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MATHEMATICAL MODEL FOR SELECTING THE AUXILIARY EQUIPMENT PARAMETERS OF AERODYNAMIC DEORBIT SYSTEMS

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Мета статті – розробка моделі для вибору проектних параметрів допоміжних систем аеродинамічних систем відведення з орбіти. Для нормальної роботи аеродинамічна система відведення з орбіти, залежно від її класу, оснащується такими системами забезпечення: розгортання; надування і зберігання на борту космічного об'єкта, що знімається з орбіти. Система розгортання аеродинамічних систем, що розгортаються, складається з двох компонентів: системи розгортання щогл, в якій зберігаються і розгортаються чотири скручені щогли, і шпинделя зберігання аеродинамічного крила, на який намотуються чотири квадранти плівкового матеріалу. Надування аеродинамічних систем може здійснюватися кількома способами: за допомогою системи зберігання і подачі газу в оболонку; за допомогою залишкового тиску; за допомогою сублімації порошкоподібної речовини. Наведено характеристики сублімованих речовин та інертних газів для надування. Наведено методику визначення параметрів газу для надування з урахуванням впливу фрагментів космічного сміття на аеродинамічну систему. До матеріалів, що використовуються для виготовлення системи зберігання аеродинамічної системи відведення, висуваються такі вимоги: стійкість матеріалу до дії космічних чинників; стійкість до динамічних навантажень на етапі виведення космічного об'єкта на орбіту; стійкість до температурних деформацій матеріалу. Розроблено математичну модель вибору параметрів допоміжних систем аеродинамічних систем для зведення космічних об'єктів з орбіти. Ця модель включає: оцінку маси системи розгортання; залежності для визначення маси системи надування аеродинамічних систем різних конфігурацій; оцінку товщини матеріалу газового балона різних конфігурацій; залежності для визначення маси системи зберігання аеродинамічної системи відведення з орбіти різних конфігурацій.

Ключові слова: *космічний об'єкт, аеродинамічна система відведення з орбіти, допоміжні системи, проєктні параметри, математична модель.*

The goal of this work is to develop a model for selecting the design parameters of auxiliary equipment for aerodynamic deorbit systems. For normal operation, an aerodynamic deorbit system, according to its class, is equipped with the following support systems: for deployment, inflation, and storage onboard the space object to be deorbited. The deployment system consists of two components: a mast deployment system, in which four rolled-up masts are stored and deployed, and an airfoil storage spindle, on which four quadrants of a film material are wound. Aerodynamic systems can be inflated in several ways: using a system of gas storage and supply to the shell, using the residual pressure, or using the sublimation of a powder substance. The characteristics of sublimable substances and inert gases for inflation are given. The paper presents a methodology for determining the inflating gas parameters taking into account the exposure of the aerodynamic system to space debris fragments. The following requirements are imposed on the storage system materials: resistance to space factors, resistance to dynamic loads in orbital injection, and resistance to thermal deformations. A mathematical model for selecting the auxiliary system parameters of aerodynamic deorbit systems is presented. This model includes deployment system mass estimation, relationships for determining the inflation system mass for aerodynamic systems of various configurations, wall thickness estimation for gas cylinders of different configurations, and relationships for determining the storage system mass for aerodynamic deorbit systems of different configurations.

Keywords: *space object, aerodynamic deorbit system, auxiliary equipment, design parameters, mathematical model.*

Introduction. For normal operation, the aerodynamic deorbiting system (ADS), depending on its class, is equipped with the following support systems: deployment; inflation and storage on board the space object being deorbited.

The deployment system is used in the case of deployable aerodynamic systems, it consists of a set of auxiliary mechanisms required to extend the mast to which the thin-film membrane is attached.

For issues related to the inflation system, inflatable structures can be separated into three primary categories [1]: continuously inflated (CI) structures that need to maintain gas pressure over the life of the mission, rigidized inflatable (RI) structures that require inflation gas only during the initial deployment, and single inflation (SI, nonrigidized in this context) devices, such as the Apollo flotation collars and Mars Pathfinder landing bags. CI structures will invariably leak, necessitating gas replenishment throughout the mission. It is not expected that a SI system concept will prove optimum for the range of sizes and categories anticipated for these inflatable structures and devices.

