+\sum_{i=1}^{n}\frac{m_i}{l_i}\int_{a_i}^{l_i}\vec{w}_i x_i dx_i+\vec{\omega}\left(\hat{I}_0\cdot\vec{\omega}+\sum_{i=1}^{n}\frac{m_i}{l_i}\int_{a_i}^{l_i}\vec{v}_i x_i dx_i\right)=\vec{M}^e+\vec{M}_{con}, \tag{2}$$

where I_0 is the inertia moment of the spacecraft with elastic elements in the main body-fixed coordinate system; $\vec{\omega}$ is the spacecraft angular velocity of rotation; l_i is the distance from the points of the extreme section of the i-th elastic element to the mass center of the spacecraft; a_i is the distance from the attachment point of the i-th elastic element to the mass center of the spacecraft; $\vec{v}_i$ refers to the relative velocities of the points of the i-th elastic element; $\vec{M}^e$ is the main moment of external forces acting on the spacecraft; and $\vec{M}_{con}$ is the main moment of the spacecraft motion control system executors.

Based on (1) and (2), it is possible to define restrictions on the microaccelerations modulus:

$$\left|\vec{w}_C+\dot{\vec{\omega}}\times\vec{R}+\vec{\omega}\times\vec{\omega}\times\vec{R}\right|\leq|\vec{w}_{max}||, \tag{3}$$

where $\vec{R}$ is the radius vector of the point (located maximally far from the center of mass) of the spacecraft internal environment, where the equipment for performing gravitation-sensitive processes is located.

For the case when $|\vec{\omega}|$, $|\dot{\vec{\omega}}|$, and $|\vec{v}_i|$ are small quantities of the same order of smallness, restriction (3) can be simplified:

$$\left|\frac{\vec{F}^e+\vec{F}_{con}-\sum_{i=1}^{n}\int_0^{m_i}\vec{w}_i dm_i}{m_0}+\hat{I}_0^{-1}\left(\vec{M}^e+\vec{M}_{con}-\sum_{i=1}^{n}\frac{m_i}{l_i}\int_{a_i}^{l_i}\vec{w}_i x_i dx_i\right)\cdot\vec{R}\right|\leq|\vec{w}_{max}||. \tag{4}$$

The solution of equations (3) or (4) with respect to $\vec{F}_{con}$ and $\vec{M}_{con}$ leads to the formation of the required control laws for the executors of the spacecraft motion control system. However, the complexity of these equations raises the question of the feasibility of the developed control laws. Taking into account the errors in modeling external disturbances (Myung, & Bang, 2003; Ulrich, 2016) and real spreads in the characteristics of the executors (Blinov et al., 2018; Bedingfield, Leach, & Alexander, 1996), the task of implementing control laws becomes much more complicated.

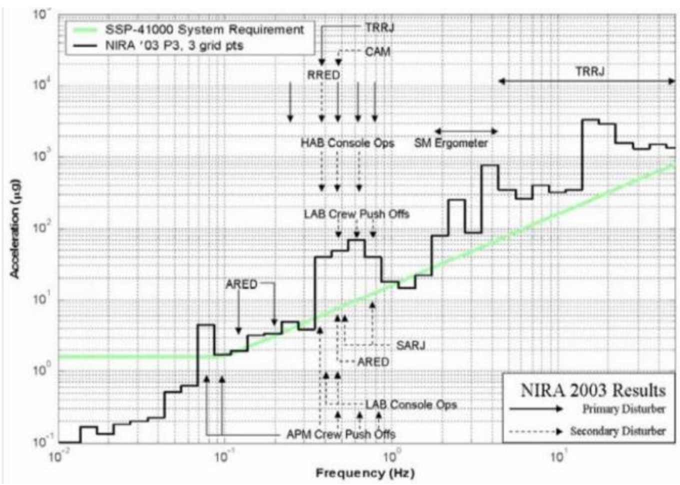
Of note, during operation in non-oriented flight, the level of microaccelerations in the internal environment of the spacecraft can both increase [spin-up due to external disturbances, e.g., Foton series spacecraft (Sedelnikov, 2020; Abrashkin et al., 2007)] and decrease [stabilization due to external disturbances, e.g., Aist small spacecraft prototype (Abrashkin et al., 2019; Sedelnikov, Taneeva, Khnyryova, Kamaletdinova, & Martynova, 2021)]. This process depends on the class of the spacecraft, orbit parameters, as well as the composition and operating modes of the scientific equipment.

