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Levels of Vibration Impact during Testing of Spacecraft Avionics Equipment

A.S. Levchenko, *Cand. Sci. (Engineering), levch.andrew@gmail.com*
Joint Stock Company "Russian Space Systems", Moscow, Russian Federation

Abstract. The tightening of avionics lifetime and reliability requirements necessitates a profound and efficient experimental method. At the same time, the not infrequent absence of even two equipment samples for conducting tests (considering the variation of properties of materials and technological processes) makes the problem of confirming hardware strength characteristics difficult to solve. The present paper describes a methodology for vibration tests of spacecraft onboard electronics that allows us to reliably confirm the strength of a random sample of the given equipment based on the testing of a single test specimen. Safety margins for different stages of equipment vibration testing are determined. These margins are necessary to ensure the given probability of design defect detection. The proposed methodology is compared with current foreign regulatory documents dedicated to testing spacecraft onboard electronics. The proposed method allows a flexible approach to the selection of vibration test levels since it takes into account the design features of the equipment affecting strength spread from sample to sample during the determination of the scope of required tests.

Keywords: vibration tests, strength test, random broadband vibration, spacecraft onboard equipment

Introduction

The specificity of the factors affecting the on-board radio equipment of spacecraft determines the complex structure of ground-based testing of this class of equipment. One of the difficulties of the operation of such equipment is counteracting the impact of a short-term (no more than 10 minutes) vibration with sufficiently high levels of spectral density of vibration acceleration during it's orbital launch.

In world practice, there are two approaches to development testing of equipment, depending on the number of samples:

1) A large number of samples can be allocated for development tests. In this case, tests for resistance to external influencing factors (hereinafter EIF) are carried out similarly to reliability tests, during which the statistical properties of the set of equipment are revealed, and the test standards can take values equal to operational ones.

2) A small or medium number of samples is allocated for development testing of equipment. In space instrumentation, this approach is used in Russia as well as in the United States and Europe. In this case, insufficient samples are allocated for development tests in order to reveal the statistical properties of the set of equipment. At the same time, a sample with large safety margins according to EIF can be submitted for testing, but it does not have reserves in operation, due to which the only way to guarantee the operability of any piece of equipment manufactured according to the developed design documentation is to test it with increased values of EIF relative to the requirements of the specifications [1, 7]. This approach is implemented in state standards for on-board spacecraft equipment of the 5th class (GOST RV 50699, GOST V 24880), American normative and technical documents (MIL-STD-1540, MIL-HDBK-340A), standards of the European Space Agency (ECSS-E-ST-10-02C, ECSS-E-ST-10-03C).

In ESA, 4-5 sets of equipment are allocated for testing, of which 3-4 samples are allocated for development tests [6]. The developer conducts large volumes of EIF resistance tests, including destructive tests, in order to obtain the maximum amount of information about the equipment. Acceptance (qualification according to ESA classification) tests are carried out on one or two samples with customer control, the scope of which is determined based on a specific situation: the achieved level of quality and reliability, the level of novelty of the equipment.

A specific feature of ground experimental testing of onboard electronic equipment of spacecraft (hereinafter referred to as the SC OEE) of the Russian Federation in modern conditions is the impossibility of selecting more than two sets of equipment for testing. Since, in addition to tests for climatic and mechanical EIF, tests for radiation resistance and life tests are included in the development, in fact, only one sample is received for developmental mechanical tests.

In the conditions of unification of the SC OEE, when a single test is necessary to ensure the quality of the equipment, which can be mass-produced at various factories for many years, the only way to organize tests of OEE is to test on single samples with the magnitudes of impacts increased by the safety factor, which makes it possible to cover the variation the components used, materials and other variations in the properties of the equipment, manufactured in the future according to the newly created documentation.

The paper considers the necessary level of the stock of loads when testing the SC OEE for stationary vibration to ensure its quality and reliability.

