Analysis of micro-acceleration requirements in the context of designing a small technological spacecraft

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Abstract. The paper analyzes the design features of a small technological spacecraft justifying the choice of design parameters and modeling the functioning of the spacecraft in terms of micro-acceleration requirements. These requirements are imposed in order to successfully implement gravitationally sensitive technological processes, determine the possibility and feasibility of their implementation and regulate the choice of design parameters, structural layout diagram and executive bodies of the orientation and motion control system of a small technological spacecraft. The experience of designing, creating and operating medium-class technological spacecraft is generalized and analyzed. Common points and differences are identified and discussed. The approaches proposed in the work and the results obtained can be used in the design of small technological spacecraft.

1. Introduction
The development of small spacecraft and their active use in all spheres of scientific and technical activities stimulates research on the applicability of this space technology in various fields. To date, sufficient experience has been accumulated in the design, manufacture and operation of space technology of the middle class and the class of orbital space stations [1–3]. Analysis and deep processing of this experience in combination with advanced research and field and computational experiments will significantly expand the scope of small spacecraft.

The miniaturization of space technology is making serious changes in well-oiled design concepts and methods for the effective functioning of this technology. Questions that have already been resolved are becoming relevant again. For example, the dense arrangement of small spacecraft revived the issue of calibrating magnetic measuring instruments due to the need to take into account the influence of the target and supporting equipment on the measurement data [4–6]. Although for spacecraft of other classes this issue was resolved back in the 70s of the last century [7, 8].

On the one hand, the issue of using small spacecraft in space materials science is new and poorly studied. Not a single project of a small technological spacecraft has been implemented until now. At present, the project of the Vozvrat-MKA spacecraft is being developed. However, despite the fact that it is a small spacecraft its mass (about 3000 kg) makes it possible to classify this spacecraft as a middle class spacecraft since the limit of the mass of a small spacecraft is 1000 kg.

On the other hand, the problems of successful and effective implementation of gravitational processes on spacecraft of the middle class and the class of orbiting space stations are still far from being solved. Multifunctional orbital space stations cannot provide favorable conditions for the implementation of gravitational-sensitive processes without additional means of protection since there
are many sources of micro-accelerations on board. These include orbit correction engines, impacts during docking of spaceships, natural vibrations of numerous elastic elements and even the structure of the orbital space station, the operation of numerous non-technological systems and equipment, crew life and much more [9]. The middle class spacecraft are more suitable for disruptive space technologies. They can only be created for the implementation of gravitationally sensitive technological processes. Currently, the concept of reusable technological spacecraft serviced by the crew of orbiting space stations is being implemented. However, the maximum level of micro-accelerations of 10 µm / s² (project "OKA-T" [10]) achievable with minimal use of auxiliary support equipment during the implementation of gravitational-sensitive processes turns out to be unacceptably high for the process of directional crystallization [11].

Significantly more efforts will be required than in the case of a middle class spacecraft to ensure favorable conditions for micro-accelerations on board a small spacecraft. Therefore, research in this area is important and timely. The creation of a small spacecraft for technological purposes will allow specialists in the field of space materials science to have wide access to an effective experimental base. It, in turn, will give a powerful impetus to the development of space technologies and the production of new materials with unique properties.

2. Specialized means of additional vibration protection.
A long history has a direction associated with the means development of additional vibration protection of technological equipment from micro-accelerations. Here, mention should be made of the Microgravity Isolation Mount (MGIM) vibration protection device developed by Canadian specialists [12, 13]. Experiments with MGIM onboard the Mir orbital complex have shown its effectiveness in a number of cases (Figure 1). However, there were also problems when the level of micro-accelerations in the protected area exceeded the level outside MGIM.

![Figure 1. There is amplitude of oscillations outside and inside MGIM](image)

Then MGIM was upgraded to the Microgravity Vibration Isolation Subsystem (MGVIS) [14] which formed the basis for the vibration protection of the Columbus laboratory module [15].

The VZP-1 vibration protection platform was developed and tested on the Mir orbital complex in Russia [16]. It was used to grow cadmium sulfide semiconductor single crystals in a Crater-VM furnace. It was possible to grow crystals weighing about 130 grams in about 130 hours. The platform was also used in other experiments in combination with other equipment, for example, the Gallar
furnace, the Onyx control complex, the Optizon-1 mirror furnace, the Crystallizator-ChSK-1 and Titus-ChSK-4 experimental installations and etc. [17].

The Chinese specialists also took this path. They developed the Microgravity Active Vibration System (MAIS) vibration protection platform which was tested in 2017 on the Tianzhou-1 spacecraft [18]. It is shown in [19] that the system meets the requirements of SSP41000D (Figure 2) but does not meet the current needs of specialists in the field of space materials science [20].

