Rationing and shock testing on-board equipment of spacecrafts

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Abstract. The article addresses the issues of valuation and testing of on-board equipment for high-intensity shocks, discusses the problems of various shock testing facilities use and compares approaches to the problem in our country and abroad. The decision to use the specific mechanical test facilities for the on-board equipment testing is taken by its developer based on the assessment of on-board equipment resistance to the impact (resulting from own experience and numerical modeling).

1. Introduction
Currently, both Russian and foreign spacecrafts are produced in accordance with unpressurized scheme. The power base of such spacecraft is cellular panels and composite materials structures. As a result, there are certain changes in the rigidity and damping properties of a spacecraft, the way in which the on-board equipment is attached and, consequently, the load on the spacecraft itself and the on-board equipment. At the same time, the existing normative documentation, which governs the loads on the on-board equipment and the adjustment methods, has remained virtually unchanged for more than 40 years [1].

2. Research question
To date, the problems arising from the adjustment of on-board equipment for quasi-static and vibratory (both harmonic and random vibrations) loads have largely been solved [1–6]. One of the most complex types of mechanical loads on a spacecraft and on-board equipment where methodological problems remain are the increased intensity shock inputs. The source of such loads is the shock inputs (primarily pyroshocks) on the part of the carrier rocket (stages separation, cone discharge etc.), as well as shocks from its own pyrotechnics (spacecraft separation, solar array release and antenna deployment, etc.) [2–5]. It should be noted that the approaches to the rate making and adjustment of the on-board equipment for shock inputs in Russia and abroad have significant differences. The USA and European shock requirements are set in the form of shock response spectra, regardless of the industry, while in Russia there is still widespread shock rate making in the form of single pulses (more often in the form of a half-sine pulse). There are no real inputs that would appear as single pulses on the spacecraft and on-board equipment. The equipment developers are constantly faced with the requirements for the application of components whose shock input is specified as single pulses, while the hardware requirements are already set in the form of shock response spectra.
3. Shock rating

The shock response spectrum (SRS) is "the graph of the maximum acceleration response to the specified input effect of the oscillator ensemble with the specified values of the acceleration constant of the oscillators own frequencies". In calculations, if not otherwise specified, the single-degree-of-freedom systems with viscosity damping are usually used (if not specified, the value of acceleration constant $Q = 10$ is assumed) [7]. Deduced from the definition, there are positive and negative SRS. That is, spectra that show the maximum positive/negative acceleration. There is also residual SRS and primary SRS, i.e. spectra which do not account for the oscillator response during the shock input or, on the contrary, assess the response only during the shock input. Various algorithms for the solution of the equation (e.g. [8]) are used in the calculation of the SRS. There are also some approximate solutions for the residual SRS on the basis of the Duhamel's integral [9, 10, 11]. Additionally, Smallwood algorithm for SRS computing has become a regular procedure recently. This requires the calculation of the SRS to be carried out at intervals of no more than 1/12 octave.

Next, the concept of the maximax SRS (primary and residual SRS) is used to rate and compute the required SRS, the amplitude value of which being assumed modulo.

Both in Russian and foreign literature there are three stages in the rating of shock input on the on-board equipment:

1. Modelling of the applied shock propagation in spacecraft frame using finite-element models and/or statistical energy analysis, with subsequent rating of loads at on-board equipment.
2. Computational and experimental approach when the measurement results for the autonomous tests of subsystems (antennas, separation systems, solar arrays, etc.) and numerical modeling provide a refined forecast of the on-board equipment load and the shock rating.
3. Confirmation of the specified (rated or normalized) inputs based on the results of the load measurements at the regular pyrotechnics application.

The first stage is that of the preliminary design. Previous projects "heritage" in the form of databases on damping, shock input values of pyrotechnics, etc. is implemented for the construction of finite-elements and statistical energy analysis models.

The second stage is that of the operational design when the results of the first phase are refined if necessary.

The third stage is the verification phase of the entire project, confirming the correctness of the decisions taken in phases 1 and 2. The results of the measurements supplement the existing database.

There are currently experimental data on ~ 20 spacecrafts built on three different platforms, which have different mass, dimensions, number and type of pyrotechnics.

Standard shock input modes to on-board equipment of spacecrafts in our country are represented in Table 1 [11]. The applied shock on all equipment is divided into 6 zones (S0, S1, S2, S3, S4, S5) depending on the distance to the source of shock (Table 1).

| Zone | Distance from the shock input source (m) |
|------|-----------------------------------------|
| S0   | To 0.3                                   |
| S1   | 0.3–0.7                                  |
| S2   | 0.7–1.5                                  |
| S3   | 1.5–3                                    |
| S4   | 3–8                                      |
| S5   | 8–15                                     |

The shock loads are set for each of the three mutually perpendicular axes in the form of shock response spectra (with the acceleration constant of the resonators $Q = 10$).
Table 2. The values of the shock spectrum of accelerations.

| Zone | Frequency range (Hz) | Shock response spectrum value (g) |
|------|----------------------|----------------------------------|
|      | 35–1000              | 1000–10000                       |
| S0   | ~ 10000 and more     |                                  |
| S1   | 25–5000              | 5000                             |
| S2   | 13–2500              | 2500                             |
| S3   | 5–1000               | 1000                             |
| S4   | 3–500                | 500                              |
| S5   | 3–100                | 100                              |

As seen from Table 2, the maximum shock response spectra for the equipment being adjusted is accepted at 5000 g and its minimum value is 100 g. In addition to that, S5 zone is usually overlapped with a reaction to the vibration input and the need to carry out shock tests on S5 zone modes is very rare. S0 zone is the one of ~ 0.3 m within the pyrotechnics location area where only shock insensitive equipment can be installed.