Methodology for vibration testing of the SC OEE

The vibration test methodology for the SC OEE should be based on the fact that one or two samples of equipment are provided for mechanical tests, none of which should be tested to failure, since these samples must subsequently undergo other stages of testing, such as life tests or tests for radiation resistance. As a consequence, such a technique should take into account the factors affecting the spread of durability between the samples of the equipment. There are three basic factors affecting the range of equipment durability:

- the variation of materials by the number of vibration loading cycles to destruction [7, p. 510-519],
- the variation of the resonant frequencies of the construct,
- the variation in quality factors of structural elements caused by the variation of stiffness and damping properties of materials.

These factors are mentioned for the reason that their influence cannot be minimized during incoming inspection and additional tests of materials and electronic components. The variation in materials by the number of vibration loading cycles to destruction and the spread of resonant frequencies do not require an increase in the load level during testing, but only require an increase in the duration of the test mode relative to the operational mode. In this work, only the influence of the variation of the quality factors of the structural elements on the required levels of the spectral density of vibration acceleration and the amplitude of sinusoidal vibration will be considered, therefore, the issues of the duration of exposure during vibration tests are not considered in this article. When choosing a test duration, one should be guided by the requirements of GOST B 24880 or other regulatory documents.

Let us consider the influence of the spread of the figure of q-factors of structural elements on the required levels of impacts during vibration tests. From the side of the landing surface of the spacecraft, the device is affected by random broadband vibration (hereinafter RBV), described by the spectral density of vibration acceleration, which is a function of frequency. You can define the effective value of the RBV acting on the device as

$$g_{eff} = \sqrt{\int_{f_n}^{f_v} S(f)df}.$$

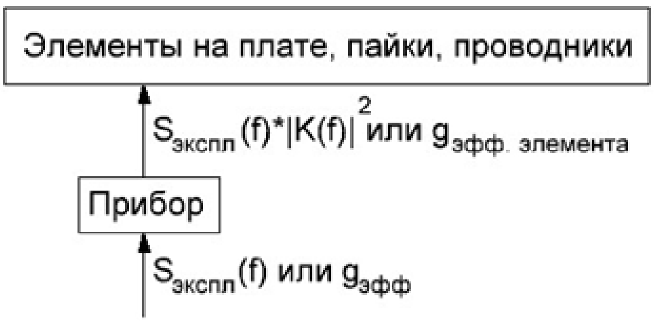


Fig. 1. Spectral density of vibration acceleration taking into account the resonance properties of the equipment

If you install vibration sensors inside the device, you can see that on the elements (board, solder, ERI, conductor) of the device, the RBV spectrum differs from the input [9] (see Fig. 1):

$$S_{element}(f) = S_{expl}(f) \cdot |K(f)|^2, \qquad (1)$$

where $|K(f)|$ is the modulus of the amplitude-frequency characteristic (hereinafter AFC) of the construct at the point under study. It should be noted here that at different points of the device the frequency response will be different. Then it is possible to determine the effective (RMS) value of the random vibration acting on the device element, described as a resonator with one degree of freedom as

$$g_{eff.elem} = \sqrt{\int_{f_n}^{f_v} S(f) \cdot |K(f)|^2 df} = \sqrt{\frac{\pi}{2} \cdot S_{expl}(f_p) \cdot f_p \cdot Q_p}, \qquad (2)$$

where f_p is the natural frequency of the resonator, Q_p is the dynamic factor at the resonant frequency. At the same time, for different copies of the device, the dynamic coefficient differs, often by several times, due to the variance in material properties, screw tightening torques, etc.

The analysis of the test results on a large sample of on-board radio-electronic devices, carried out during the research work in the 80s, showed that the dynamic factors have a distribution close to the normal distribution truncated at the level of ± 3s (see Fig. 2).

With such a distribution, samples of the same device with average strength characteristics are usually produced. However, both samples with a low dynamic factor (hereinafter "good" sample) and samples with a high dynamic factor (hereinafter "bad" sample). Elements (for example, electrical and radio products, soldering, adhesive joints, etc.) of a "bad" sample of the device receive a mechanical load that is significantly greater than the elements of a "good" device. If a "good" sample is tested (marked with a solid vertical line in Fig. 2), then such tests can confirm the strength of only 16% of the manufactured device samples. Naturally, in real conditions, it is impossible to determine which of the samples was tested, but this is not required when using the proposed method.

