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DEVELOPMENT OF R&D FRAMEWORK FOR THE MODERNIZATION OF THE AERODYNAMIC DEORBIT SYSTEM FOR THE USE IN THE UPPER STAGE OF *CYCLONE-1M* LAUNCH VEHICLE

Introduction. *Growing interest in space exploration and new satellite navigation and communication technologies has led to an increase in the number of spacecraft in Earth orbits and the formation of orbital groups. Today, spacecraft are launched into Earth orbits mainly by launch vehicles, the defunct upper stages of which, after the spacecraft launch, remain in Earth orbits and become the one of the sources of space debris (SD).*

Problem Statement. *The problem of increasing the number of SD is one of the key issues in modern cosmonautics. A significant accumulation of SD fragments on some clusters of orbits may cause significant obstacles to operating spacecraft and lead to global problems (the Kessler effect). One of the sources of SD growth is defunct upper stages of launch vehicles (LV). Means for deorbiting LV upper stages from near-Earth orbits needs to be designed urgently. In turn, the light class LV Cyclone-1M created by the Yangel Pivdenne Design Office is one of the promising developments.*

Purpose. *Development of R&D framework for the modernization of aerodynamic deorbit system for its use in the upper stage of the Cyclone-1M launch vehicle.*

Material and Methods. *Methods of applied mechanics, mathematical and computer modeling of spacecraft motion.*

Results. *The R&D framework for the creation of a new aerodynamic deorbit system (ADS) of the Cyclone-1M upper stage has been developed. A new design of the aerodynamic element of the ADS in the form of three orthogonally placed round disks, which allows raising the ADS efficiency, has been created. The design scheme*

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and manufacturing technology of the container for the ADS storage on the upper stage of the Cyclone-1M launch vehicle with the use of honeycomb technologies, which allows minimizing the weight of the system, have been proposed.

Conclusions. *The proposed development has enabled raising the ADS efficiency in the case of non-oriented angular motion during the deorbit of launch vehicles and reducing the weight of the storage system.*

Keywords: upper stage of launch vehicle, aerodynamic deorbit system, design parameters.

The emergence of new technologies in the field of satellite navigation, Internet, and communication requires an increase in orbital groups in near-Earth orbits. This leads to an increase in the number of launch vehicles that launch space vehicles (SC) into near-Earth orbits. Only one private company *Space-X* is going to launch about 42,000 artificial satellites into low Earth orbits, as part of the *Starlink* project [1]. This trend of increasing the number of space vehicles in near-Earth orbits may lead to a rapid growth in the number of space debris (SD) after the decommissioning of these space vehicles.

Today, the problem of space pollution has a global status and is widely discussed in astronautics research circles of the leading space countries. As of February 2021, NASA has cataloged more than 15,000 SD of various origins in Earth orbits [2]. It has been also found that the main sources of space debris are defunct spacecraft and abandoned upper stages of launch vehicles (LV) [2].

Yangel *Pivdenne* Design Office has designed promising light-class *Cyclone-1M* launch vehicles. According to data available in open information sources: *Cyclone-1M* is a three-stage launch vehicle that ensures the launch of spacecraft weighing up to 750 kg into a 600 km high sun-synchronous orbit. The approximate starting weight of *Cyclone-1M* launch vehicle is 63 tons, the diameter of the stage housing is 2.25 m, the approximate length of the launch vehicle is 29 m [3]. Given such parameters and a lower cost, as compared with the foreign analogs, thanks to the use of new composite materials for the manufacture of the main body elements of the stages, including tanks for cryogenic fuel components [3], the *Cyclone-1M* launch vehicle may become quite promising and enjoy demand on the world market.

Thus, in the case of its use, it is quite easy to predict that its upper third stage, having orbited the artificial satellites of the Earth to a certain point in space, remains in the orbit as space debris. Thus, the development of a means for deorbiting the upper stage of *Cyclone-1M* launch vehicle is a rather urgent task for both the domestic and world cosmonautics.

THE PARAMETERS OF *CYCLONE-1M* UPPER STAGE

The upper stage of *Cyclone-1M* launch vehicle is a truncated cone with the following dimensions (Fig. 1):

- height: 0.915 m;
- upper base diameter: 0.937 m;
- lower base diameter: 1.99 m.

Despite the fact that this launch vehicle is designed for a near-circular, sun-synchronous orbit with an altitude of 600 km, if the mass of the payload is reduced to less than 750 kg, its deorbiting altitude may increase to 700—800 km. The study proposes to consider the possibility of deorbiting from near-circular orbits with an altitude up to 800 km. The orbital life at the given altitudes is given in Table 1.

