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Analysis of pulse-launched nanosatellite stability in the atmosphere

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Abstract. The article shows the effects of various aerodynamic parameters, the possibilities of their change are determined. The increase in the length of the lightweight stern, the diameter of the skirt and the thinning of the tube and skirt material improve the stability, but adversely affect the strength or aerodynamic properties of the product in question. The uniform distribution of mass over the nanosatellite volume is preferable in the process of acceleration with high-speed throw and exit from the railgun, but it negatively affects the stability in flight.

1. Introduction

The creation of nanosatellite cluster space systems (satellite weight below 10 kg) is a perspective trend in space technology development. The transition to small vehicles requires changes in the technology of satellite delivery into orbit.

One of the most effective ways to launch a nanosatellite is a pulse launch. Advantages of throwing satellites into orbit are widely discussed in the contemporary literature, for example, in [1] - [3]. In the long term this type of transport benefits economically, technologically and environmentally.

The nanosatellite is assumed to acquire an initial starting velocity in a pulse accelerator, and then a passive suborbital section of the path follows. In the process of a nanosatellite movement, its trajectory can be corrected according to the specified program by means of a correcting impulse device and an ion engine. The launch pad can be on the surface of the Earth, on a hill, or at heights of up to 40 km in an air start system.

In the paper, the main parameters of the nanosatellite structure providing stabilization in the atmosphere in the altitude range of 30-80 km above the Earth are investigated. Models with a continuous mass distribution over the volume of a nanosatellite and with a lightweight stern are considered.

2. Analysis of aerodynamic moments and forces

A nanosatellite is an axisymmetric high-fineness-ratio configuration body, stabilized in flight by an aerodynamic skirt. The aerodynamic scheme is shown in Figure 1. Nanosatellite dynamics is determined by the principal vector of aerodynamic forces and the moment with respect to a certain pole. In the body coordinates, the principal vector of aerodynamic forces can be decomposed into axial, normal and side components (in the wind coordinates - into the drug, lift and lateral forces, respectively) [4].

The calculation of flow parameters is defined by Reynolds and Knudsen numbers. The parameters of the atmosphere are defined according to the tables of the standard atmosphere [5]. Density $\rho$, temperature $T$, the air dynamic viscosity $\mu$ and the mean free path $\lambda$ are specified in the Table 1 for

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several points in altitude range. Relevant Reynolds $Re = \frac{\rho \cdot V \cdot l}{\mu}$ and Knudsen $Kn = \frac{\lambda}{\delta_{nopt}}$ numbers for a body of the length $l = 1.2$ m moving with the velocity $V = 8000$ m/s are given. According to [4], the thickness of the boundary layer reaches $\delta_{nopt} = 4.64 \frac{l}{\sqrt{Re}}$.

### Table 1.

| Altitude(km) | Density(kg/m$^3$) | Temperature(K) | Viscosity(mkPa·c) | Re     | Kn     |
|--------------|-------------------|----------------|-------------------|--------|--------|
| 30           | $1.84 \cdot 10^{-2}$ | 226.5          | 14.753            | $1.50 \cdot 10^{7}$ | 0.00307 |
| 40           | $4.00 \cdot 10^{-3}$ | 250.4          | 16.009            | $3.00 \cdot 10^{6}$ | 0.00632 |
| 50           | $1.03 \cdot 10^{-3}$ | 270.7          | 17.037            | $7.23 \cdot 10^{5}$ | 0.0121  |
| 60           | $3.10 \cdot 10^{-4}$ | 247.0          | 15.837            | $2.35 \cdot 10^{5}$ | 0.0228  |
| 70           | $8.28 \cdot 10^{-5}$ | 219.6          | 14.377            | $6.91 \cdot 10^{4}$ | 0.0463  |
| 80           | $1.85 \cdot 10^{-5}$ | 198.7          | 14.426            | $1.53 \cdot 10^{4}$ | 0.0980  |

The table shows that at altitudes up to 80 km the air molecule mean free path is much smaller than the thickness of the boundary layer and the calculation is made using the continuum model. At the preliminary stage, viscous friction and bottom resistance are not considered. These parameters are supposed to be considered in a selective numerical experiment.

