Study of Strength and Thermal Characteristics of University Nano-Satellites

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Abstract: This paper presents strength and thermal studies, as well as an analysis of the design material for the development of a nanosatellite model. By using the SolidWorks software environment, an effective solid-state finite-element model of a nanosatellite are developed, on the basis of which the stress-strain state of the nanosatellite is analyzed, as well as the criteria for evaluating the strength of nanosatellite structural elements made of composite materials. The strength reserves are determined, the maximum displacements of the structural elements are found. It is determined that the developed model of the nanosatellite meets the conditions of strength and thermal conditions.

Keywords: Nanosatellite, Spacecraft, Strength, Thermal regime, SolidWorks, Alloy, Solar flow

Introduction

Satellite technologies are of global importance in the social and economic development of the entire state as a whole, and also allow us to raise the information and space support systems of various countries to a high level. Along with large-budget serious devices, there are small ones called nanosatellites. Currently, satellite technology is being developed in miniature sizes and components up to a weight of 1 kg. The nanosatellite belongs to the class of small satellites with a mass of less than 10 kg [1,2].

Within the framework of small satellites, we should mention nanosatellites developed at universities for educational, scientific and technological purposes. The main objectives of these initiatives are:

1. engage students in complex teamwork aimed at designing, developing, and producing a complex product; thus training students ' ability to solve real-world problems;

Nurgizat, Y., Balbayev, G., & Bakhtiyar, B. (2021). Study of strength and thermal characteristics of university nano-satellites. In M. Shelley, W. Admiraal, & H. Akcay (Eds.), *Proceedings of ICEMST 2021-- International Conference on Education in Mathematics, Science and Technology* (pp. 108-117), Antalya, TURKEY. ISTES Organization.

2. for in-orbit testing of components and materials intended for ground use in order to reduce the cost of future space missions;
3. demonstrate the feasibility of innovative missions and system concepts [3].

The development and implementation of nanosatellites is one of the most promising areas of engineering and technology in the aerospace industry. Thanks to the continuous evolution, and with the preservation of low cost, small spacecraft (MCA) have become a flexible tool for conducting scientific, educational and technological experiments in outer space [1]. The strength analysis of spacecraft under random loads contains the computational-theoretical and experimental stages. The computational study involves the development of an adequate simulation model (IM) of a spacecraft subject to random vibrations, and the determination of the numerical characteristics of the stochastic stress-strain state on its basis [3].

In this article, we consider the problem of constructing a simplified model of the nanosatellite body and its finite element model for the strength analysis of the structure, and also perform a static calculation of the loading of the nanosatellite body, namely, thermal calculations.

Statistical calculation of the nanosatellite body strength

The resistance of the materials and equipment elements used in their creation to the effects of the surrounding space environment plays a crucial role in ensuring the long-term trouble-free operation of nanosatellites. According to the available expert estimates, more than half of the spacecraft failures and failures are caused by the adverse impact of the space environment [7]. The strength of the nanosatellite body provides additional requirements for the structural materials used in the manufacture of the body, namely:

1. high vibration and impact strength;
2. resistance to corrosion and abrasive wear;
3. high crack resistance at sharp and abrasive temperature changes.

Thus, according to [8], the ultimate tensile strength is an important criterion for any structural material. Figure 1 shows the typical stress-strain curves of four different aluminum alloys in uniaxial tensile tests compared to: -low

1. carbon steel;
2. high-strength steel;
3. titanium alloy.

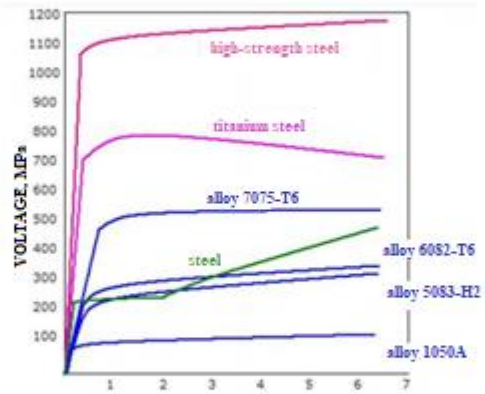

Figure 1. Curves of the stress-strain state of aluminum alloys in comparison with other structural materials [4]

In accordance with [4], with the strength that is achieved per unit mass, dividing the strength by the density, we get a completely different picture (Figure 2). With this approach, the most effective structural material for the model is aluminum alloy 7075, and alloys 5083-H12 and 6082-T6 will be more effective, relative to low-carbon steels.