In general, an optimum inflation gas will meet the following criteria, providing guidance for initial screening of candidate inflation gases and their storage/supply systems [1]: 1) low molecular weight, 2) noncontaminating to the spacecraft instrumentation and environment, 3) noncondensing within the anticipated range of operating temperatures and pressures (either in the structure or supply system), 4) nonreactive with structural elements, and 5) reliably and controllably deliverable from a low-mass, high-density storage system.

The storage system is a container in which the ADS is placed in a folded form with a closed lid, and when it is necessary to move away, the lid is unchecked, the aerodynamic element is deployed and the space object starts to move away from the orbit.

1. Deployment system parameters

The deployment system of deployable aerodynamic systems consists of two components: a deployable mast deployment system in which the four twisted masts are stored and deployed, and an airfoil storage spindle around which the four quadrants of film material are wound. The deployment system of deployable masts consists of coils, pressure rollers and an electric drive. Thus, the mass of the deployment system m_{DS} is determined using the following expressions:

$$m_{DS} = m_C + m_{PR} + m_S + m_{ED} \,, \qquad (1)$$

where m_C is the mass of coils on which deployable masts are wound; m_{PR} is the mass of pressure rollers; m_S is the mass of the spindle on which the aerodynamic element is wound; m_{ED} is the mass of the electric drive that starts the deployment mechanism. We assume that deployable aerodynamic systems have similar deployment mechanisms.

2. Inflation system parameters

Inflation of the ADS can be carried out in several ways:

– a) with the help of a gas storage and supply system to the shell;
– b) using residual pressure;
– c) with the help of sublimation of a powder substance.

When using the first method, the mass of the inflation system m_{IS} is determined by the sum of the gas mass m_G and the mass of the gas storage and supply system to the shell m_{GSSS}:

$$m_{IS} = m_G + m_{GSSS} \,. \qquad (2)$$

When using the second and third methods, the mass of the inflation system will be determined by the gas mass m_G or the mass of the powder substance m_{PS}, respectively:

$$m_{IS} = m_G = m_{PS} \,. \qquad (3)$$

The gas mass m_G required to ensure the excess pressure p_{EP} of the inflatable element with a volume $V_{НЭ}$, is determined from the Clapeyron-Mendeleev equation [2]:

$$p_{EP}V_{IE} = \frac{m_G}{\mu_G} R_0 T_{atm}\ , \tag{4}$$

$$m_G = \frac{p_{EP}V_{IE}\,\mu_G}{R_0 T_{atm}}\ , \tag{5}$$

where $\mu_Г$ is the molecular mass of the gas; R_0 is the universal gas constant, $R_0 = 8{,}31 Дж/(моль \cdot К)$; $p_{ИД}$ is the excess pressure in the shell, which is determined by the formula [3]:

$$p_{EP} = \frac{\rho_{atm}V^2}{2}\ , \tag{6}$$

where $\rho_{атм}$ is the atmospheric density; V is the spacecraft velocity.

When choosing a gas for inflation, it is necessary to take into account the peculiarity of the neutrality of the gas to the material of the shell of the aerodynamic element of the system. For space inflatable systems with a forced inflation method, inert gases can be used, which are used in rocket engine supercharging systems, the molar masses of which are given in Table 1.

Table 1 – Molar masses of inert gases for inflating

Gas	Helium	Neon	Argon	Xenon
Molar mass, mol/kg	4.003	20.179	39.948	131.29

The successful use of powder substances for inflating space inflatable systems was demonstrated on the Echo spacecraft [4]. Substances whose characteristics are listed in Table 2 can be used as sublimating substances.

When choosing a substance for inflation, it is necessary to take into account a number of nuances: it should correspond to the requirements for pressure and temperature; the melting temperature must be higher than any temperature expected while the ADS is packed inside the container to prevent liquid flow that could unbalance the spacecraft payload; the lowest molecular weight should be chosen to minimize weight requirements; it must be non-toxic for safe use.