In order to confirm the strength of any sample of the device made according to the worked out design documentation, it is necessary to take into account possible variations in the dynamic factor during testing. Therefore, when conducting tests on one sample, it should be assumed that it has low dynamic coefficients and should be increased by times to the level in such a way that the vibration acceleration on the elements of the tested device would be the same as in the worst case scenario:

$$\alpha^2 = \frac{S_{test}(f)}{S_{oper}(f)} = \frac{|K_{bad}(f)|^2}{|K_{good}(f)|^2} = \left(\frac{Q_p{}^{av} + K_{norm}(\gamma)\sigma_Q}{Q_p{}^{av} - K_{norm}(\gamma)\sigma_Q}\right)^2, 0$$

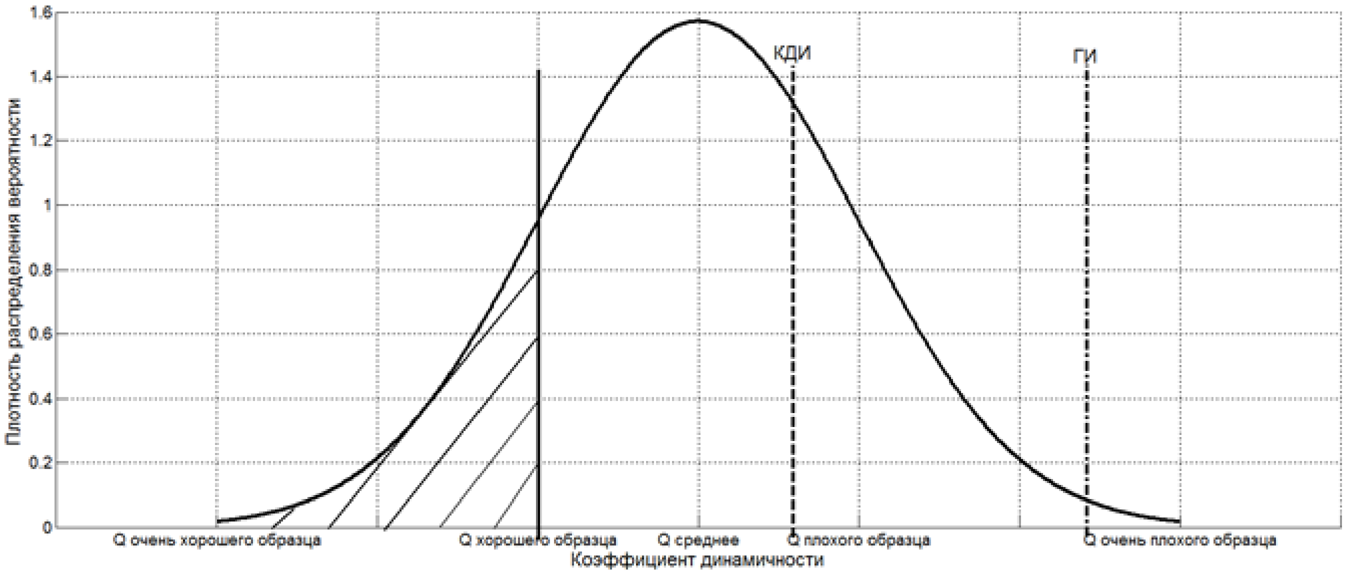


Fig. 2. Distribution of dynamic factors for different instances of one device

where $K_{norm}(\gamma)$ is the quantile of the truncated normal distribution of the level γ, σ_Q is the dispersion of the spread of the dynamism coefficient, Q_p^{av} is the average level of the dynamism coefficient for the samples of this device. The definition of Q_p^{av} for a particular device is an impossible task, therefore, it should be replaced with the coefficient of variation, as a statistical characteristic with the least variance in the general selection:

$$\alpha^2 = \left(\frac{Q_{\mathrm{p}}{}^{av} + K_{norm}(\gamma)\sigma_Q}{Q_{\mathrm{p}}{}^{av} - K_{norm}(\gamma)\sigma_Q}\right)^2 = \left(\frac{1 + K_{norm}(\gamma)\frac{\sigma_Q}{Q_{\mathrm{p}}{}^{av}}}{1 - K_{norm}(\gamma)\frac{\sigma_Q}{Q_{\mathrm{p}}{}^{av}}}\right)^2 =$$

$$= \left(\frac{1 + K_{norm}(\gamma)V_Q}{1 - K_{norm}(\gamma)V_Q}\right)^2, \quad (3)$$

where V_Q is the coefficient of variation for the coefficient of dynamism, it is used because it varies little from one type of device to another.