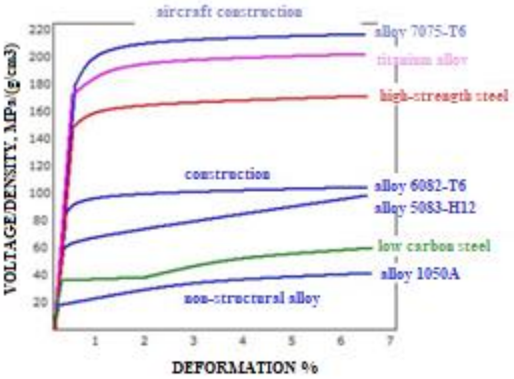

Figure 2. Strength per unit density of aluminum alloys and other structural materials [6]

Under static loads, during tensile testing, the ultimate strength (вb) or yield strength (σ0, 2,тt) - characterizes the resistance of the material to plastic deformation. To approximate the static strength, the hardness of HB is used. For materials used in aviation and space technology, the mass efficiency of the material is important [10].

The experimental sample is an element of full-scale structures of the nanosatellite body in the form of a cube, measuring 100mm*100mm*100mm, made of aluminum alloy with a thickness of 2 mm, the mass of the nanosatellite body is 300 g (see Figure 3).

The digital model is simplified in two stages.

Task of the first stage:

Removal from the model of all elements that do not contribute to the strength characteristics of the model, such as:

- fasteners;
- electronic elements with small dimensions;
- electrical connectors.

The main task of the second stage:

- correction of interference of parts.

Interference is observed for the following reasons:

- build errors of the original model;
- errors in the coupling of electronic components with the boards;
- errors in the holes of the boards.

To determine the force load on the body, the gravity force formula was taken (see formula 1) [5].

$$F = G\frac{m1m2}{(H+R)^2} \qquad (1)$$

From here,

$$F = 6{,}67 \cdot 10^{-11}\,\frac{0{,}3 \cdot 5{,}97 \cdot 10^{21}}{(6310 \cdot 160)^2}$$

$$F = 3\ [\text{кН}]$$

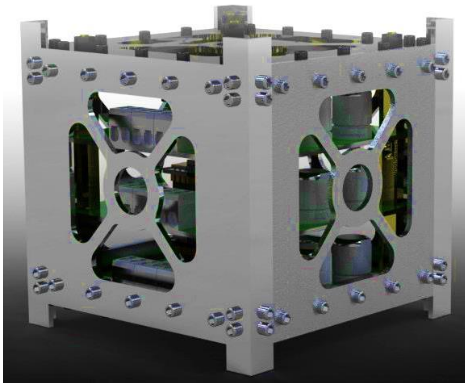

Figure 3. Initial model of the nanosatellite

The preliminary parameters of the nanosatellite body and the impact load were loaded into SolidWorks to determine the strength, see table 1.

Table 1. Parameters for performing calculations in SolidWorks

Load on the housing	**Housing parameters**	
Power-1=3 kN	**Objects:**	31 faces
	Reference:	Edge < 1 >
	Type:	To apply a force
	Values:	3 000 N