Thus, at the current stage of space technology development, such an approach is more of a theoretical nature owing to the complexity of implementing optimal control laws from the point of view of minimum microaccelerations.

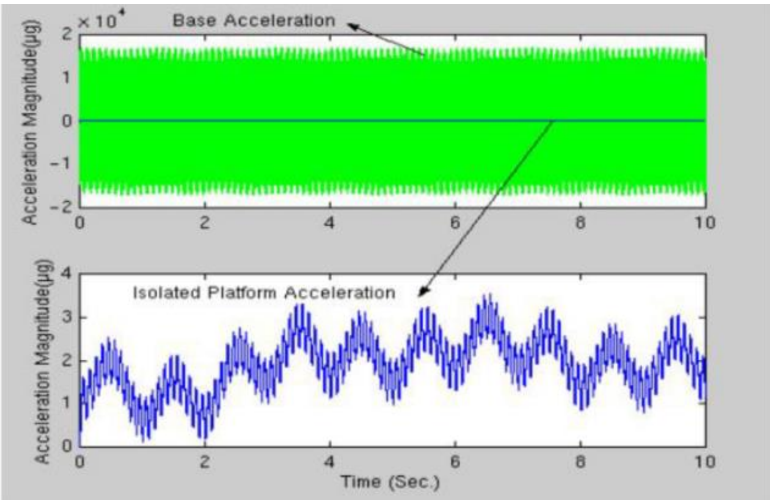
This approach consists of providing favorable conditions for the implementation of gravity-sensitive processes not in the entire internal environment of the spacecraft but inside a special vibration-isolating device. In this case, the problem of ensuring the requirements for microaccelerations is shifted from the motion control system executors to the vibration-isolating device. Moreover, the solution of this problem is greatly simplified by choosing the appropriate characteristics of the vibration-isolating device. That is why this approach is now widely used. A number of effective vibration-isolating devices based on various operating principles have been developed:

- mechanical [e.g., MGIM (Owen, Jones, Owens, & Robinson, 1990), MGVIS (Labib et al., 2010), VZP (Levtov, Romanov, Ivanov, Riaboukha, & Sazonov, 2001)];
- rotary [e.g., Fluger (Akulenko, Bolotnik, Borisov, Gavrikov, & Emel'yanov, 2019), SPmgLab (Amselem, 2019)];
- magnetic [MAVI (Dong, Duan, Liu, & Zhang, 2019), g-LIMIT (Whorton, 2000)]; and
- external [Payload (Primm, Krupacs, & Jules, 2015), ExPA Payload (Sedelnikov, & Salmin, 2022)].

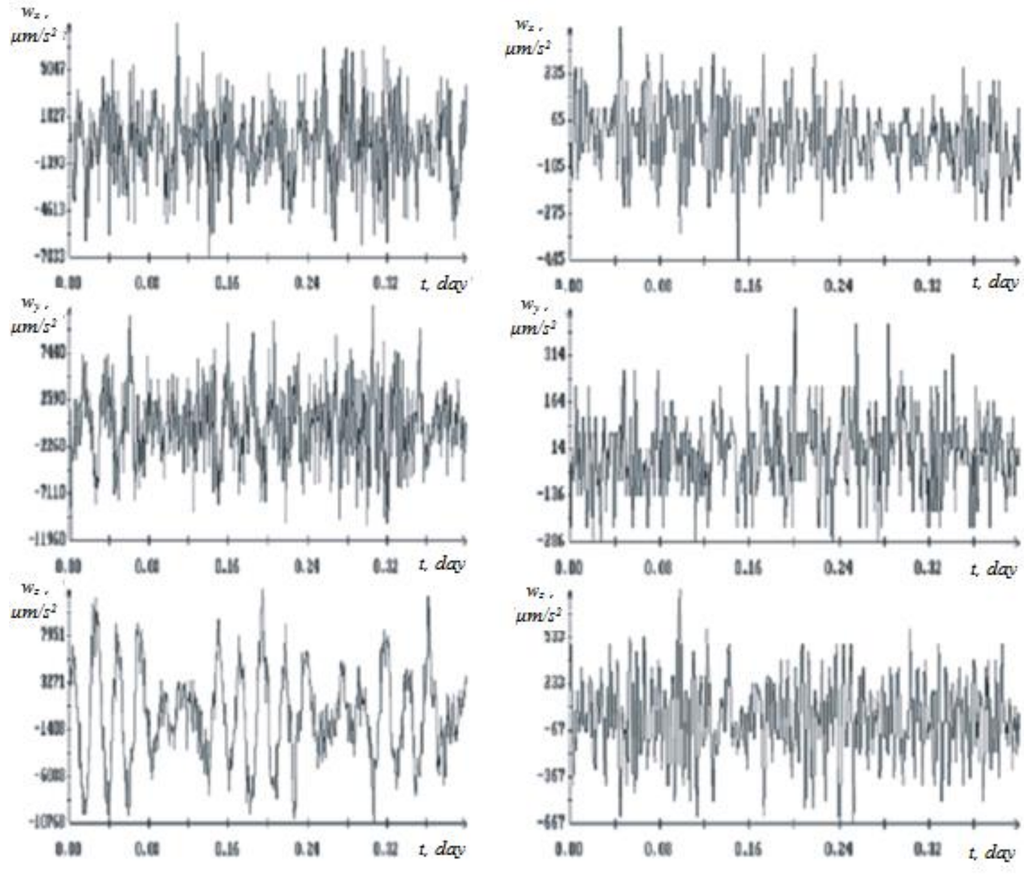
Their use today is associated with orbital space stations. Thus, MGIM and VZP were used at the Mir orbital complex; MGVIS, g-LIMIT, and Fluger were used at the International Space Station; MAVI was used at Tiangong-2. The obtained experimental data demonstrate the effectiveness of vibration-isolating devices in terms of reducing the level of microaccelerations. Figure 1 shows the experimental measurements of vibrations and microaccelerations inside the protected areas of MGIM, g-LIMIT, and VZP devices.