For electronic devices developed in the 1980s, the value, determined from a large sample of different types of devices, was 0.15. Naturally, the design solutions used in modern devices require a revision of the value. Unfortunately, in view of the fact that for the last 10 years more than two samples have rarely been supplied for developmental mechanical tests of spacecraft equipment, it has not yet been possible to collect enough statistics to estimate the coefficient of variation for a sample for modern instruments. However, even the available statistics show that this value exceeds 0.15. For example, the dynamics coefficients of three images of the MUM L1-CHR device during development tests at the same input load at one of the points took the values 22, 43, 62 (see Fig. 3). Consider how such values correspond to a coefficient of variation of 0.15.

The dynamic coefficients of γ percent of the total number of instrument samples must fall within the range of values, which is defined as

$$Q_{\mathrm{p}}^{av} \cdot \left[1 - K_{norm}(\gamma)Vs_Q\right] < Q_\gamma < Q_{\mathrm{p}}{}^{av} \cdot \left[1 + K_{norm}(\gamma)V_Q\right].$$

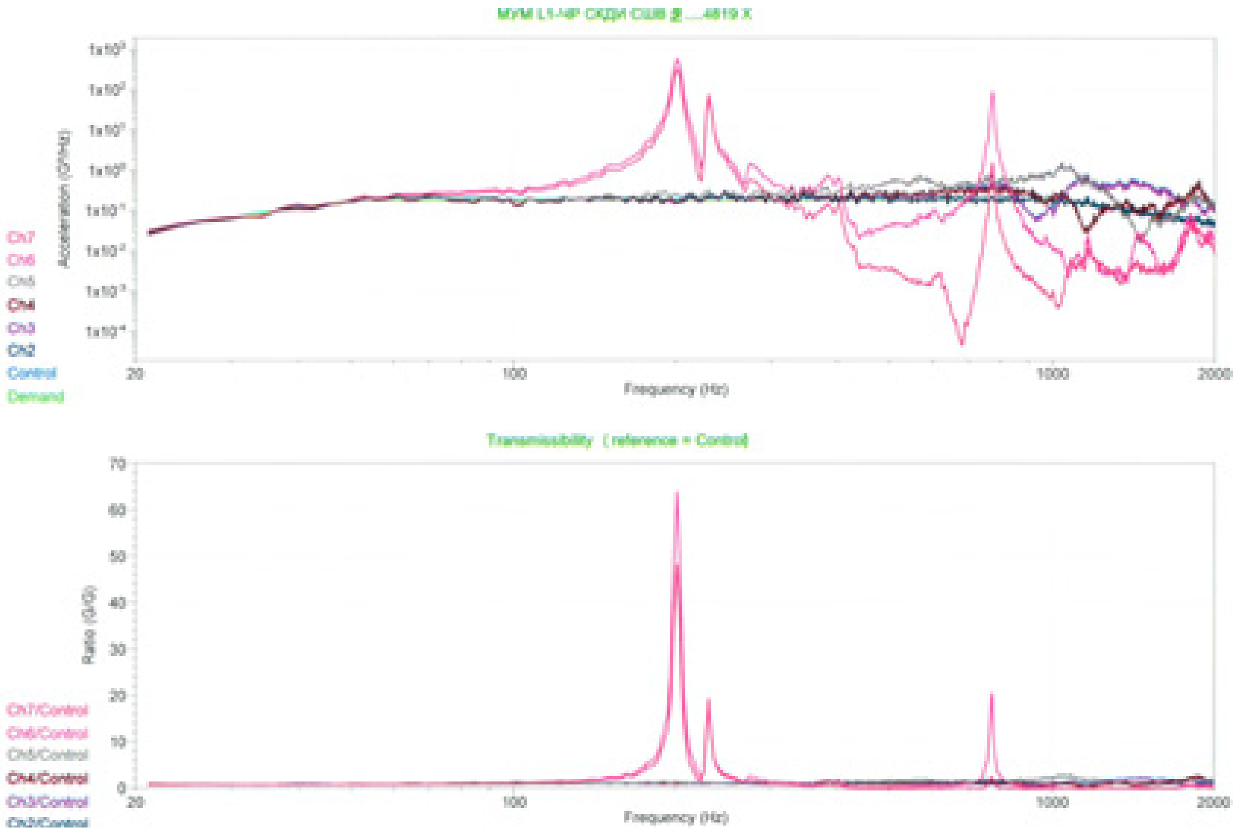
For the device MUM L1-CHR Q_p^{av} is approximately 42. With a coefficient of variation of 0.15 for 75% of instrument samples, the value of the dynamic coefficient should not exceed the range