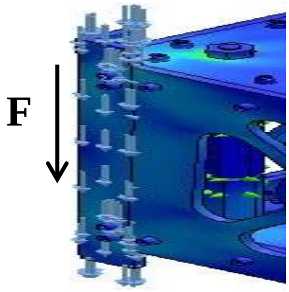

Figure 4. Nanosatellite framework in SolidWorks

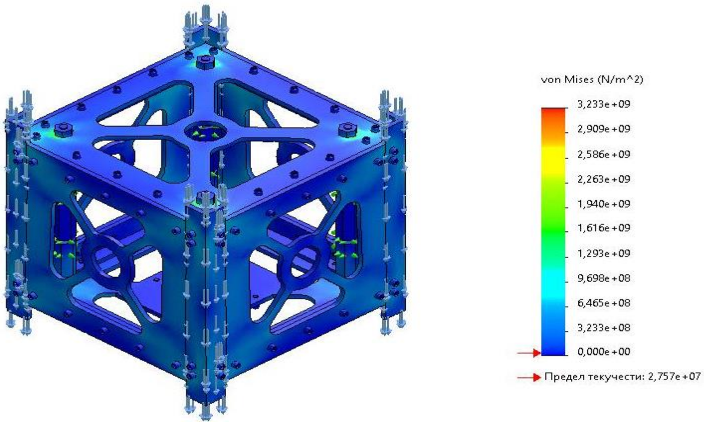

Figure 5. Statistical calculation

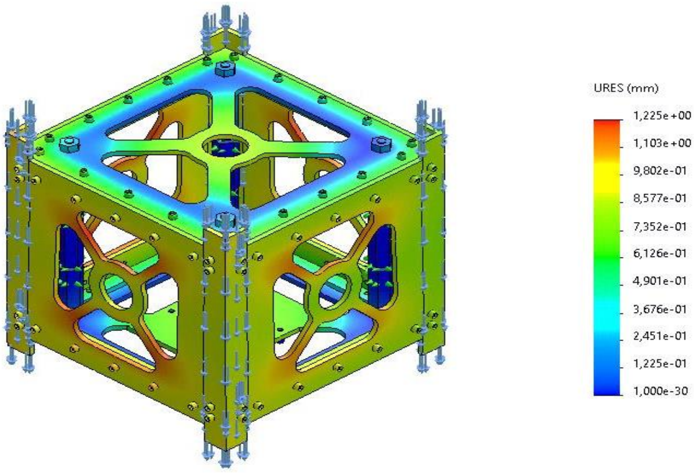

Figure 6. Statistical calculation of the displacement

As a result of this research on the analysis and selection of the most suitable design material for the development of a nanosatellite model, studies of the strength characteristics of aluminum alloys of various grades, a 3D model of a nanosatellite was constructed in SolidWorks. In statistical calculations, the displacement of the frame is equal to-1.225 mm.

Simulation of the thermal regime of a nanosatellite

In flight, the spacecraft is affected by a vast complex of factors of outer space that are different in their physical nature and origin: high-energy electron and ion fluxes, cosmic plasma, solar electromagnetic radiation, meteor matter, solid particles of artificial origin, etc. As a result of such an impact, various physical and chemical processes occur in the materials and elements of the spacecraft's onboard equipment, leading to a deterioration in their operational parameters. Depending on the nature of the processes initiated by the impact of the space environment, the changes in the properties of materials and equipment elements may have a different time scale, be reversible or irreversible, and pose a different danger to on-board systems.

Thermal control Module Objective of the satellite’s thermal control module is to maintain temperature for each module/component within its specified range during all the phases of this mission. In order to save on project costs, the thermal balance in the satellite shall be achieved through passive methods such as thermal coating, use of heat pipes, sunshades, integration of multi-layer insulation etc. The targeted range of temperatures for some of the modules are provided in the Table 2. Thermal design of nanosatellites is discussed in details in one of the current researches [11]. It is also concluded that a basic passive control should be adequate to maintain working temperature ranges for most of nanosatellite components using thermal coatings/tapes [11]. Use of heaters is recommended to keep batteries warm during extreme conditions. Thermal design of a Multi Mission Bus Demonstration (MBD) Spacecraft developed at The Johns Hopkins Applied Physics Laboratory (JHU/APL) is discussed in detail while providing details on the thermal testing performed in [12]. Bulut and Sozbir have proposed a thermal model and later designed a thermal control system of the nanosatellite emphasizing the importance of appropriate surface coating [13].

It is proposed that 80% of the CubeSat area shall be covered by the solar panels and the rest shall be covered by thermal coating. Sources of heat radiations in the Low-Earth-Orbit include, the heat radiated from the Sun, and Albedo or the reflection of solar radiation besides planetary heating from the Earth. During thermal design, Orbital variations in the solar activity shall also be considered. Few challenges are anticipated during thermal design and it will be interesting to analyze and devise newer methods to meet these problems. There shall be difficulties in maintaining required operating temperatures for batteries since they have smaller temperature range compared to other electronic components. The outer structure of the satellite is exposed to most extreme temperatures and therefore requires special considerations. Optical elements and Laser also requires thermal isolation and stable temperature control.

According to the nanosatellite assembly standard [11], the nanosatellite structure has the shape of a cube formed as a result of connecting four frames, six ribs and five solar panels. The power elements of the structure, represented by the ribs, are made of aluminum alloy (D16). The nanosatellite equipment is a set of electronic boards connected by a "bookcase" by means of rigid racks.

Table 2. Range of temperature

Modules	Operating Temperature		Survival Temperature	
	Min., °C	Max., °C	Min., °C	Max., °C
Structure	-45	150	-50	155
Power	0	50	-5	55
Magnetometer	-35	75	-40	80
IMU+GPS	-40	80	-45	85
Camera	0	60	-5	65
OBC	-25	60	-30	65
Antenna	30	70	-35	75

The main method of calculation of the thermal regime is the graphic-analytical method [12]. The task of calculating the thermal regime of a nanosatellite, as a rule, is to determine the temperature and temperature overheating of the components. Overheating of any point or area of the nanosatellite structure is the result of the superposition of the thermal fields of various IT (semiconductor crystals or resistors), so it consists of its own and induced overheating. Its own overheating is determined by the action of the IT located at the i-th point, provided that the other IT is turned off. Induced overheating is caused by the action of all IT, except for the one located at the i-th point.