a)



b)



c)

Figure 1 Levels of microaccelerations inside the protected area of various vibration-isolating devices: a) ExPA Payload (Primm et al., 2015); b) g-LIMIT (Whorton, 2000); c) VZP-1K (Levtov et al., 2001).

However, in this case, the requirements for microaccelerations are met only in a significantly limited protected area, and the internal environment of the spacecraft is used inefficiently (Sedelnikov, & Salmin, 2022; Krestina, & Tkachenko, 2022). For a small spacecraft, an important role is played by an additional vibration-isolating device, the installation of which reduces the target equipment mass. That is why the regular operation of vibration-isolating devices is currently associated with orbital space stations.

4. Results and discussion

To improve the effectiveness of enabling a process of creating favorable conditions, it is necessary to take advantage of both approaches. First, for many vibration-isolating devices, the level of microaccelerations inside the protected area depends on microaccelerations in the internal environment of the spacecraft. It is not a coincidence that Figure 1c shows data on microaccelerations inside and outside the protected area. A combined approach will be rational for small technological spacecraft. These spacecraft can be designed specifically for a particular gravity-sensitive process. Thus, we are talking about the installation of technological equipment for this process on a vibration-isolating device. This does not require creating the conditions for microaccelerations in other parts of the internal environment of a small spacecraft. Therefore, the use of a vibration-isolating device does not reduce its capabilities because other gravity-sensitive processes are not implemented.

Let us consider the possibilities of providing conditions for microaccelerations with the use of executors of the motion control system and without their use for the VZP-type vibration-isolating platform. Let us choose the internal longitudinal force arising from the thermal shock of large elastic elements of the spacecraft as a perturbation (described in Orlov, 2021; Sedelnikov, & Orlov, 2020; Sedelnikov, & Orlov, 2021). We approximate the vibration-isolating platform in the form of a damping system with one degree of freedom (Figure 2) because the internal longitudinal force acts only along one axis (Orlov, 2021; Sedelnikov, & Orlov, 2020; Sedelnikov, & Orlov, 2021).

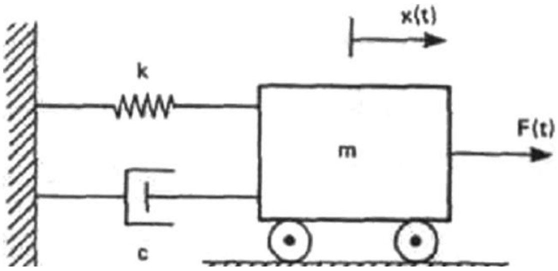


Figure 2 Scheme of the vibration-isolating platform with one degree of freedom

The equation of motion of such system for forced harmonic excitation F(t) can be written as:

$$m\ddot{x}+c\dot{x}+kx=F(t)e^{i\omega t}$$

where *c* is the viscous damping coefficient; *m* is the mass of the vibration-isolating platform; ω is the frequency of the exciting force; *F*(*t*) is the internal longitudinal force (Orlov, 2021; Sedelnikov, & Orlov, 2020; Sedelnikov, & Orlov, 2021); and *k* is the spring stiffness.