Table 2 – Characteristics of sublimable substances for inflating

Substance	Molecular weight	Density $\mathrm{kg/m^3}$	Melting point, K	Boiling point, K	Sublimation parameters	
					Heat of sublimation, $\frac{\mathrm{J}}{\mathrm{kg\times K}}$	Vapor pressure, $\log p = A' - \frac{B'}{T}$
d-Camphor	152.23	1000	451.5	477	5.073×10^{8}	$26.571-\frac{6090}{T}$
Naphthalene	128.16	1145	353.22	490.9	6.739×10^{8}	$31.948-\frac{8326}{T}$
Benzoic acid	122.12	1265.9	394.7	602.22	6.848×10^{8}	$29.595-\frac{8223}{T}$
Anthracene	178.22	1250	490	627	10.339×10^{8}	$36.530-\frac{12436}{T}$
Anthraguinone	208.2	1419	559	652	12.307×10^{8}	$40.145-\frac{15206}{T}$

The mass of the powder substance m_{PS} is calculated according to the formula:

$$m_{PS} = \frac{p_{EP} V_{SI} \mu_{PS}}{R_0 T_{atm}}, \quad (7)$$

where μ_{PS} is the molecular mass of the powder substance.

With the forced inflation method, the shell is inflated by supplying gas from the gas storage tank. The mass of the gas storage and supply system m_{GSSS} is determined using the expressions:

$$m_{GSSS} = m_{GSC} + m_{GSS} + m_G, \quad (8)$$

where m_{GSC} is the mass of the gas storage container; m_{GSS} is the mass of the gas supply system to the shell, according to [5], for a single-component gas, it has been accepted $m_{СПГ} = 0.01\ldots0.2$ kg.

When moving in low Earth orbits, the inflatable elements of the ADS are exposed to fragments of space debris, which, when interacting with the shell, form holes in it and thus break the airtightness of the inflatable element. When designing the inflating system of the aerodynamic system, it is necessary to assess the influence of fragments of space debris (FSD).

The assessment of the effect of FSD on ADS is carried out using the algorithm:

– determination of the minimum size of the FSD $d_{\min}$ capable of penetrating the shell thickness δ;

– calculation of the collision frequency N of the ADS shell with the FSD;

– assessment of pressure losses in the ADS shell.

To determine the minimum size $d_{\min}$ of the FSD capable of penetrating a shell with a thickness δ, the ballistic equation [1] is solved:

$$d_{\min} = \left(0{,}106022 \cdot t \cdot H_B^{1/4} \cdot \sqrt{\rho_t / \rho_p} \cdot (c/V)^{2/3}\right)^{0{,}947368}, \quad (9)$$

where $d_{\min}$ is the FSD diameter; H_B is the Brinell hardness of the target material; ρ_t, ρ_p are the densities of FSD and film materials; c is the sound velocity in FSD material, for aluminum $c = 5{,}1\,\text{km/s}$; V is the FSD velocity (average velocity is $V \approx 10\,\text{km/s}$).

On the basis of the found value, the frequency of collisions of the ADS shell with the FSD is calculated [1]:

$$N = S_П \cdot Q(d_i), \quad (10)$$

$$d_{\min} \le d_i \le d_{\max}, \quad (11)$$

where $S_П$ is the surface area of the inflatable elements of the ADS; $Q(d_i)$ is the average flow of FSD with a diameter at a given flight altitude, calculated using the MASTER-2009 space debris environment model [6]; $d_{\min}, d_{\max}$ are the minimum and maximum size of FSD in MASTER-2009.

After that, an assessment is held of pressure losses inside the ADS shell due to the effect of FSD during t_L. Based on the values d_i and the calculated flow $Q(d_i)$ for the ADS with the surface area S_{SA} of the inflatable elements, the area of the formed holes S_H in the shell is calculated over time t_L

$$S_H = \int_0^{t_L} \sum_{i=1}^{n} \frac{\pi d_i^2}{4} \cdot N(d_i)\, dt, \quad (12)$$

where d_1 is the minimum size, $d_1 = d_{\min}$; d_n is the maximum size of FSD, the flow of which is calculated using MASTER-2009; $N(d_i)$ is the frequency of collisions of the diameter FSD with the shell, which is determined from the expression [1]:

$$N(d_i) = Q(d_i) \cdot S_{SA}, \quad (13)$$

where $S_П$ is the surface area of the ADS shell.