As is known, the thermal circuit of a functional cell is a parallel connection of the thermal resistances of the boards and their connecting layers [6]. Therefore, the calculation of thermal modes of functional cells is reduced to the calculation of overheating it, located on the Board, in accordance with the thermal model. To obtain the calculation formulas for the construction of thermal models, we take the following data:

1) The altitude of the nanosatellite H=160 km;
2) The satellite's orbit is near-Earth;
3) The effect of various thermal loads on the nanosatellite during flight.

Two cases of operation of the thermal regime were considered:

1) when the nanosatellite is located in the shadow segment of the orbit;
2) when the nanosatellite is located on the solar side of the orbit.

The scheme of the nanosatellite flight in a given orbit for two limiting cases is shown in Figure 7 [4].

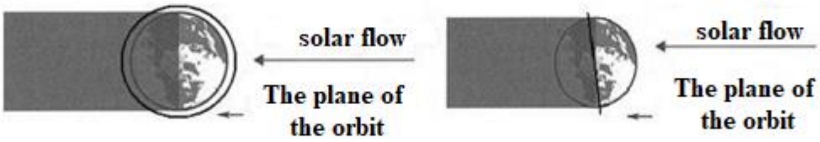

Figure 7. Orbital flight diagrams [4]

The calculation of thermal loads is performed for a three-dimensional model of a nanosatellite. The simulation was performed for several orbits in orbit. The thermal state of the nanosatellite was calculated using the Simulation SolidWorks environment. The finite element model of the nanosatellite is built automatically, and the load is applied consistently across all the faces and components of the nanosatellite. The results of the thermal calculation for the case with shadow areas are shown in Figure 8. The results of the thermal calculation for the case without a shadow area are shown in Figure 9.

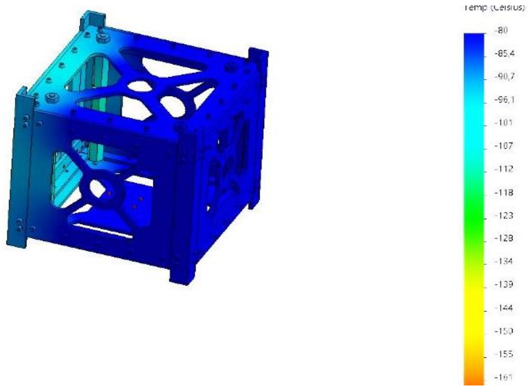

Figure 8. The result of calculating the nanosatellite in the shadow segment of the orbit

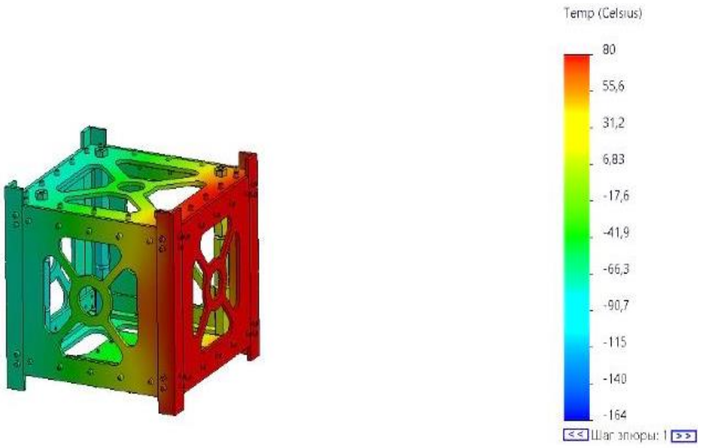

Figure 9. The result of calculating the nanosatellite in the shadow segment of the orbit

As a result, according to the conducted research, the most suitable thermal regime for the nanosatellite in different parts of the orbit was selected. Aluminum alloy is well suited for assembling the nanosatellite frame. It can withstand temperature loads from -80 C to +80 C.

Conclusion

This study will simplify the launch of small spacecraft into space, due to the insignificant requirements for the creation of a nanosatellite design. The analysis of criteria for assessing the strength of nanosatellite structural elements made of composite materials has been carried out. The strength reserves have been determined, the maximum displacements of the structural elements were found. It turned out that the conditions of strength and thermal conditions were met for the nanosatellite. In the SolidWorks software environment, an effective solid-state finite-element model of a nanosatellite was developed, on the basis of which the stress-strain state of the nanosatellite was analyzed.

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