Then, the equation of forced oscillations of this platform will have the form (Gordeev, Filatov, & Ainbinder, 2018; Li, Liu & Yang, 2020; Anshakov, Belousov, Sedelnikov, & Gorozhankina, 2018):

$$\ddot{x}+2\xi\dot{x}+\omega_0^2x=\omega_0^2\frac{N(t)}{k}e^{i\omega t}, \quad (5)$$

where $\xi=\frac{c}{2m}$ is the damping coefficient; *c* is the viscous damping coefficient; *m* is the mass of the vibration isolating platform; and $\omega_0=\sqrt{\frac{k}{m}}$ is the frequency of natural oscillations.

Figure 3 shows the microaccelerations caused by the internal longitudinal force from the temperature shock of large elastic elements outside the protected area of the vibration-isolating platform and in its protected area.

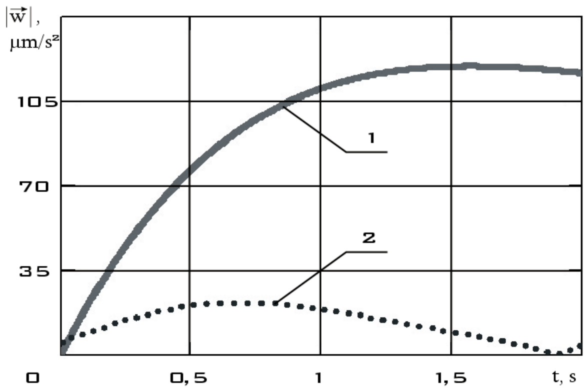


Figure 3 The level of microaccelerations from the thermal shock of large elastic elements of the Vozvrat–MKA spacecraft in the case without the control outside the protected area of the vibration-isolating platform [curve 1, (Sedelnikov, & Orlov, 2020)] and in its protected area (curve 2)

Curve 2 is obtained by integrating the differential equation (5). In this case, data from the Vozvrat–MKA spacecraft were used (Sedelnikov, & Orlov, 2020). Let us further consider the control aimed at reducing microaccelerations from the thermal shock, as considered previously (Sedelnikov, & Orlov, 2020). Figure 4 shows the level of microaccelerations for this case.

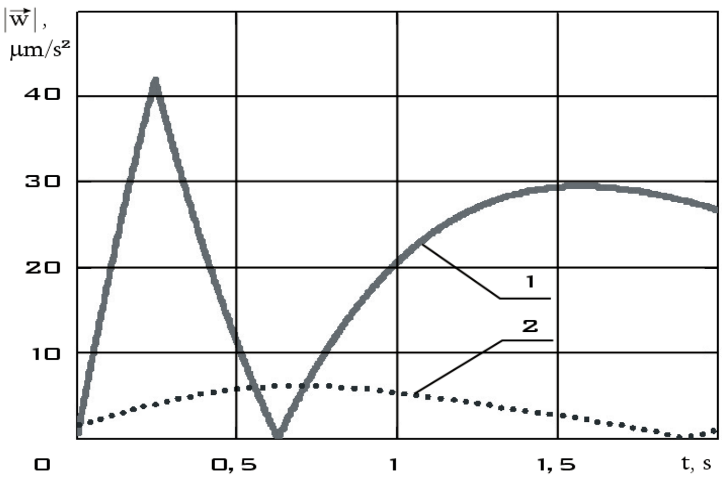


Figure 4 The level of microaccelerations from the thermal shock of large elastic elements of the Vozvrat–MKA spacecraft in the case with the control outside the protected area of the vibration-isolating platform [curve 1, (Sedelnikov, & Orlov, 2020)] and in its protected area (curve 2)

5. Conclusion

The abovementioned figures show that at the maximum level of microaccelerations of approximately 116 μm/s^2 (Sedelnikov, & Orlov, 2020), the vibration-isolating platform can attain microaccelerations of no more than 20 μm/s^2 (Figure 3), and at the maximum level of microaccelerations of approximately 42 μm/s^2 (Sedelnikov, & Orlov, 2020), the vibration-isolating platform can attain microaccelerations of no more than 7 μm/s^2. This confirms the effectiveness of the combined approach for small technological spacecraft.

The proposed combined approach is more complex in terms of technical execution. However, it allows us to combine the advantages of two classical approaches to ensure microacceleration requirements for the implementation of gravity-sensitive processes on board a small spacecraft. The application of this approach will lead to an increase in the cost of implementing the space project;

however, the range of gravity-sensitive processes being implemented will be significantly expanded.

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