Based on the obtained results, given the recommendations of limiting the stay of the SD in near-Earth orbits to 25 years [4], it has been determined that the orbital life of the upper stage of *Cyclone-1M* launch vehicle shall be reduced starting with an altitude of 626 km in near-circular orbits. If there is a danger for functioning orbital groups, the debris may be deorbited from altitudes below 626 km in a shorter term.

Given this, the authors have analyzed drag augmentation devices [5—8] for deorbiting space

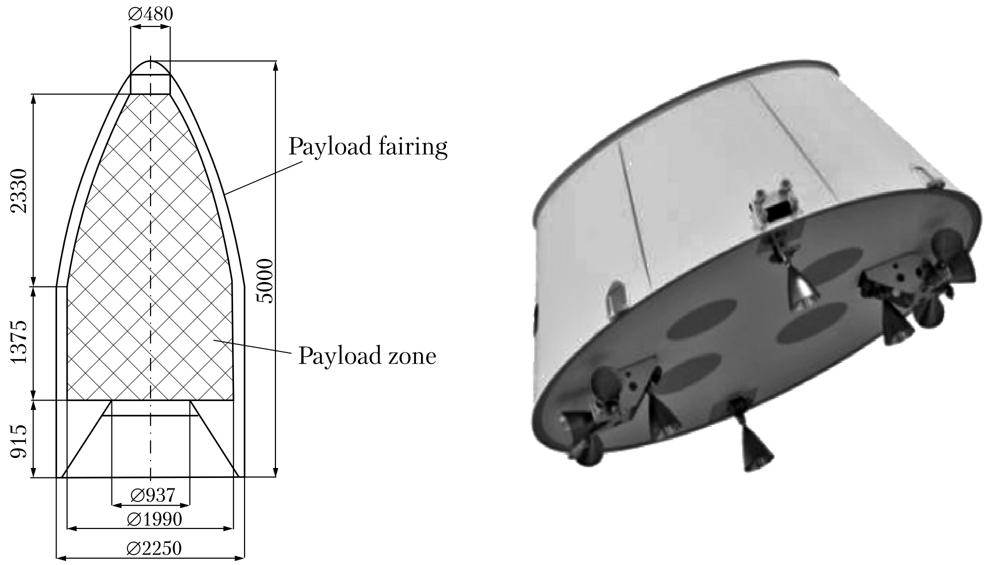

Fig. 1. Computer model and main parameters of *Cyclone-1M* upper stage

debris from near-Earth orbits and found that, for the upper stages of launch vehicle, it is most appropriate to use drag-enhancing deorbit devices or drag augmentation devices (DAD) based on the passive deorbit methods. This is explained by the fact that, as a rule, defunct upper stages of launch vehicles are space objects that have neither operational orientation and stabilization systems, nor power systems, nor means of measuring the necessary parameters of the near-Earth space, and therefore cannot be equipped with active or combined [9—11] deorbit devices. Also, the authors of [7] have shown that the upper stage of the rotating launch vehicle is quite difficult to capture with a manipulator, a net or to hit with a harpoon from a service spacecraft. The flight tests have confirmed the effectiveness of DAD among the passive deorbit systems [12—17].

Based on the DAD analysis [12—17], the following conclusions can be drawn:

1) The aerodynamic elements of these DAD are represented by flat sails that deploy with the use of special mechanisms.

2) In [12], the disadvantage of using flat sail elements in the DAD has been discussed. This disadvantage is related to the aerodynamic instability of these systems, which leads to a decrease in the effectiveness of the DAD application in the case of non-oriented motion of SC- DAD system.

3) At altitudes of 400—700 km, the effectiveness of the use of DAD data has been stated, as confirmed by a significant decrease in the orbital life of small spacecraft in the specified demo missions [17].

4) Flat sails have smaller weight and dimensions as compared with inflatable DAD of the same class.

Table 1. **Orbital Life of the Upper Stage of *Cyclone-1M* Launch Vehicle (the orbit eccentricity is 0.0001, the inclination is 81 degrees)**

Weight, kg	Area of the middle section, m^2	Orbital life of *Cyclone-1M* upper stage in near-circular orbits (e = 0.0001), years, at a perigee altitude, km				
300	2.2557	Altitude, km	500	600	700	800
		Time, year	2.9	13.83	55.68	189.182

However, despite the given certain advantages of flat sails, their use at the upper stages of launch vehicles is quite a difficult task. First of all, the installation of a mechanical system for deploying such a sail on the upper stage of launch vehicle causes difficulties associated with the geometric shape and mass-dimensional characteristics of this type of SC. Also, despite the fact that the sails are passive means of deorbiting, their deployment with the use of electromechanical systems requires a certain amount of electrical energy. Unlike artificial satellites, the upper stages of launch vehicles do not have on-board energy recovery sources, which causes additional difficulties during the deployment process.

