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Об альтернативном методе отработки динамической прочности конструкции малого космического аппарата

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В данной статье представлен анализ возможности применения альтернативного метода отработки на механические воздействия конструкции малого космического аппарата дистанционного зондирования Земли, имеющего изделие-аналог, прошедший полный цикл наземной экспериментальной отработки. Однако, несмотря на схожую силовую схему и максимальное заимствование бортовой аппаратуры с минимальными доработками, планируемый к отработке космический аппарат имеет ряд существенных отличий. Рассмотрено применение основных альтернативных методов в зарубежной и отечественной практике при наземной экспериментальной отработке космической техники, описаны их преимущества и недостатки. Приведены некоторые рекомендации принятия решений об отказе от применения традиционных методов наземной экспериментальной отработки космической техники на механические воздействия.

Анализ принятой в отечественной отрасли нормативно-технической документации в части уточнения перечня отработочных испытаний космических аппаратов, допущений применения расчетно-экспериментального метода к отработке динамической (вибрационной) прочности и анализ конструкции планируемого к отработке космического аппарата в сравнении с изделием-аналогом показал, что наиболее предпочтительным для отработки динамической (вибрационной) прочности является метод «протоквалификации». В соответствии с выбранным методом были определены задачи, которые позволят уточнить перечень отработочных испытаний объекта исследования.

Ключевые слова: вибрационная прочность, динамические испытания, наземная экспериментальная отработка, протоквалификация.

On an alternative method for testing the dynamic strength of a small spacecraft structure

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This article presents an analysis of the possibility of applying an alternative approach to testing the mechanical effects of the design of a small spacecraft for remote sensing of the Earth, which has an analog product that has passed a full cycle of ground experimental testing. However, despite the similar power *scheme and the maximum borrowing of onboard equipment with minimal modifications, the spacecraft planned for testing has a number of significant differences. The application of the main alternative strategies in foreign and domestic practice in the ground-based experimental development of space technology is considered, their advantages and disadvantages are described. Some criteria for decision-making on the rejection of the use of traditional methods of ground-based experimental testing of space technology for mechanical effects are given.*

The analysis of the normative and technical documentation adopted in the domestic industry in terms of clarifying the list of development tests of spacecraft, the assumptions of applying the computational and experimental method to the development of dynamic (vibration) strength and the analysis of the design of the spacecraft planned for testing in comparison with an analog product showed that the most preferred method of testing dynamic (vibration) strength is the strategy "protocol qualifications". In accordance with the chosen strategy, a list of tasks was defined that will clarify the nomenclature of the development tests of the research object.

Keywords: vibration strength, dynamic testing, in the ground experimental development, protoqualification.

Introduction

One of the main stages of the life cycle of a spacecraft (SC) is its ground-based experimental testing, and, as a rule, this is a very costly and time-consuming stage.

With the traditional approach to testing dynamic (vibration) strength, structural samples that have passed the certification tests are not allowed for flight operation. However, in foreign practice, alternative approaches are used that make it possible to reduce the list of samples used during development tests – test methods that, individually or in combination with other methods, can be used during testing.

At the same time, it is recognized that the use of alternative methods leads to a greater risk compared to the standard procedure regulated by the current regulatory documentation in industry, when the flight sample passes acceptance tests, and the qualification reserves are demonstrated on a separate sample corresponding to the type of tests during the final tests. The increase in risk with such testing methods can be compensated by more thorough design and finishing tests (DFT), an increase in project safety coefficients [1].

Working out methods

In foreign practice, according to [1-12], the following main alternative methods of experimental testing are used (it should be noted that these methods can be used at various levels of completing, including their various combinations

at levels of completing units: spacecraft as a whole, its subsystems or equipment):

1) redundancy method – a prototype (a mock-up corresponding to the type of testing) that has passed the test tests can be admitted to flight operation, provided that the risk is minimized by carrying out (if necessary) repair and restoration work, replacing dimensional and mass models of equipment with regular ones and provided that the prototype successfully passes acceptance tests;

2) method without certification tests – flight samples are subjected to acceptance tests for increased exposure levels (but below the qualifying exposure levels), while there is a risk that the remaining design resource may be insufficient (since there is no demonstration of qualification reserves);

3) the "protocol qualification" method – the first flight product is subjected to certification tests with some changes (softened loading levels are used with calculated support for the analysis of loading and structural strength of the product).

The acceptance of components that have passed the protoflight type tests is carried out based on the results of the analysis of the actually spent resource, which allows determining the need for restoration work.

Despite the fact that the criteria for deciding not to test in foreign practice, as a rule, are not defined and fixed and decisions are made on the basis of a detailed analysis in which increased safety coefficients can be used, there are still certain recommendations [1]:

– simplicity of design solutions (for example, static definiteness, geometric immutability), distribution and transfer of loads to substructures are simple and predictable. All possible load combinations are fully modeled and analyzed for all cases of the intended operation of the object under study;

– the design is similar in terms of the overall configuration, design features and load combinations of the previously successfully tested design of an analog product, provided that the calculation results are confirmed by measurements;

– successful DFT or tests of single elements that are considered difficult to analyze have been carried out, while the results of tests and calculations correlate well with each other.