Aerodynamic coefficients calculation is carried out according to the theory of Newtonian flow. Such a model leads to an estimate of the aerodynamic forces, which is in satisfactory agreement with the experiment in the hypersonic stream [4]. The aerodynamic coefficients of the nanosatellite are estimated in body coordinates, under hypersonic flow conditions.

The following parameters of the nanosatellite are used:

- The midsection diameter $d_{mid}$;
- Fore body length $X_1$;
- Cylindrical part length $X_{cyl}$;
- Bottom diameter $D_{s}$ and skirt length $H_s$.

The coefficient of pressure at the surface is calculated by the condition that the molecules of the incident flow lose momentum component normal to the surface:

$$p = 2 \sin \beta \cdot \cos \alpha - \sin \alpha \cdot \cos \beta \cdot \cos \gamma)^2,$$

where: $\beta$ is a local slope angle of streamlined surface to the nanosatellite axis; $\alpha$ is the angle of attack; $\gamma$ is the integration parameter equal to the angle between the plane of the angle of attack and the meridian plane. The range of $\gamma > \gamma_{Shadow}$ corresponds to the wind shadow area, it is marked by shading in Figure 1.
The formulae for the coefficients of axial and normal forces and pitching moment are [4]:

\[
\begin{align*}
C_R &= \frac{2}{S_{mid}} \int_0^l dx \cdot r \cdot \frac{\gamma_{shadow}}{\bar{\gamma}} \int_0^\gamma d\gamma \cdot \bar{p} \\
C_N &= \frac{2}{S_{mid}} \int_0^l dx \cdot r \int_0^\gamma d\gamma \cdot \bar{p} \cdot \cos \gamma \\
m_z &= \frac{2}{l \cdot S_{mid}} \int_0^l dx \cdot r \cdot \int_0^\gamma d\gamma \cdot \bar{p} \cdot \cos \gamma
\end{align*}
\]

(2)

where: \( r \) is the local radius of the axially symmetrical body; 
\( l \) is the length of nanosatellite.

The coefficients of axial \( C_R \) normal \( C_N \) forces and pitching moment \( m_z \) are calculated depending on the angle of attack \( \alpha \) in the body coordinates. The corresponding graphs are shown in Figure 2. The following parameters are chosen:

\( d_{mid} = 60 \text{ mm}; X_1 = 2d_{mid}; X_{cyl} = 10d_{mid}; X_3 = 1,1d_{mid}; D_s = 1,5d_{mid}. \) (3)

The graph \( C_R(\alpha) \) shows that growth of the wind shadow of the cylindrical skirt part slightly reduces the axial resistance of the incident stream. The knee on the graphs corresponds to the critical angle of attack \( \alpha_\ast \), where the wind shadow from the cylindrical part reaches the edge of the skirt. At the chosen fineness-ratio configuration \( \alpha_\ast \approx 1,7^\circ \). The graphs of the coefficient of axis force \( C_R \) at \( D_s = 1,3d_{mid} \) and \( D_s = 1,8d_{mid} \) are shown in the dashed lines. With increasing diameter of the skirt there is a significant increase in air resistance.
Figure 3.

The nature of the wind shadow influence on the nanosatellite dynamics in flight is clearly visible in the graphs of Figure 3. Figure 3a shows the dependencies of the pitching moment relative to the center of mass on the angle of attack for different geometric configurations (the proportions are shown in Figure 3c) of a 10-kg nanosatellite in the hypersonic flow with dynamic pressure 33 kPa. According to [5], the selected dynamic pressure corresponds to a flight at the altitude of 50 km at a speed of 8000 m/s. In the set of geometrical parameters (3) the diameter of aerodynamic skirt was varied. On Figure 3b the dependence of the stability coefficient on the angle of attack is shown at different diameters of the aerodynamic skirt: Dsk = 1.3dmid; 1.5dmid; 1.85dmid.