Given the mentioned shortcomings, the expediency of using inflatable DAD for deorbiting the upper stages of launch vehicles has been substantiated in previous studies [18]. However, as mentioned, the inflatable DAD have larger mass-dimensional characteristics than the flat sails and require more volume for the storage system. Given this and the mass-dimensional characteristics of the *Cyclone-1M* upper stage, **it has been proposed to conduct a study of the feasibility of creating a modernized DAD** with the use of the honeycomb structure technology for the storage system and a new geometry of the aerodynamic element.

The purpose of the study is to develop a design and to select design parameters of the modernized DAD for the *Cyclone-1M* upper stage.

To achieve this goal, the following tasks have been set:

1) To study the specific features of deorbiting the *Cyclone-1M* upper stage with the use of cone and spherical configurations of DAD and to justify the expediency of creating new aerodynamic elements of the **3D sail type**.

2) To develop an aerodynamic element of the **3D sail type** for the modernized DAD for the *Cyclone-1M* upper stage.

3) Develop a storage system for the aerodynamic element of **the 3D sail type with the use of honeycomb structures**.

4) To estimate the time of deorbiting the *Cyclone-1M* upper stage with the use of a modernized DAD.

5) Determine the design parameters of the modernized DAD for the *Cyclone-1M* upper stage.

The mathematical model of orbital motion for studying the time of deorbiting the Cyclone-1M upper stage

To describe the orbital motion of *Cyclone-1M* upper stage, it is advisable to apply a system of differential equations in the osculating elements where the derivatives are taken by latitude argument u [11, 19]. This is explained by the fact that when integrating system of differential equations [19] by latitude argument u with the use of the Adams-Bashforth method [20], one can take large steps of integration (turnwise integration, 1 point for several turns) meeting the specified accuracy. Research [11] has shown that the solution of system [19] is degenerate in the cases of SC motion in near-circular orbits ($e \to 0$). Given this shortcoming, we use the method given in [21] and proceed to new parameters as follows:

$$\begin{aligned} e_x &= e \cdot \cos\omega, \\ e_y &= e \cdot \sin\omega, \end{aligned} \tag{1}$$

where e is orbital eccentricity; Ω is right ascension of the ascending node; ω is perigee argument; and i is orbital inclination.

Further, having made the following substitutions

$$\begin{aligned} \frac{de_x}{du} &= \frac{\partial e_x}{\partial \omega} \cdot \frac{d\omega}{du} + \frac{\partial e_x}{\partial e} \cdot \frac{de}{du}, \\ \frac{de_y}{du} &= \frac{\partial e_y}{\partial \omega} \cdot \frac{d\omega}{du} + \frac{\partial e_y}{\partial e} \cdot \frac{de}{du}, \end{aligned} \tag{2}$$

we get a new system of differential equations, which allows eliminating the above-mentioned shortcomings. With the help of this substitution, system of differential equations [19] is written in the following form:

$$\left.\begin{aligned}
&\frac{d\Omega}{du}=\frac{1}{\gamma}\cdot\frac{r_{KA}^{3}}{\mu\cdot p}\cdot W\cdot\frac{\sin u}{\sin i}\\
&\frac{di}{du}=\frac{1}{\gamma}\cdot\frac{r_{KA}^{3}}{\mu\cdot p}\cdot W\cdot\cos u\\
&\frac{dp}{du}=\frac{1}{\gamma}\cdot 2T\frac{r_{KA}^{3}}{\mu}\\
&\frac{de_x}{du}=\frac{1}{\gamma}\cdot\frac{r_{KA}^{2}}{\mu}\left[\sin u\cdot S+\left(\left(1+\frac{r_{KA}}{p}\right)\cos u+\frac{r_{KA}}{p}e_x\right)T+\right.\\
&\left.+\frac{r_{KA}}{p}e_y\sin u\cdot\cot i\cdot W\right]\\
&\frac{de_y}{du}=\frac{1}{\gamma}\cdot\frac{r_{KA}^{2}}{\mu}\left[-\cos u\cdot S+\left(\left(1+\frac{r_{KA}}{p}\right)\sin u+\frac{r_{KA}}{p}e_y\right)T-\right.\\
&\left.-\frac{r_{KA}}{p}e_x\sin u\cdot\cot i\cdot W\right]\\
&\frac{dt}{du}=\frac{1}{\gamma}\cdot\frac{r_{KA}^{2}}{\sqrt{\mu\cdot p}}
\end{aligned}\right\},\qquad (3)$$

where $\gamma=1-\frac{W\cdot r_{KA}^{3}}{\mu\cdot p}\sin u\cdot\mathrm{ctg}\,i$, r_{KA} is the radius vector of the spacecraft; a is the major semi-axis; p is the orbit focal parameter, $p = a(1 - e^2)$; μ is the gravitational constant; t is the time of spacecraft motion along the orbit; Ω is right ascension of the ascending node; i is orbital inclination; S, T, and W are the projections of the radial, transverse, and normal perturbing accelerations on the axis of the orbital coordinate system.