37.77<<46.23,

and for 95% of devices - the range of

37.72<<52.28,

Figure 3 shows that for two samples of three devices, the value of the dynamism coefficient went beyond this range. The probability of such an event with a coefficient of variation of 0.15 is less than percent. Taking into account also the significant scatter of the dynamism coefficients observed in pairs of prototypes of other devices, we can confidently assert that the real value of for the equipment developed by JSC Russian Space Systems is higher than 0.15. Naturally, for the application of this technique in other organizations of the industry, it is necessary to estimate for the equipment for their development, however, for electronic devices, the indicated value can be used as a first approximation.


Acceleration (G²/Hz)
Frequency (Hz)
Ch7
Ch6
Ch5
Ch4
Ch3
Ch2
Control
Demand
Transmissibility (reference = Control)
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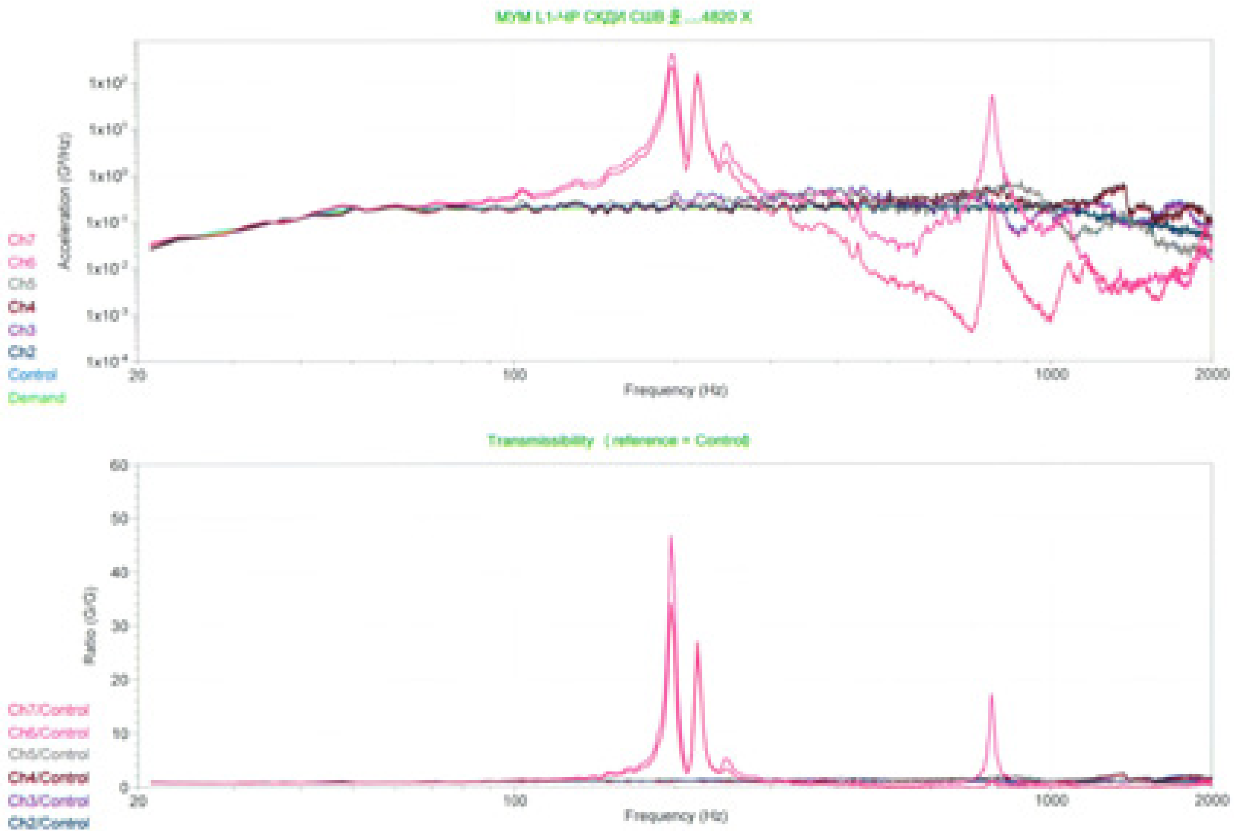
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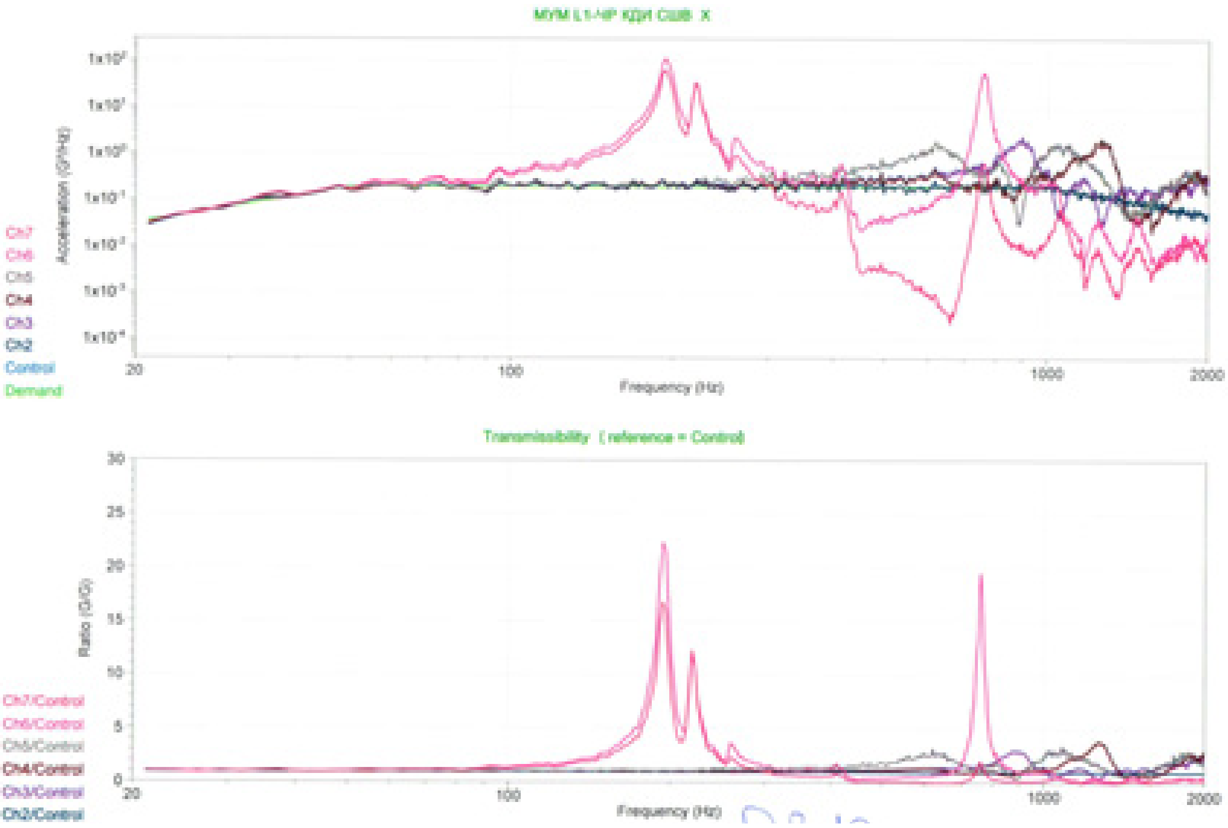

Fig. 3. The dynamism coefficient of three samples of the MUM L1-ChR device

The greater the probability γ we want to guarantee that any sample of the device meets the operational requirements, the larger the quantile . Table 1 shows the values of the quantiles [4] and the safety factor for the spectral density of vibration acceleration for different γ at =0.15. The values of the spectral density during testing should be increased by times, and the amplitude of vibration acceleration according to (2) - by times.