![Figure 2](image.png)

**Figure 2.** There is the required and confirmed level of micro-accelerations with the MAIS vibration protection platform on board the Tiangong-2 orbital station (cited in [19] and [20]):

- 1 is SSP41000D requirements;
- 2, 3, 4, 5 are measurements on 30.04, 16.05, 24.06 and 30.08.2017, respectively;
- 6 is requirements from Institute of Metallurgy and Material Science named after A.A. Baikov

At present, specialists of the Perm State National Research University taking into account the experience in the development and operation of VZP-1 [16] and the automatic rotary vibration protection platform "Fluger" [21] are developing a universal vibration protection platform VZP-U with better characteristics than MAIS [11]. It is especially true of quasi-static micro-accelerations which are not shown in Figure 2. It is believed that the most significant reasons for the occurrence of macro- and microinhomogeneities in the grown single crystals are micro-accelerations having frequencies no more than 10-2 - 10-3 Hz even of the order of 1 μm / c2 [22]. The successful course of gravitational-sensitive processes essentially depends not only on the magnitude but also on the direction of the vector of quasi-static accelerations. The direction and nature of emulsion separation, the structure and intensity of convective flows in liquids, the structural perfection of grown crystals and etc. depend on the orientation of the container with a gravitationally sensitive medium relative to the vector of micro-accelerations. It is necessary to ensure satisfactory conditions for most technological processes that the perpendicular component of the micro-acceleration vector to the selected axis of the technological unit (crystallization axis, temperature gradient, impurity density gradient, etc.) should be no more than 3 μm / s2 [11, 23]. Its tests aboard the International Space Station are scheduled for 2023.

3. Analysis of the experience in the development and operation of technological spacecraft of the middle class.

The direction of developing specialized space technology for technological purposes has been significantly developed after understanding the objective problems with the implementation of gravitational-sensitive processes on board multifunctional orbital space stations. Moreover, two paths in this direction stood out to the cut. The first way was to create disposable spacecraft. They carried
out their mission and delivered the results of experiments to Earth by a descent vehicle. Small spacecraft are not capable of operating in this mode since the presence of a descent vehicle imposes a limitation on the minimum mass. The advantage of this route is the ease of developing a disposable spacecraft as compared to a reusable one. Examples of such spacecraft are Russian spacecraft of the Foton [24] and Bion [25] series, as well as Chinese spacecraft of the SJ series [26] and Tianzhou [18]. One of the most promising projects of the disposable space laboratory was the project of the NIKA-T spacecraft which was not implemented [2, 10].

The second way involved the creation of a reusable space laboratory. It offers many advantages over the first:
– multiple use of unique technological equipment and supporting equipment;
– significant reduction in project implementation costs;
– more rational use of the inner space of the space laboratory due to the absence of a descent vehicle;
– the possibility of changing and supplementing scientific and experimental programs;
– the ability to carry out maintenance and repair work, etc.

However, such a spacecraft must work in conjunction with an orbiting space station. Initially, the project of the MAKOS-T spacecraft was planned [27]. Then it was transformed into the OKA-T project [10] the development of which continues. The base station for OKA-T is supposed to be the international space station. The maximum level of micro-accelerations admissible according to the OKA-T technical specifications is 10 µm / s² [10]. Let us compare it with the flight test results shown in Figure 2. It can be seen that on spacecraft of the middle class without additional means of vibration protection it is possible to achieve a level of micro-accelerations similar to the level on an orbital space station with the use of vibration protection means. If these tools are applied on a middle class spacecraft, then it is possible to achieve the level of micro-accelerations indicated by line 6 in Figure 2. Indeed, the estimates of the authors of [19] show the maximum possibility of reducing micro-accelerations using MAIS by two orders of magnitude. Therefore, it is possible to satisfy the requirements for micro-accelerations presented in Figure 2 already at the present stage of development. However, it should be understood that the high cost and long term implementation of projects of middle class spacecraft are unlikely to make them widely available for solving problems of space materials science. Its effective development is impossible without a cheaper and more efficient way of carrying out gravitational-sensitive experiments in space. Such an opportunity at the present stage of development can only be provided by small spacecraft.

4. Analysis of the requirements for micro-accelerations and the possible role of small technological spacecraft.
Let us analyze the requirements of gravitational-sensitive processes to the level of micro-accelerations in comparison with actually achievable levels (Table 1) to identify the possible role of small spacecraft in the field of space technologies.

| Process | The required level of micro-accelerations, µm / s² | Spacecraft | Launch year | The real level of micro-accelerations, µm / s² |
|---------|-----------------------------------------------|-------------|-------------|---------------------------------------------|
| Getting semiconductor germanium | 100–1000 | Skylab | 1974 | 10³–10⁵ |
| Growing single | 10–500 | Mir | 1986 | 10³–10⁴ |
The requirements given in Table 1 are approximate and do not take into account the specifics of concrete processes. As already noted, some processes impose restrictions not only on the magnitude of micro-accelerations but also on the dynamics of its change [11, 23].