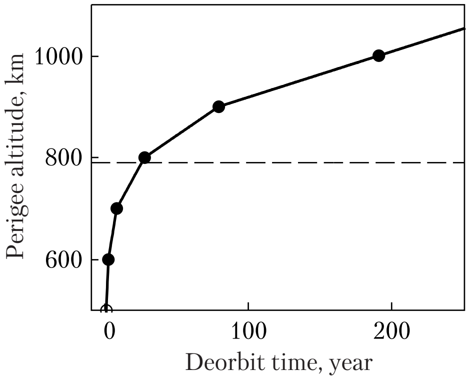

Fig. 2. Time of deorbiting the upper stage of *Cyclone-1M* with the use of 4 m spherical DAD
– – – – — an altitude of 790 km that corresponds to a deorbit time of 25 years

When calculating S, T, and W, we take into consideration the aerodynamic, solar pressure, and gravitational disturbances that affect the motion. The atmosphere model of the European Space Agency (ECSS atmosphere standard) [22] has been used to calculate the aerodynamic disturbances. The gravitational disturbances take into account the influence of the first six zonal harmonics of the Earth gravitational potential expansion in a series by spherical functions in the form of Legendre polynomials. The solar disturbances estimated by the method given in [19].

Given the fact that the spacecraft motion is considered to be non-oriented, the Euler dynamic equations do not apply, so we solve the three-step problem. The average middle section area is calculated as a fourth part of the full surface area of the DAD and the SC [11, 18].

Design of the aerodynamic element of the modernized DAD

In order to choose the design of the modernized DAD, we have analyzed the deorbit time in the case of using known types of inflatable DAD: the cone-shaped [18] and the spherical ones. Let us consider for the use in *Cyclone-1M* upper stage, a 4 m diameter spherical DAD and a cone-shaped DAD with a base diameter of 4 m and a height of 2 m. The results of calculations of the deorbit time from near-circular orbits (e = 0.0001) at an altitude from 500 to 1000 km, in the case of using these types of DAD are shown in Figs. 2 and 3.

Having analyzed the obtained results for the deorbit time of *Cyclone-1M* upper stage, we may conclude that the use of the spherical DAD is more effective, because of the following reasons:

1) effective application for higher altitude of deorbit at the required deorbit period of 25 years (790 km, for the spherical type, and 741 km, for the cone-shaped DAD);

2) a higher deorbit speed at the required altitude, in comparison with the cone-shaped DAD.

The advantages of the spherical DAD are explained by the fact that, in the case of non-oriented motion, the average middle section area of the sphere is much larger than that of the cone, and hence the average aerodynamic braking force is also greater.

Therefore, the spherical geometry has been proposed for the design of the aerodynamic element of the modernized DAD. It has been noted that large inflatable DADs have quite significant mass-dimensional characteristics and require powerful inflating systems.

Given the above-mentioned shortcomings, a new approach to the design of DAD has been developed. It foresees the development of **3D sail type DAD**. This approach makes it possible to ensure the necessary parameters of DAD by combining the design advantages of the inflatable 3D DAD and the aerodynamically unstable flat sailing elements.

The research proposes to combine the design features of the spherical and the flat sail DADs by creating a 3D sail consisting of three orthogonal inflatable discs (Fig. 4). This approach makes it possible to reduce the mass of the aerodynamic element in comparison with the spherical design. In the case of non-oriented motion, in the course of deorbiting the *Cyclone-1M* upper stage, the average middle section area is the same as that of the spherical DAD. The frame of the aerodynamic element (Fig. 5) is hermetically made of high-strength lightweight polymer material (polyimide film) in the form of three outer *3* and three inner *1* toroidal shells connected to each other by spacers *2* (Fig. 5).

The “cloth” of the aerodynamic element is made of high-strength light polymer material (polyimide film) shaped as a sail. It serves to create additional aerodynamic resistance to the space object.

The connecting flange of the aerodynamic element is made of high-strength polymer material with a ball support for connection with the rod of the bracket.