Table 1. Values and for different levels of γ

γ	**0.75**	0.95	0.96	0.97	0.975	0.98	0.985	**0.99**
K_{norm}	**0.672**	1.633	1.736	1.862	1.938	2.028	2.137	**2.280**
a	**1.224**	1.649	1.704	1.775	1.820	1.874	1.943	**2.040**
a^2	**1.499**	2.719	2.905	3.152	3.312	3.513	3.776	**4.157**

In conditions where the requirements for the probability of no-failure operation of the device over the period of autonomous existence can reach 0.999, the failure of devices due to mechanical destruction after launch (i.e. at the beginning of the LES) is categorically unacceptable and its probability should be reduced as much as possible.

Onboard equipment tests according to GOST RV 50699 and OST V 92-9096 are divided into different stages, including KDI and GI [3], during which mechanical tests are carried out. OST V 92-9096 implies that in case of successful completion of the KDI, it is required to guarantee the strength of 75% of the samples of the tested device (Fig. 2, left vertical dashed line and Table 1, column with γ = 0.75), according to the results of GI, the strength of 99% of the samples (Fig. 2, right vertical dash-and-dot line and Table 1, column with γ = 0.99). In this case, the levels of vibration effects during KDI will coincide with those required by GOST B 24880 [2].

The main disadvantage of the proposed method is that for structural elements with a low spread of the dynamic coefficient (for example, for load-bearing structural elements), the test loads will exceed the possible ones even for the worst instances of the device. The organization's standards applied in JSC Russian Space Systems provide that each failure during the GI associated with the strength characteristics of the devices is analyzed, and if it is proved that the variance of characteristics of the device element causing the failure is less than that assumed when setting the test standards, then the failure is admissible and does not require hardware modification.

Comparison of test modes according to the proposed methodology with those established in the norms and specifications of Russia and foreign countries

Comparison of modes during vibration tests according to US specifications [8, p. 31] (see Fig. 4), specifications of the European Space Agency (see Fig. 5) [6, p. 48], GOST B 24880, OST B 92-9096 and modes according to the proposed method are given in Table 2.

It can be seen from the table that the vibration exposure levels during the qualification tests in the USA are close to those proposed for the GI stage. The ESA proficiency test exposure levels are higher than the proposed CDI exposure levels. GOST B 24880 establishes more stringent test modes than the proposed method, but does not provide for margin or development tests. The test levels for OST B 92-9096 almost coincide with those proposed.

Table 2. Summary table of margin factors for vibration tests

Safety margin factor when tested against performance levels		US specifications	ESA specifications	GOST V 24880	OST V 92-9096	proposed method
Qualification tests	For spectral density of vibration acceleration	4	2	2.0	1.56	1.499
	For the effective value of vibration acceleration	2	1.5	1.5	1.25	1.22
Development tests or GI	For spectral density of vibration acceleration	determined by the developer, exceed qualifying		not held from 1.78 to 2.00	from 3.16 to 4.00	4.15
	For the effective value of vibration acceleration				2.04	

Test	Units	Vehicle
Shock*	6 dB above maximum expected environment, 3 times in both directions of 3 axes	1 activation of all shock-producing events; 2 additionalactivations of controlling events (6.2.3.3)
Acoustic*	6 dB above acceptance for 3 minutes	6 dB above acceptance for 2 minutes
Vibration*	6 dB above acceptance for 3 minutes, each of 3 axes	6 dB above acceptance for 2 minutes, each of 3 axes
Thermal Vacuum (Tables V, VI)	10°C beyond acceptance temperatures for 6 cycles	10°C beyond acceptance temperatures for 13 cycles
Combined Thermal Vacuum and Thermal Cycle (Tables V, VI)	10°C beyond acceptance temperatures for 25 thermal vacuum cycles and 53 1/2 thermal cycles	10°C beyond acceptance temperatures for 3 thermal vacuum cycles and 10 thermal cycles
Static Load	1.25 times the limit load for unmanned flight or 1.4 times the limit load for manned flight, for a duration close to actual flight loading times	Same as for unit, but only tested at subsystem level