Alternative methods of testing strength are also used in domestic practice. So, for example, V. D. Kureev, S. V. Pavlov, Yu. But. Sokolov (Research Institute named after A. But. Maximov, branch of the FSUE named after M. V. Khrunicheva) in their article described a promising scheme for the application of the protoflight approach in the ground-based experimental development of nanosatellites [13]. In the work of V. I. Kopytova and S. A. Orlov (JSC "Information Satellite Systems" named after Academician M. F. Reshetnev") considered the order of formation of flight test modes [14]. I. I. Zimin et al . in the article on the principles of building a unified space platform, it is proposed to carry out a full cycle of ground testing for submodules of a unified platform, and for subsequent platforms to reduce the amount of testing to the minimum required [15].

Analysis and selection of the working method

According to the current requirements of the regulatory technical documentation, all newly created, modernized spacecraft, as well as spacecraft for which the operating conditions have been fundamentally changed, are subjected to ground tests and the list of specific types of development tests includes dynamic (vibration) tests. However, it is possible to clarify (define) the list of specific types of development tests included in the comprehensive program of experimental testing.

Vibration strength testing includes design and experimental testing. Analysis of the requirements of vibration testing standards has shown that, despite the improvement of analytical strength testing methods using proven software systems (Nastran, Ansys, etc.), the criterion used as a basis for confirming the calculation is its experimental verification, and in some cases loading (shock load, vibration loading) is allowed to be carried out exclusively with experimental verification. However, in some cases, the same standards regulate assumptions that make it possible to clarify the list of development tests of spacecraft under certain conditions:

– availability of analog products on which the necessary development tests of the spacecraft have been carried out;

– correction of the calculated analysis of loading and strength according to the results of the experiment;

– the full volume of the autonomous testing of the components of the spacecraft;

– compliance with the requirements of the strength standards based on the results of the refined calculation of the design of the spacecraft;

– double margin of safety for structural elements modified in comparison with the analog product, but with the same power circuit, materials, manufacturing technologies, dynamic characteristics, etc.

The design and layout of the remote sensing SSC D33, unlike the SSC Aist-2D [16], despite a similar power scheme and maximum borrowing of onboard equipment with minimal modifications, has a number of fundamental differences:

– another set of target equipment for stereo shooting mode has been added to the remote sensing SSC;

– a significant redesigning of the installation scheme of the target equipment with the use of hinge attachment to the power platform of the device was carried out;

– a propulsion system has been added to the composition of the SSC D33 to maintain the parameters of the orbit during the entire period of existence in the working orbit.

A change in the composition of the target and supporting equipment, and, consequently, a change in the installation locations of the devices for the changed composition of the target and supporting equipment leads to a change in the mass-centering and stiffness characteristics of the SSC D33 compared with the SSC Aist-2D.

With the above differences from the analog product in accordance with the regulatory and technical documentation adopted, the assumption of the use of the computational and experimental method for testing the dynamic (vibration) strength of the SSC requires the development of a solution agreed with the customer and the parent institute, in which it is necessary to determine the method of confirming the dynamic (vibration) strength of the product, specify the order of work and clarification of the nomenclature of the development tests of the SSC assembly.

An analysis of various experimental testing methods in the EU and the USA shows that the most appropriate is the use of the "protocol qualification" method, which will potentially reduce the risk of insufficient resource after testing (compared with the method without certification tests), as well as potentially minimize the amount of repair and restoration work (compared with the backup method).

Confirmation of the goals and solutions of the tasks of testing the dynamic (vibrational) strength of the SSC D33 can be performed using the developed computational and experimental method. When implementing the computational and experimental method, the following works will be performed, which will clarify the list of development tests of the SSC D33:

– autonomous testing of spacecraft components (DFT);

– analysis of loads and strength according to the finite the finite element model (FEM) of the SSC D33 (in accordance with the operating conditions), developed on the basis of design documentation and the results of ground-based experimental testing on the strength of a product analog of the SCC Aist-2D;

– development of recommendations for the installation of sensor-converting equipment for monitoring the loading of a flight sample during its protocol qualification dynamic (vibration resistance) tests;

– determination of the modes of prequalification loading of the flight model of the SSC D33;

– conducting protocol-qualification dynamic (vibration-resistance) tests of the flight model of the SSC D33;

– correction of the calculated FEM of SSC D33, creation of a high-precision FEM of SSC D33, calculation of loads and strength according to the corrected high-precision FEM;

– determining the scope and carrying out repair and restoration work (if necessary);

– development of a conclusion on the strength of the SSCD33 and its admission to flight tests in terms of strength.

Conclusion

As a result of the analysis of the regulatory technical documentation adopted in the industry, as well as the analysis of the differences between the spacecraft design planned for testing for mechanical effects from an analog product that has successfully passed the full cycle of ground experimental testing, a method of computational and experimental testing of the dynamic (vibration) strength of the SSC D33 based on the "protocol qualification" method used in foreign practice was developed.

In order to be able to use an alternative method when working out the SSC D33, it is necessary to develop recommendations for design work, which can be presented as a demonstration of the calculation work with their correction based on the results of tests for protocol qualification levels of loading, confirmation of the sufficiency of the model resource after conducting the protocol qualification tests of the flight model of the SSC D33 with the definition of criteria by which further repair and restoration work (if necessary) can be made.

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