The thrust of the device (Fig. 6) connects the aerodynamic element with the space object. It consists of a cable *1* and two ball supports *2* at the

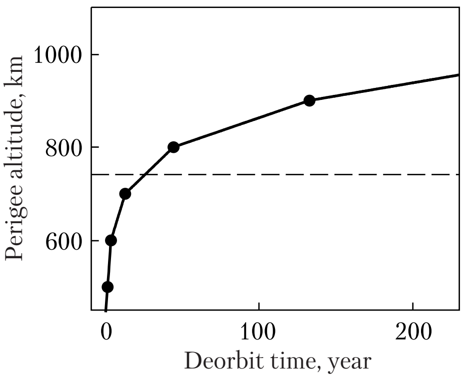

Fig. 3. Time of deorbiting the upper stage of *Cyclone-1M* with the use of cone-shaped DAD with a base diameter of 4m and a height of 2 m
– – – – — an altitude of 741 km that corresponds to a deorbit time of 25 years

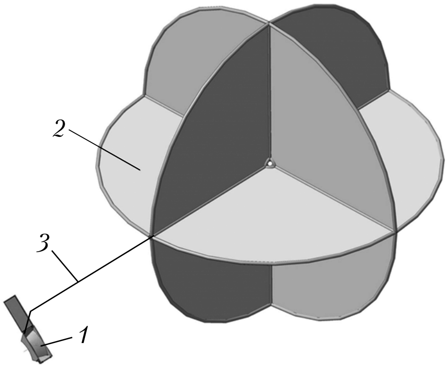

Fig. 4. General view of the 3D sail modernized DAD: *1* — container for storage; *2* — aerodynamic elements; *3* — cable attachment to the storage system

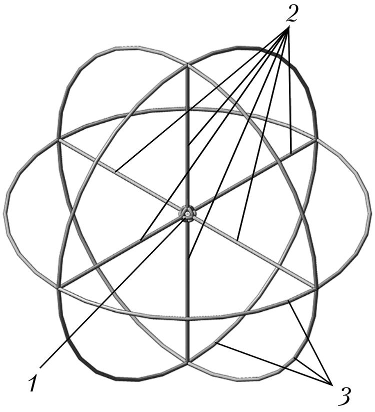

Fig. 5. Aerodynamic element body: *1* — inner shell; *2* — spacer; *3* — outer shell

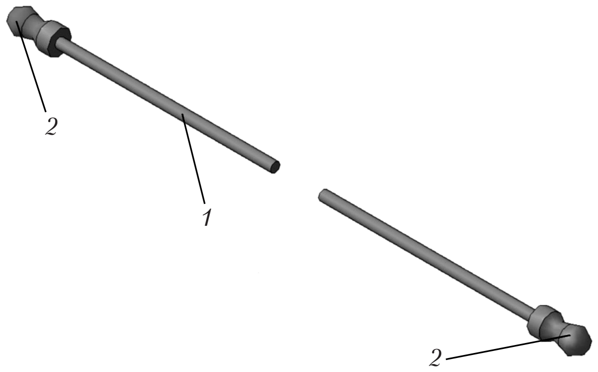

Fig. 6. DAD thrust: *1* — rod; *2* — ball support

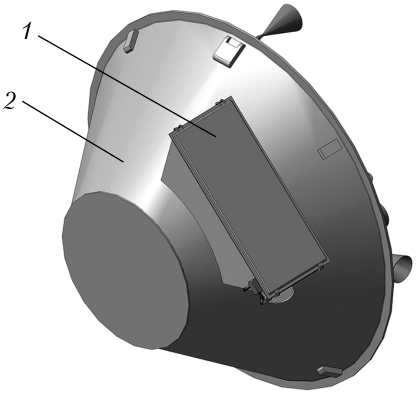

Fig. 7. DAD in transport position: *1* — container; *2* — space object deorbited

ends of the cable, which are made of high-strength polymer material (Fig. 6).

The device operates as follows.

On the outer surface of the space object *2* (Fig. 7), there is fixed a container of the deorbit device *1*, in the inner cavity of which the aerodynamic element is placed in a folded form. The container lid is locked by the fasteners of the lock lever and fixed by the trigger of its drive.

At the specified time, the command to activate the trigger of the mechanism for closing the lid of the container comes from the upper stage. The trigger releases the drive rod of the cover lock, which moves in the drive housing under the action of a compression spring. The rod that is connected by an earring to the arm of the lock lever, turns its fasteners around the axis of the shaft and releases the spring-loaded container lid. The container lid opens thereby freeing the zone of exit of the aerodynamic element. The rod arm that rotates around its axis is set in the working position. The aerodynamic element shells that come out of the container are inflated under the action of the air remaining in their internal cavity to the working state. The aerodynamic element is held on the upper stage of *Cyclone-1M* by the device thrust.

Designing the DAD storage system with the use of the honeycomb structures technology

The advanced modern aviation, rocket and space technology (ARST) is associated with a reduction in the mass of products while ensuring regulated operational requirements. In this aspect, the use of polymer composite materials in combination with honeycomb structures in ARST units, which play an important role in ensuring high load-bearing capacity of products and other characteristics that depend on their operating conditions, has created new opportunities. [23].