Fig. 4. Safety factors for qualification tests according to US specifications

No	Test	Levels	Duration	Number of applications	NOTES
1	**Life**	Expected environment and maximum operational load	For duration and cycles: For mechanisms, apply ECSS-E-ST-33-01 Table 4-3 For batteries, apply ECSS-E-ST-20	1 test	
2	**Static load**	KQ x Limit Load The qualification factor KQ is given in ECSS-E-ST-32-10 clause 4.3.1	As needed to record data (10 seconds minimum)	Worst combined load cases	Worst combined load cases are determined by analysis
3	**Spin**	$\sqrt{KQ}$ x spin rate The qualification factor KQ is given in ECSS-E-ST-32-10	As specified by the project	1 test	
4	**Transient**	KQ x Limit Load The qualification factor KQ is given in ECSS-E-ST-32-10 clause 4.3.1	As needed to record data	As specified	
5	**Random vibration**	Maximum expected spectrum +3 dB on PSD values If margins higher than 3 dB are specified by the Launcher Authority, they apply.	2 minutes	On each of 3 orthogonal axes	
6	**Acoustic**	Maximum expected acoustic spectrum +3 dB If margins higher than 3 dB are specified by the Launcher Authority, they apply	2 minutes	1 test	
7	**Sinusoidal vibration**	KQ x Limit Load Spectrum The qualification factor KQ is given in ECSS-E-ST-32-10 clause 4.3.1	sweep at 2 Oct/min, 5 Hz - 140 Hz	On each of 3 orthogonal axes	

Fig. 5. Safety factors for qualification tests according to ESA specifications

Thus, the proposed method involves vibration tests with safety factors close to those used in foreign scientific and technical documentation. However, in contrast to the aforementioned regulatory documents, the proposed technique allows for specific types of devices, depending on the value of the coefficient of variation of their structural elements, to establish the levels of impacts both more and less, while ensuring the constant reliability of identifying design defects.

Conclusion

The proposed vibration test method has shown its effectiveness, since over the past decade, the equipment developed by JSC RSS has not had a single defect associated with the mechanical strength according to the results of deployment. At the same time, during the LEO, more than a third of structural defects are detected during mechanical tests. Moreover, these are structural defects that cannot be evaluated by modeling methods (since in the world practice, all conductors, microcircuit leads, mastics for gluing relays, etc. are never included into strength models), and the manifestation of these defects is provoked by minor deviations in the properties of materials or technological processes. The identification of such weak points in the design allows, before the manufacture of the flight model, to make a correction to the design documentation, which prevents possible personnel errors.

The proposed methodology establishes the levels of exposure during tests for stationary vibration, depending on the characteristic spreads of the dynamic factor used in the devices. The test levels obtained for the design solutions characteristic of the equipment developed by JSC Russian Space Systems are comparable to the requirements of the regulatory documents of the European Space Agency and NASA. The proposed method allows a more flexible approach to the selection of vibration test levels, since if a lower coefficient of variation of the dynamic factor is shown for certain typical design solutions based on the results of statistics collection, the vibration impact levels during testing can be reduced according to formula (3) without compromising quality. And on the contrary, if some types of devices are characterized by higher spreads of the dynamic coefficient, the method allows determining the levels of impacts during vibration tests to achieve the required reliability of identifying structural defects.

The application of this technique is especially important in the context of unification of on-board equipment, when the number of design solutions is reduced, and due to the high serial production, it becomes possible to collect statistical data to assess .

The provisions of the proposed methodology should be taken into account by all organizations that create spacecraft equipment when determining the scope of vibration tests, since the existing regulatory documents (such as GOST V 24880) does not take into account the outlined features of on-board radio electronic devices for spacecraft in the context of a decrease in the number of development samples that has occurred over the past four decades.

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