The amount of gas that can flow out of the opening with the area S_O of the inflatable element of the ADS is obtained by the formula [7]:

$$\Delta_3 = \int_{t_0}^{t_L} \frac{1}{\sqrt{2\pi R}} \left(\frac{p_1}{\sqrt{T_1}} - \frac{p_2}{\sqrt{T_2}} \right) S_0\, dt, \quad (14)$$

where p_1, p_2 is the gas pressure in the shell and exosphere, respectively; T_1, T_2 are the temperatures of gas in the shell and exosphere, respectively; R – universal gas constant, $R = 8{,}3144621 \dfrac{\text{m}^2 \times \text{kg}}{\text{s}^2 \times \text{K} \times \text{Mol}}$. To determine the weight of the ADS inflation system of various configurations, Table 3 shows the main dependencies.

Table 3 – Relationships for determining the mass of the inflation system of aerodynamic systems of various configurations

ADS configuration	The mass of the inflation system
«Sphere»	$m_{IS}=\dfrac{\left(\dfrac{\rho_A V^2}{2}\right)\left(0.755\sqrt{S_M^3}\right)\mu_G}{R_0 T_A}+m_{GSSS}$
«Round shield»	$m_{IS}=\dfrac{\left(\dfrac{\rho_A V^2}{2}\right)\left(0.01\sqrt{S_M^3}\right)\mu_G}{R_0 T_A}+m_{GSSS}$
«Dihedral panels»	$m_{IS}=\dfrac{\left(\dfrac{\rho_A V^2}{2}\right)\left(0.011\sqrt{S_M^3}\right)\mu_G}{R_0 T_A}+m_{GSSS}$
«Prism Triangle»	$m_{IS}=\dfrac{\left(\dfrac{\rho_A V^2}{2}\right)\left(0.017\sqrt{S_M^3}\right)\mu_G}{R_0 T_A}+m_{GSSS}$
«Prism Square»	$m_{IS}=\dfrac{\left(\dfrac{\rho_A V^2}{2}\right)\left(0.015\sqrt{S_M^3}\right)\mu_G}{R_0 T_A}+m_{GSSS}$
«A cone made of tori»	$m_{IS}=\dfrac{\left(\dfrac{\rho_A V^2}{2}\right)\left(\sum_{n=1}^{k}V_{TO_n}\right)\mu_G}{R_0 T_A}+m_{GSSS}$
«A cone made of tori with spheres placed inside»	$m_{IS}=\left(\sum_{n=1}^{k}m_{IS}=\dfrac{\left(\dfrac{\rho_A V^2}{2}\right)V_{S_n}\mu_G}{R_0 T_A}\right)+m_{GSSS}$
«Bulk sail»	$m_{IS}=\left(\sum_{n=1}^{v}\dfrac{\left(\dfrac{\rho_A V^2}{2}\right)V_{IE_n}\mu_G}{R_0 T_A}\right)+m_{GSSS}$

Table 3.4 shows: m_{IS} is the mass of the inflation system; ρ_A is the atmospheric density; V is the orbital velocity of the SO; S_M is the cross-sectional area; μ_G is the molecular weight of the gas for inflation; R_0 is the universal gas constant; T_A is the atmospheric temperature; m_{GSSS} is the weight of the gas storage and supply system to the inflatable element of the system; V_{TS_n} is the volume of the n-th torus, is determined by the following expression:

$$V_{TS_n}=2,467 d_{T_n} d_{SO}^2, \qquad (15)$$

where d_{T_n} is the diameter of the n-th torus; d_{SO} is the diameter of the deorbit space object; V_{IE_n} is the volume of the n-th inflatable element, in this case it is the volume of the spherical shell and is determined by the expression:

$$V_{IE_n} = 0,5236 d_s^3, \tag{16}$$

where v is the total number of spherical shells, which is determined by the following ratio:

$$\upsilon = n_{SIS} + n_{STS}, \tag{17}$$

$$m_{GSSS} = m_{GSC} + m_{GSS}, \tag{18}$$

$$m_{GSC} = S_{SA}^{GSC} \cdot \delta_M^{GSC} \cdot \rho_M^{GSC}, \tag{19}$$

$$m_{GSS} = m_{PR} + m_{PS} + m_V, \tag{20}$$

where n_{SIS} is the number of spheres placed in the inflatable shield; n_{STS} is the number of spheres placed in the torus shell; m_{GSSS} is the mass of the gas storage and supply system for inflation; m_{GSS} is the mass of the gas supply system for inflation; m_{PR} is the mass of the inflation pressure regulator; m_{PS} is the mass of pressure sensors; m_V is the mass of the valves; V_{IE} is the volume of AE inflatable elements; m_{GSC} is the mass of the gas storage cylinder; δ_M^{GSC} is the thickness of the gas cylinder material; ρ_M^{GSC} is the density of the material from which the gas cylinder is made.