The analysis of foreign and domestic experience in using HS in ARST has shown a wide application of them in various units, including [24]:

- the structural ones: payload fairings of launch vehicles, spacers, gargrot, transitional adapter compartments [25];
- the elements that for a long time work in the conditions of open space: panels of solar batteries, panels of non-hermetic spacecraft, dimensionally stable platforms, satellite bodies [25].

Honeycomb fillers (HF) and honeycomb structures have been widely used in the corresponding units of aircraft of all major classes: passenger and military aircraft, helicopters, aircraft engines, launch vehicles and spacecraft.

The wide application of these structural and technological solutions is associated with the high efficiency of HF and HS. This is due to the fact that for destroying HS we need higher compression and shear stresses as compared with other structures; they have high fatigue strength during bending and low surface mass in a wide range of compressive and bending linear loads.

In addition, HSs have other specific properties: increased thermal conductivity, increased sound-insulating ability, long-term acoustic resistance, low mass when used as thermal insulation of hypersonic aircraft. The replacement of monolithic structures by a honeycomb with the use of polymer composite materials leads to a 20—40% reduction in the spacecraft weight. In addition, HS panels have damping properties, which is important in terms of reducing dynamic loads on spacecraft equipment [24]. For the manufacture of spacecraft bodies and HS payload plates, the weight decreases from 15% to 60% as compared with the conventional solutions.

Given the advantages of HS and HF, their use for the storage system of modernized DAD has been proposed. The modernized DAD container (Fig. 8) is designed for long-term storage of the aerodynamic element in the internal cavity, its opening to the working position and keeping in the working position. It is a 3D box structure that is rigidly fixed on the space object (the upper stage of *Cyclone-1M*). It consists of a body *4*, a lid *5*, a mechanism for opening the container *6* (see Fig. 8) and a rod *7*. The lid is installed on top of the body on two axes *8* and is spring-loaded in the direction of its opening by lid springs *9*. The rod is installed inside the container on its side wall that secures and keeps the aerodynamic element of the device in its working position.

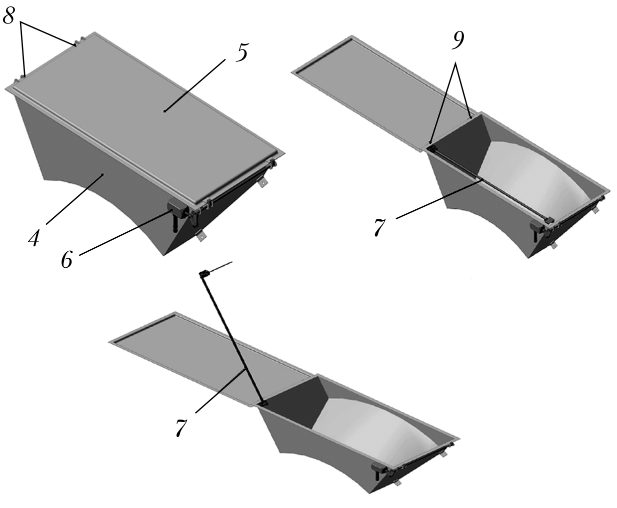

Fig. 8. Container with a lid of the storage system of the modernized DAD: *4* — body; *5* — lid; *6* — container opening mechanism; *7* — rod; *8* — axes of the container lid; *9* — lid springs

The body (Fig. 8) and the lid of the container are made of a light and strong titanium alloy with

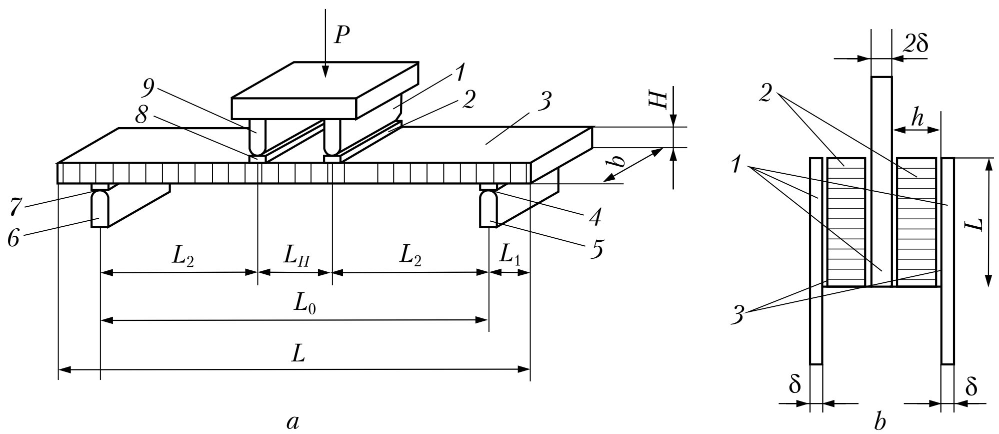

Fig. 9. Scheme for testing the container (*a*) and the side walls (*b*) of the modernized DAD storage system: *a* — 1, 9 — metal presses; *2, 4, 7, 8* — gaskets made of stamped rubber; *3* — lid of the container of the storage system; *5, 6* — metal supports; *b* — *1* — plate; *2* — side wall of the storage system; *3* — cladding