It will be more difficult to meet the micro-acceleration requirements for a small spacecraft than for a middle class spacecraft. The high energy intensity of gravitational-sensitive processes necessitates the use of large-area solar panels. In this case, the ratio of the body mass of a small spacecraft to the mass of its elastic part is less than for a middle class spacecraft. Consequently, natural oscillations of solar panels will significantly more affect the level of micro-accelerations.

The small internal volume of a small spacecraft will not allow large-scale series of experiments. Therefore, small spacecraft should not be viewed as a possible replacement for middle class spacecraft. Although in other areas such a replacement is possible. Thus, the small spacecraft "Aist-2D" in its characteristics is not inferior to the spacecraft of remote sensing of the Earth of the middle class [28] and is a serious competitor to them.

However, this disadvantage can be turned into an advantage. The small technological spacecraft can have an even narrower focus than middle-class spacecraft. In theory, a small spacecraft can be designed to implement one gravitationally sensitive process. In this case, it will be possible to take into account the specifics of this process as fully as possible and create the most favorable conditions for its implementation which the space technology being developed can only allow. The low cost of a small spacecraft makes this path quite feasible. At the same time, the use of a middle-class spacecraft for the implementation of one technological process at the present stage of development of space technology is practically impossible. It is evidenced by the experience of operating middle-class spacecraft which was analyzed in the previous section.

The additional means of vibration protection can be used to limit the level of micro-accelerations no worse than a similar level on orbital space stations. Of course, these funds will constrain the already small capabilities of small spacecraft. However, these capabilities should be quite enough in the context of using a small spacecraft to implement one gravitational-sensitive process. Thus, the automatic rotary vibration protection platform "Fluger" developed in Russia (Figure 3) has its own mass of 55 kg and can be effectively used to compensate for micro-accelerations including on a small spacecraft [29].
Figure 3. There is an external view of the automatic rotary vibration protection platform "Fluger"

Specialized scientific equipment has already been developed to work with the "Fluger" platform. For example, the "Growth setup" designed to obtain highly homogeneous and perfect germanium crystals with a diameter of 25-30 mm using directional crystallization by the Bridgman method and has a self-weight of 33 kg [30]. The mass of the target and scientific equipment of the small spacecraft "Aist-2D" is 145 kg [28]. Currently, a small spacecraft "Aist-2T" is being developed on the Aist-2 platform with an active life of at least five years [31]. The launch of two vehicles of this type is scheduled for 2023.

5. Conclusions

Thus, a number of conclusions can be drawn according to the results of the research carried out.

– At present, it is possible to meet the requirements for micro-accelerations (line 6 in Figure 2) on spacecraft of the middle class using additional vibration protection means

– Providing favorable conditions at orbital space stations is difficult due to their multifunctionality, habitability and the presence of a large number of sources of micro-accelerations that are not associated with the need to implement gravitational-sensitive processes. However, it is possible to organize pilot production in space in conditions of increased vibration protection in a separate laboratory module of the orbital space station. At the same time, the improvement of vibration protection means will expand the list of gravitational-sensitive processes implemented in such conditions.

– The most promising way seems to be the way of creating autonomous spacecraft of the middle class working in conjunction with an orbiting space station. In essence, it can be thought of as a stand-alone laboratory module. It is devoid of the main sources of micro-accelerations at the time of the gravitational-sensitive processes. Moreover, it is possible to turn off auxiliary systems and operate only the equipment necessary for the implementation of processes. This spacecraft then docks with the base station to reboot the process cycle and carry out maintenance work. The absence of the need for a descent vehicle and the use of additional vibration protection means significantly expand the technological capabilities of such a spacecraft.

– The small spacecraft have significantly less capabilities than middle-class spacecraft. In addition, it is more difficult to provide the required level of micro-accelerations on a small spacecraft than on a middle-class spacecraft. However, today only they can provide wide access to technological experiments in a real space environment. Therefore, this resource under current conditions can be used to conduct advanced research and experiments in order
to form further full-fledged scientific and technological programs that can later be implemented on the middle-class spacecraft. The small spacecraft are also suitable for early-stage disruptive technologies when all the significant factors influencing the process have not yet been fully identified and the method for conducting the experiment has not been finally formed. The small spacecraft have broad prospects in these areas.

6. Acknowledgments
This work is supported by the Ministry of education and science of the Russian Federation in the framework of the State Assignments to higher education institutions and research organizations in the field of scientific activity (the project FSSS-2020-0017).

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