We assume that the gas cylinder has several configurations: sphere, torus, cylinder. The working pressure in the cylinder is orders of magnitude higher than the ambient pressure, and the thickness of the cylinder material is calculated according to the momentumless theory. Formulas for calculating material thickness δ_M^{GSC} and surface area S_{SA}^{GSC} of gas cylinders of different configurations are shown in Table 4 [8].

Table 4 – Material thickness of gas cylinder in different configurations

Gas cylinder shape	Cylinder material thickness, m	Surface area of the cylinder, m^2
Cylinder	$\delta_M^{GSC} = \frac{p_{WP} d_{GSC}}{2\sigma}$	$S_{SA}^{GSC} = 1.57 d_{GSC}^2 + 3,142 d_{GSC} l_{GSC}$
Torus	$\delta_M^{GSC} = \frac{p_{WP} d_{GSC} (d_T - d_{GSC})}{2\sigma(d_T - d_{GSC})}$	$S_{SA}^{GSC} = 9.87 d_T d_{CS}^{GSC}$
Sphere	$\delta_M^{GSC} = \frac{p_{WP} d_{GSC}}{4\sigma}$	$S_{SA}^{GSC} = 3.142 d_{GSC}^2$

The formulas in Table 4 indicate: d_{GSC} is the diameter of the cylinder; p_{WP} is the working pressure in the cylinder; σ is the tensile strength of the cylinder material; d_T is the torus diameter; l_{GSC} is the length of the cylinder; d_{CS}^{GSC} is the cross-sectional diameter of the torus cylinder.

The practice of designing gas cylinders for launch vehicle propulsion systems shows that aluminum and titanium alloys [9] are used for their manufacture, the characteristics of which are given in Table 5.

3. Storage system parameters

The following requirements are imposed on the materials used to manufacture the ADS storage system: material resistance to space factors; resistance to dynamic loads at the stage of launching a space object into orbit; resistance to temperature deformation of the material. Material selection and assessment of the possibility of its use at the initial stages of design is based on the analysis of some basic material characteristics, such as parameters characterizing strength and stiffness properties, and mass characteristics. A variety of metal alloys, polymeric and composite materials are used in the design of space technology elements. Table 5 shows some characteristics of the main structural materials.

Table 5 – Characteristics of structural materials of rocket and space technology

Material	Density $\rho, \mathrm{kg/m^3}$	Modulus of elasticity σ_{np}, Pa
Metals		
Aluminum alloys		
AlMg-6 [10]	2640	7.1×10^{9}
1420 [10]	2470	7.5×10^{9}
1460 [10]	2600	8×10^{9}
2090 [10]	2590	7.6×10^{9}
8090 [10]	2560	7.7×10^{9}
Titanium alloys		
Ti–6Al–4V [11]	4430	1.14×10^{11}
Ti-5Al-2Sn-2Zr-4Mo-4Cr [12]	4650	1.15×10^{11}
Ti–10V–2Fe–3Al [13]	4650	1.1×10^{11}
Ti–5.5Al–3.5Sn–3Zr–1Nb [14]	4540	1.25×10^{11}
Composite materials		
Honeycomb structures with aluminum filling [15]	37	1.1×10^{11}
Carbon fiber plastics [16]	1500	1.8×10^{11}
Fiberglass plastics [16]	2100	5.7×10^{10}

To determine the mass of the storage system, we will assume that it is made in the form of a cube. The parameters of the storage system are determined by the volume of the aerodynamic element in the folded state and the volume of the material of the inflating system. In general, the mass of the storage system m_{SS} is calculated using the following relationship:

$$m_{SS} = 6\left(\sqrt[3]{V_{MIE} + V_{MDE} + V_{GSSS}}\right)^2 \cdot \delta_{MSS} \cdot \rho_{MSS}\,, \quad (21)$$

where V_{MIE} is the volume of material of inflatable elements; V_{MDE} is the material volume of deployable elements; V_{GSSS} is the volume of the gas storage and supply system to the inflatable element; δ_{MSS} is the thickness of the storage system material; ρ_{MSS} is the density of the storage system material. We assume that at the initial design stage of the ADS, the material thickness of its onboard storage system is the same as the material thickness of the structure of the space object being deployed. Table 6 shows the main dependencies for determining the mass of the ADS storage system of various configurations.