a thickness of 0.5 mm. The bottom of the body is made sloping and provides a free exit of the inflatable structure of the aerodynamic element from the container into the orbit. The mechanism for opening the container is fixed on the outside of the container body and consists of a drive, a lever, a lid lock and an earring. In order to manufacture the storage system from honeycomb structures, it is necessary to conduct deflection tests for the container lid, in accordance with [26], and shear tests for the container side walls, according to the scheme shown in Fig. 9.

So, in this part of the research, we have shown the design of the storage system of the modernized DAD with the use of honeycomb technologies and methodical recommendations for testing it during its manufacture.

Determining the limit of effective use of the modernized DAD for the *Cyclone-1M* upper stage

It is known that today the creation of orbital groups is one of the most interesting problems of modern cosmonautics. Given the current trends in the creation of orbital groups of satellite Internet in low Earth orbits, *Cyclone-1M* launch vehicles may be used for these tasks. *SpaceX* is going to launch up to 42,000 *Starlink* satellites weighing up to 300 kg into low Earth orbits at altitudes ranging from 550 km to 1,500 km with inclinations of 53.2°, 70°, and 97.6°. Given this, the modernized DAD system may be employed for deorbiting the upper stages of *Cyclone-1M* from the given range of orbits.

Table 2. **Deorbit Time for the Upper Stage of *Cyclone-1M* with the Modernized DAD Having the 3D Sail Aerodynamic Element with a Diameter of 4 m (eccentricity of orbits is 0.0005, the range of orbits with inclinations of 53.2°)**

Weight of the stage, kg	The middle section area, m^2	Deorbit time for the upper stage of *Cyclone-1M* in the case of using the modernized 3D Sail DAD with a main disc diameter of 4 m, years, at the perigee altitude, km						
		Altitude, km	500	600	700	800	900	1000
300	2.2557	Time, years	0.43	2.1	8.835	31.32	97.372	220.761

Table 3. **Deorbit Time for the Upper Stage of *Cyclone-1M* with the Modernized DAD Having the 3D Sail Aerodynamic Element with a Diameter of 4 m (eccentricity of orbits is 0.0005, the range of orbits with inclinations of 70°)**

Weight of the stage, kg	The middle section area, m^2	Deorbit time for the upper stage of *Cyclone-1M* in the case of using the modernized 3D Sail DAD with a main disc diameter of 4 m, years, at the perigee altitude, km						
		Altitude, km	500	600	700	800	900	1000
300	2.2557	Time, years	0.4	1.96	8.26	29.12	90.55	205.308

Table 4. **Deorbit Time for the Upper Stage of *Cyclone-1M* with the Modernized DAD Having the 3D Sail Aerodynamic Element with a Diameter of 4 m (eccentricity of orbits is 0.0005, the range of orbits with inclinations of 97.6°)**

Weight of the stage, kg	The middle section area, m^2	Deorbit time for the upper stage of *Cyclone-1M* in the case of using the modernized 3D Sail DAD with a main disc diameter of 4 m, years, at the perigee altitude, km						
		Altitude, km	500	600	700	800	900	1000
300	2.2557	Time, years	0.385	1.89	7.992	28.159	87.56	198.53

So, using the model of orbital motion (3), let us consider deorbiting the upper stage of *Cyclone-1M* from near-circular low Earth orbits (e = 0.0005) of different altitudes with inclinations of 53.2°, 70°, and 97,6°.

Based on the obtained results, it can be seen that the modernized 3D sail DAD with the given parameters meets the requirements for a deorbit time of 25 years in the altitude range from 700 km to 800 km. It has been determined that the limit of effective use is 771.9 km at perigee.

Let us consider orbits with inclinations of 70° (Table 3).

The limit of effective use at an inclination of 70° is an altitude of 780.25 km at perigee.

Table 4 shows the estimated deorbit time for an inclination of 97.6°.

The limit of effective use at an inclination of 97.6° is an altitude of 784.336 km at perigee.