It is noteworthy that the test modes presented in Table 2 include the data for some pressurized spacecrafts, which reduces the "transition frequency" to 1 kHz. The more appropriate test modes are the ones shown in Table 3 with the transition frequency of to 2.5 kHz. In the frequency range preceding the transition frequency, the load in Tables 2 and 3 is changed by linear law at logarithmic scale by frequency and amplitude of the shock response spectra. The loads for S3–S5 zones are to be taken in accordance with Table 2. The safety factor used to generate the load modes of on-board equipment is 2.

Table 3. Shock spectra of accelerations.

| Zone | Frequency range (Hz) | Shock response spectrum value (g) |
|------|----------------------|----------------------------------|
|      | 35–2500              | 2500–10000                       |
| S0   | From 100 to 10000 and more | 10000 and more |
| S1   | 50–5000              | 5000                             |
| S2   | 25–2500              | 2500                             |

In general, the transition rate of the normalized shock response spectra generated by the implementation of pyrotechnics in the Western specification is ~ 2–3 kHz (e.g. [15]).

Both the ECSS and NASA standards differentiate only 3 zones in the shock rating. The applied shocks on the spacecraft board equipment are divided into three zones: near-field (up to 15 sm), middle (15–60 sm) and far-field (over 60 sm). These zones differ in both the magnitude (amplitude) of the applied shocks and the rated frequency range. The near-field zone includes shocks with the amplitudes of more than 5000 g and up to 100 kHz by frequency; medium zone corresponds to those from 1000 g to 5000 g by amplitude and from 10 to 100 kHz by frequency and far-field zone corresponds to those of less than 1000 g by amplitude and 10 kHz by frequency [13,16].

Undoubtedly, the development of a zone rating methodology is an exceptional task. A large number of zones leads to difficulty in devices borrowing from one project to another due to a greater probability of a mismatch between requirements and specifications; and a small number of zones can lead to an unreasonable increase in the mass of the devices.
4. Shock testing

There are a number of features in carrying out the shock testing in the form of the shock response spectra shown in Tables 2 and 3, so we will look further at the use of a variety of testing facilities to apply shock input by the SRS method while testing the spacecraft on-board equipment.

To date, a sufficiently wide range of shock testing facilities is used in conducting the high-intensity shock tests (the exposure levels reach a few thousand "g"). These can be roughly divided into three groups:

- Mechanical shock testing facilities with a free falling Table and an accelerated Table drop.
- Mechanical pendulum (piling) shock testing facilities.
- Pyrotechnic testing facilities.

Mechanical shock test systems with a free falling Table and with an accelerated Table drop are focused mainly on setting the acceleration of the shock pulse.

Most often in Russia, there are shock testing facilities with a free falling Table produced by Lansmont (United States) and with an accelerated Table drop produced by Tira (Germany). In the RF Tira products under the brand VSTS gained wider distribution. The effectiveness of such facilities is determined primarily by the used programming tools as well as by the seismic mass and the type of seismic mass shock absorber. A significant drawback of the falling Table facilities is their dimensions (primarily the height of the stand) with relatively small desktop sizes for the subject equipment and their high cost. Merits include a wide range of reproduced acceleration pulses (both amplitude and duration) and relatively small "residual" noise (less than 20 per cent, which meets the requirements of domestic standards, e.g. [17]). Like the falling Table facilities, the Table with the accelerated drop of the Table is designed to create an acceleration pulse, but its dimensions are much smaller and, consequently, the working mass and instruments dimension ranges are not wide.

Pile shock stands were the first equipment to be used for shock testing. They have not changed in essence until today. The stand consists of a hammer, which creates the necessary shock input, a frame with a hammer suspension system fixing a braked anvil, a rotating traverse to fix the hammer, the counterweight, the anvil suspension system, the anvil for the installation of the subject equipment, the pneumodampers of the anvil and the hammer.

The levels of impact of the test object are determined by the impact velocity of the hammer against the anvil, its mass and braking mechanics, and by the mass of the test object mounted on the anvil. The shape of the impulse is determined by the size and shape of the striker, as well as the crusher installed between the hammer and the anvil. Such stands allow for the reproduction and input of nonstationary vibration. This is, for example, a well-known domestic stand K200 [18]. Pendulum shock test facilities are being further developed into stands with resonance panels and resonance beams. The merits of such facilities include the ability to test sufficiently massive and positional equipment in a wide range of impacts. Often, the stands are geared towards creating the necessary shock response spectra resulting from the nonstationary vibration caused by the impact. Shortcomings include the difficulty of adjusting and the size of the stands. Such stands are usually custom-designed and have high costs. It should be noted that the regulatory documentation does not recommend the use of such stands for testing the shock sensitive on-board equipment [19].

5. Conclusion

The decision to use the specific mechanical test facilities for the on-board equipment testing is taken by its developer based on the assessment of on-board equipment resistance to the impact (resulting from own experience and numerical modeling).

Most of the sources, both in our country and abroad, recommend the use of equipment shock test by pyrotechnic device when creating high intensity shock inputs which corresponds to the actual physics of the on-board equipment load and does not result in unreasonable loading of the equipment structure and components from the test methodology used [1, 2, 6, 9, 13, 16]. Methodologies and equipment for shock testing have now been developed with the use of a special pyrotechnic device [20–22]. The device has several regulatory parameters that create the desired shock input. These are
the thickness and material of the pin; mass, material and shape of the striker; the power of generator; the initial volume of the cavity; the piston stroke prior to the impact. With a large number of adjustable parameters it is possible to create shock inputs in all the required amplitude and frequency range given in Tables 2 and 3.

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