The behavior of nanosatellite body materials during electromagnetic launch

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Abstract. Current development of aerospace technology and demands for the economic feasibility have led to a reduction in weight and size characteristics of the on-board electronics and other on-board equipment. There is a tendency to use small-scale spacecraft: midi-satellites, mini-satellites, nanosatellites etc. Reducing the weight and size characteristics of the satellites makes electromagnetic launching techniques more promising compared to traditional methods of sending payload into orbit. Electromagnetic launch does not require expensive space centers – it is cost-efficient, environmentally friendly and enables frequent low-cost launches.

1. Introduction

The aim of this work was to develop an effective approach to the calculation and analysis of the stress-strain behavior accounting for the thermal effect on a nanosatellite body under constant exposure to a concentrated particles stream.

The aim required solving the following objectives:

- to identify the nanosatellite body elements subjected to the greatest load and to determine the methods of improving the strength characteristics of these components;
- to determine the stress-strain behavior of a rigidly fixed structure element from OT 4 alloy (the most frequently used material in aircraft with the highest density and strength characteristics), when exposed to a concentrated stream of high-energy particles and mechanical load;

The approach used in this paper is based on the finite element method that allows solving the heat transfer and the strength theory equations to the best degree of accuracy, taking into account all conditions, such as non-linear temperature distribution and plastic deformation. The numerical calculation of the most loaded elements of the nanosatellite body was performed using the ANSYS software package. In the process of solving the thermal stress problem, a specialized macro for the ANSYS Mechanical APDL software package was created using the APDL language to determine the resulting temperature fields and the stress-strain parameters (at proton energies from 3 to 12 MeV with 1 MeV increment).

2. Identifying the most loaded zones of a nanosatellite body

According to [1], the most effective nanosatellite design is a streamlined shape with 1:10 elongation. This design is shown in Fig. 1; its basic characteristics are given in Table 1. The following additional parameters were used for the numerical modeling: 1:10 aerodynamic shape extension; titanium wrought alloys OT 4 as the body material; 5000 m altitude; 6000 m/s velocity.
**Figure 1.** Nanosatellite design

**Table. 1.** Nanosatellite main characteristics

| Parameter                | Value   |
|--------------------------|---------|
| Midship section diameter | 60 mm   |
| Skirt diameter           | 120 mm  |
| Total length             | 600 mm  |
| Head cone length         | 120 mm  |
| Cylinder length          | 450 mm  |
| Wall thickness           | 0.5 mm  |
| Total mass               | 10 kg   |

In case of the high velocity incident flow (6000 m/s) with compression shocks, the nanosatellite body can be divided into three zones with regard to its stress-strain behavior, as shown in Fig. 2 and 3.

**Figure 2.** Stress distribution along the aircraft case in accordance with the Huber-Mises theory of plastic yield in hypersonic flight (6000 m/s)
Figure 3. Stress distribution in the tail-end section of the aircraft case in accordance with the Huber-Mises theory of plastic yield in hypersonic flight (6000 m/s). Longitudinal cross-section.

One of the most loaded zones (zone 1) is located in the nose part of the nanosatellite hull. The form of this zone is affected by the incident stream velocity and depends on the position of the (compression) wave front determined by the incident flow velocity and the headcone divergence angle. According to Fig. 2, the compression stress values increase considerably following the first shock wave front.

Zone 2 is a very narrow area on the border of the nose cone and the cylindrical part of the body. Significant loads acting upon the fairing nose as well as the body inertia-loading component lead to stress-strain localization. The zone subjected to the greatest load is the aerodynamic skirt contour. This happens because the compression fronts overlap with the skirt contour. In the instance of a serious manufacturing error leading to the insufficient structural stiffness, elastic vibrations may occur in the nanosatellite. So, with the flow being unstable, the shock wave front will become asymmetric in the aerodynamic skirt area. That, in turn, causes a high gradient stress-strain on the skirt and additional aerodynamic vibration, which leads to an unsteady flight and consequently a crash.

The design process should take into account these stress-strain areas. For instance, the fairing and the aerodynamic skirt of the aircraft could be strengthened and a thermal protection shield added.

3. Estimating the protons stream effect

After determining the most loaded and, as a result, the weakest parts of the nanosatellite body during the electromagnetic launch, we need to consider these parts in detail and take into account the impact of the quasi-stationary concentrated stream of protons through a selected volume surface. The volume selection is dictated by the available computer operating memory and speed, as well as by the character of the stress-strain state in a given area. With the memory and performance level limited, all available resource must be used to the full. We can conveniently assume the selected volume to have a parallelepiped form. The following parameters appear to be most realistic: 140 mm length, 100 mm width and 5 mm thickness. The material is OT4 alloy.

To solve the thermal-strength problem we obtained temperature distribution in a plate exposed to 3 to 12 MeV protons stream, with 1 MeV increment. By way of illustration, Fig. 4 shows the temperature distributions for 3 MeV protons stream.
It is evident from the distributions that the temperature maximum is at the maximal penetration depth of the protons with the specified energy characteristics. This is due to the fact that the heat distribution is directly related to the protons stopping power. For clarity, we present the vertical temperature distributions for the combined energy values (Fig. 5).

We use the above results as initial conditions to determine the stress-strain behavior of the plate. The choice of the applied pressure is based on the extent of the incident flow effect on the aircraft.

The coordinate dependence of stress in the plate according to the Huber-Mises theory illustrates the magnitude of the emerging stresses and their distribution (see Fig. 6). It is evident that the maximal stresses occur within the protons stream zone (that is, in the center) and over the edges of the plate. The reason for this is that the center of the sample, apart from the mechanical stresses, is subjected to the thermal stresses from the heat of the protons beam. Stresses at the edges occur due to the rigid fixing conditions.

The stress distributions do not clearly indicate whether the stress-strain parameters are close to critical. For this purpose, we use the maximum strain criterion, which helps identify the point where a sample is most likely to fail, with the thermal and mechanical effects parameters specified. The maximum strain
criterion is defined as the ratio of the actual strain at a given point to the failure strain for this type of load. If the maximum criterion is greater than unity in at least one point of the test sample, the critical stresses occur at this point, which could lead to the entire sample failing. This criterion serves as the basis for the further analysis. By way of example, Fig. 7 shows the criteria distribution for 3 MeV protons streams.

The calculation results are summarized in a graph showing the maximum strain criterion as a function of the proton stream energy at the point of the maximum heat dissipation (Fig. 8). It is evident from the graph that the value of the maximum strain criterion is greater than unity for the 3-6 MeV protons stream.

![Maximum strain criterion, MeV](image)

**Figure 7.** The maximum strain criterion for 3 MeV protons stream

**Figure 8.** Maximum strain criterion as a function of the proton stream energy

### 4. Conclusion

In the course of research, the stress-strain behavior of a nanosatellite during launch was analyzed numerically and the highest risk areas were identified. We also performed the analysis of a rigidly fixed element (a rectangular plate made of the OT 4 alloy) that was simultaneously exposed to a pulsed proton beam and mechanical loading. We estimated the possibility for the stress-strain parameters of the material to reach the critical failure values.

### References

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