Thus, based on the obtained results for the effective use of the modernized 3D sail DAD, we have concluded that the maximum altitude of deorbiting the upper stage of *Cyclone-1M* is 784.336 km for near-circular orbit with an eccentricity 0.0005 and an inclination of 97.6°. On near-circular orbits with inclinations of 53.2° and 70°, the maximum deorbit altitudes are 771.9 km and 780.25 km, respectively. Decreasing maximum altitude of deorbit when the orbital inclination approaches the equator is explained by uneven distribution of the gravitational potential and the average density of the atmosphere. The estimated maximum altitudes of deorbiting the upper stage of *Cyclone-1M*, which correspond to a deorbit time of 25 years, have been obtained for the 3D sail aerodynamic element with a diameter of 4 m (the average middle section area is 12.566 m^2). When setting a maximum deorbit altitude of 700 km on orbits with such an eccentricity, the diameter of the flat discs of 3D sail can be reduced to 2.38 m (with an average middle section area 4.448 m^2).

The system weight is about 3% of the weight of the upper stage, which meets the requirement that the deorbit system should not weight more than 5% of the deorbited spacecraft. A decrease in the weight of the modernized 3D Sail DAD ranges from 30% to 40% as compared with similar spherical and cone-shaped systems.

Thus, the orbital motion of the upper stage of *Cyclone-1M* with aerodynamic deorbit systems of the spherical and cone-shaped configurations has been studied. It has been established that the 3D sail DAD (an altitude of 790 km, with a sphere diameter of 4 m) has the maximum limit values of effective use in terms of the altitude of deorbiting from near-circular orbits. In turn, the flat sail elements that deploy have the smallest weight. Given the advantages and disadvantages of the use of the spherical, cone-shaped, and flat sail aerodynamic systems, the structural type and design parameters of the modernized DAD have been chosen. A new type — 3D sail DAD — has been developed.

The use of the honeycomb structures technology for the storage system of the modernized DAD has been substantiated. The storage system of the aerodynamic element of the modernized DAD, which is attached to the upper stage of *Cyclone-1M*, has been designed. The method statement for conducting tests of the container and side walls of the storage system, which are manufactured with the use of the honeycomb structures technologies has been developed.

Due to applying the technology of honeycomb structures and developing the new 3D sail aerodynamic element, the weight of the upper stage of *Cyclone-1M* has been reduced by 30—40% as compared with similar spherical and cone-shaped systems. The limits of the effective use of the modernized DAD and its design parameters for near-circular orbits of various dislocations have been determined.

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РОЗРОБКА НАУКОВО-ТЕХНІЧНОГО ЗАБЕЗПЕЧЕННЯ МОДЕРНІЗАЦІЇ АЕРОДИНАМІЧНОЇ СИСТЕМИ ВІДВЕДЕННЯ ДЛЯ ВИКОРИСТАННЯ НА ВЕРХНЬОМУ СТУПЕНІ РАКЕТИ-НОСІЯ «ЦИКЛОН-1М»

Вступ. Зростання інтересу до освоєння космічного простору та нові технології супутникової навігації та зв'язку призвели до збільшення кількості космічних апаратів (КА) на навколоземних орбітах і створення орбітальних угрупувань. На сьогодні головним засобом, що здійснює виведення КА на навколоземні орбіти, є ракети-носії, відпрацьовані верхні ступені яких, після виведення КА, залишаються на навколоземних орбітах і уворюють космічне сміття (КС).

Проблематика. Проблема зростання кількості КС є однією із ключових у сучасній космонавтиці. Значне накопичення фрагментів КС на деяких кластерах орбіт може чинити значні перешкоди діючим КА, а також призвести до глобальних проблем — ефекту Кеслера. Одним із джерел зростання КС є відпрацьовані верхні ступені ракет-носіїв (РН). Розробка засобів відведення верхніх ступенів РН з навколоземних орбіт є актуальною, а проєкт РН легко класу «Циклон-1М» розробки ДП «КБ «Південне» ім. М. К. Янгеля» є однією з перспективних розробок.

Мета. Розробка науково-технічного забезпечення модернізації аеродинамічної системи відведення для використання на верхньому ступені ракети-носія «Циклон-1М».

Матеріали й методи дослідження. Застосовано методи прикладної механіки, математичного й комп'ютерного моделювання руху космічних апаратів.

Результати. Розроблено науково-технічне забезпечення для створення нової аеродинамічної системи відведення (АСВ) верхнього ступеня РН «Циклон-1М». Створено нову конструкцію аеродинамічного елементу АСВ у формі трьох ортогонально розміщених круглих дисків, що дозволяє підвищити ефективність застосування АСВ. Запропоновано конструктивну схему та технологію виготовлення контейнера для зберігання АСВ на верхньому ступені РН «Циклон-1М» з використанням сотових технологій, що дозволяє мінімізувати масу системи.

Висновки. Технічний результат запропонованої розробки демонструє збільшення ефективності застосування АСВ при неорієнтованому кутовому русі під час відведення РН та дозволяє зменшити масу системи зберігання.

Ключові слова: верхній ступінь ракети-носія, аеродинамічна система відведення з орбіти, проєктні параметри.