The moment of external aerodynamic forces relative to the center of mass is calculated by the formula:

\[ M_z = \left( m_z - C_N \cdot \frac{X_{CM}}{l} \right) \cdot l \cdot S_{mid} \cdot q, \]  

(4)

where:

- \( X_{CM} \) is a position of the center of mass relative to nanosatellite fore body;
- \( q = \frac{\rho \cdot V^2}{2} \) is the dynamic pressure.

Factor of static stability is calculated by the formula [4]:

\[ S = \frac{X_{CM}}{l} \cdot \frac{m_z}{C_N}, \]

Graphs in Figure 4 show that the necessary stability of the nanosatellite is provided by a significant diameter of the skirt.

Another parameter that allows varying streamlining of the nanosatellite in flight is the shape of skirt. Figure 4a shows the dependence of the axial force on the angle of attack. The length of the skirt is increased from sample 1 to 3 by means of decreasing the cylindrical part while retaining all other dimensions, as it is shown in Figure 4c. Graphs in Figure 4b show the dependence of the corresponding coefficients of stability. A comparison of the graphs suggests that improving the flow conditions of the skirt leads to regimes with loss of stability.
Figure 4.

Thus, with a continuous mass distribution, an acceptable stability of a nanosatellite is ensured by the deterioration of the flow patterns.

3. Dependence of the stability coefficient on the nanosatellite layout

An alternative way to ensure the nanosatellite stability is the displacement of the center of mass relative to the pressure center by redistribution of the mass and selection of the lightweight stern of the length $X_{\text{light}}$, as shown in Figure 5. The average material density of the working compartment and the walls of the lightweight part is assumed to be equal to 6000 kg/m$^3$. The average weight of the lightweight part varies due to the average density $\rho$; the wall thickness is assumed to be 2 mm. Fuel and oxidizer is located in the stern for changing the orbit and reducing the bottom resistance.

Graphs in Figure 5 show the static stability coefficient dependence on the angle of attack for different ratios between the geometric characteristics of a nanosatellite with a lightweight stern.

Basic set of parameters ($d_{\text{mid}} = 60$ mm; $X_1 = 2d_{\text{mid}}$; $X_{\text{cyl}} = 10d_{\text{mid}}$; $X_s = 1.1d_{\text{mid}}$; $D_s = 1.5d_{\text{mid}}$) was varied while mass (10 kg) and density (6000 kg/m$^3$) were constant.
Figure 5.

The Figure 5a shows graphs of the stability coefficient dependence on the angle of attack for different lengths of the lightweight stern $X_{\text{light}} = 0, 1.5 \, d_{\text{mid}}, 3 \, d_{\text{mid}}$. From the graphs it is seen that without a lightweight cylindrical part, stability is acceptable in the range of angles of attack up to $\alpha \approx 5^\circ$; at $X_{\text{light}} = 1.5 \, d_{\text{mid}}$ it is up to $8^\circ$, at $X_{\text{light}} = 3 \, d_{\text{mid}}$ the acceptable range is more than $12^\circ$.

Each curve in Figure 5b corresponds to the particular fineness-ratio configuration. The structure length is increased by $\lambda = 0.8, 1.2, 1.5$ due to the reduction of the midsection, while the total mass of the nanosatellite and the density of the material remain constant.

Figure 5c shows the effect of mass redistribution in a nanosatellite while reducing thickness of the lightweight central shell.

4. Conclusion

The article shows the effects of various aerodynamic parameters, the possibilities of their change are determined. The increase in the length of the lightweight stern, the diameter of the skirt and the thinning of the tube and skirt material improve the stability, but adversely affect the strength or aerodynamic properties of the product in question [1], [6]. The uniform distribution of mass over the nanosatellite volume is preferable in the process of acceleration with high-speed throw and exit from the railgun, but it negatively affects the stability in flight.

The tasks to be solved in the following works: development of a rational aerodynamic scheme and layout; the problem of the nanosatellite stability in the orbit.
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