Table 6 – Dependencies for determining the weight of the ADS storage system of different configurations

ADS configuration	Weight of the storage system
«Sphere»	$m_{SS} = 6\delta_{MSS}\rho_{MSS}\left(\sqrt[3]{4S_M\delta_{MIE} + V_{GSSS}}\right)^2$
«Round shield»	$m_{SS} = 6\delta_{MSS}\rho_{MSS}\left(\sqrt[3]{1.224S_M\delta_{MIE} + 1.388S_M\delta_{MDE} + V_{GSSS}}\right)^2$
«Dihedral panels»	$m_{SS} = 6\delta_{MSS}\rho_{MSS}\left(\sqrt[3]{1.06S_M\delta_{MIE} + 1.5S_M\delta_{MDE} + V_{GSSS}}\right)^2$
«Prism Triangle»	$m_{SS} = 6\delta_{MSS}\rho_{MSS}\left(\sqrt[3]{1.344S_M\delta_{MIE} + 2.657S_M\delta_{MDE} + V_{GSSS}}\right)^2$
«Prism Square»	$m_{SS} = 6\delta_{MSS}\rho_{MSS}\left(\sqrt[3]{1.342S_M\delta_{MIE} + 2.654S_M\delta_{MDE} + V_{GSSS}}\right)^2$
«A cone made of tori»	$m_{SS} = 6\delta_{MSS}\rho_{MSS}\left(\sqrt[3]{(S_{SATS} + S_{SAIM})\delta_{MIE} + V_{GSSS}}\right)^2$
«A cone made of tori with spheres placed inside»	$m_{SS} = 6\delta_{MSS}\rho_{MSS}\left(\sqrt[3]{(S_{SATS} + S_{SAIM} + S_{SAS}\cdot k)\delta_{MIE} + V_{GSSS}}\right)^2$
«Bulk sail»	$m_{SS} = 6\delta_{MSS}\rho_{MSS}\left(\sqrt[3]{(S_{SATS} + S_{SAIM} + S_{SAS}\cdot \upsilon)\delta_{MIE} + V_{GSSS}}\right)^2$

Table 6 shows: S_{SATS} is the surface area of the torus shells; S_{SAIM} is the surface area of the inflatable masts; S_{SAS} is the surface area of the sphere shell which placed inside in the torus shell; k is the sphere shell number in ADS «A cone made of tori with spheres placed inside»; υ is the sphere shell number in ADS «Bulk sail».

Conclusions. For normal operation, the aerodynamic deorbiting system, depending on its class, is equipped with the following support systems: deployment; inflation and storage on board the space object being deorbited. The deployment system of deployable aerodynamic systems consists of two components: a deployable mast deployment system in which the four twisted masts are stored and deployed, and an airfoil storage spindle around which the four quadrants of film material are wound. Inflation of the aerodynamic systems can be carried out in several ways: with the help of a gas storage and supply system to the shell; using residual pressure; with the help of sublimation of a powder substance. Characteristics of sublimable substances and inert gases for inflating are shown. A methodology for determining the parameters of the gas for inflation is presented, taking into account the effect of space debris fragments on the aerodynamic system. The following requirements are imposed on the materials used to manufacture the aerodynamic deorbiting system storage system: material resistance to space factors; resistance to dynamic loads at the stage of launching a space object into orbit; resistance to temperature deformation of the material. Mathematical model for selecting auxiliary systems parameters of aerodynamic systems for space objects deorbiting is developed. This model include: mass estimation of the deployment system; relationships for determining the mass of the inflation system of aerodynamic systems of various configurations; material thickness estimating of gas cylinder in different configurations; dependencies for determining the weight of the aerodynamic deorbiting system storage system of different configurations.

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