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FLIGHT VEHICLE DESIGN

Small-Size Automatic System for the Controllable Launch of Nanosatellites on a Desired Trajectory

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Abstract—We consider the methods of mathematical modeling and calculation of main parameters of small-size magnetic induction ejectors (separation systems) for precision launch into orbit nano- and microsatellites. Examples of some technical solutions are presented.

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Emergence of ultra-light spacecraft (ULS) known as micro and nano satellites (MS, NS) has imposed on the researchers many new challenges [1], one of them is the injection of spacecraft into orbit. Spring mechanisms [2, 3] are used in the most separation systems (adapters). As the number of tasks solved by these spacecraft increases, high requirements are imposed on separation accuracy [4]. This requires the development of new, highly efficient devices that use different physical principles [5].

The separation system of ULS should meet the following primary requirements [6]:

—separation of the satellite at a preset velocity in the range of 0.5 to 5 m/s;

—launch of the satellite in a certain direction relative to the orientation and attitude of the delivery system or the planet;

—the separation system should provide multiple launches of nanosatellite groups with a prescribed accuracy;

—the separation system should be of minimal mass and dimensions (as compared to payload it is optional);

—the separation control system should allow changing the separation velocity value quickly.

Analysis of the current separation systems of ULS [7] with the desired values of initial velocities shows that the magnetic induction systems with discharge circuit satisfy all the above requirements to the greatest extent. The most efficient energy storage in the conditions of outer space is a capacitor that allows us to accumulate rapidly the necessary energy and to adjust quickly its consumption for an actuating device.

In general case, any magnetic induction separation system (MISS) is a serial *RLC*-circuit, in which the parameters of inductance $L(i)$ and resistance $R(i)$ are the variable quantities that depend on the current $i(t)$. In order to increase the effectiveness of the electromechanical launch system considered [7], it is necessary to raise the flux density of the magnetic field, to increase the efficiency of conversing the field momentum inside the conductor into the mechanical impulse $dP_m = Fdt$. This task can be partially solved by placing an inductor (a high current solenoid) inside the armored core.

The main reason for the low efficiency of the approach proposed [7] is that the energy stored in the conductor using the solenoid is disproportionately larger the useful energy that can be obtained from a small part of the energy of the magnetic field induction currents and magnetic field [3] in the process of magnetization.

Therefore, in order to significantly enhance the effectiveness of the ejection system, the *RL*-circuits should be placed in the integrate (closed) core of shell type (Fig. 1a). In this case, almost all of energy of the magnetic field of the solenoid associated with the magnetic component, will be closed in the magnetic core. It should also be noted that outside of the scope of such a system, the magnetic field is practically absent, that is the useful condition because the question on the impact of the electromechanical pulse on electronic satellite equipment is removed.

In order to implement the ejection effect in such a system, it is sufficient to locate the winding with opposite directions of the winding [8] in the halves of the armored core. In this case, the magnetic field in each half of the core will be directed towards each other.

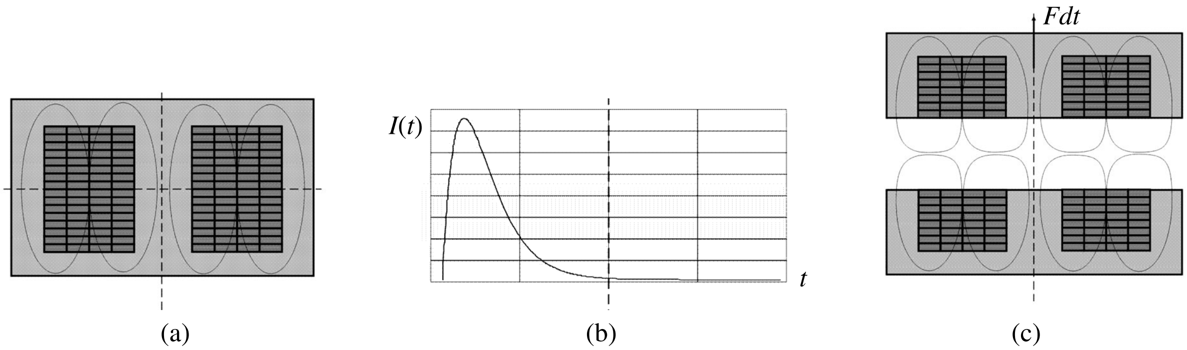

Fig. 1. The principle of operation of the magnetic induction ejector for the nanosatellite separation systems.

In applying the current pulse, the form of which is shown in Fig. 1b, the windings will tend to repel each other. The momentum change $dP = Fdt$ will be determined by the intensity of the magnetic field generated, rate of its change, and moving masses. Therefore, if one half of such a magnetic induction ejector to bind to the carrier platform (see Fig. 1c) and the other half, which is movable relative to the means of delivery into orbit, to the nanosatellite, then the NS will also acquire the corresponding momentum change dP_n and will be able to separate from the platform at the lower energy consumption [9].

Implementation of this type of the magnetic induction ejector is shown in Fig. 2. It is advisable to connect coils of ejectors using the own key devices. This gives the possibility to modify the current in coils *8, 11* and allows varying the mechanical impulse of the nanosatellite launch.

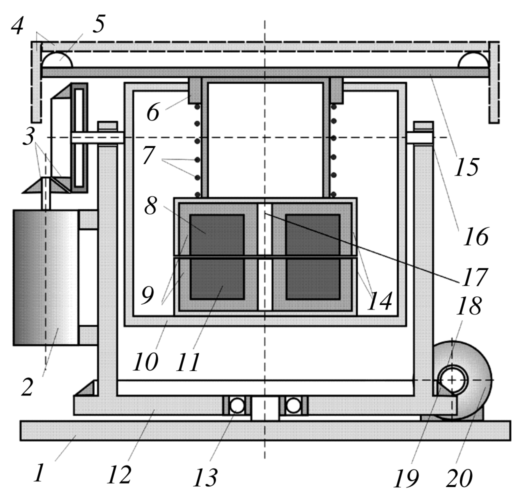

Fig. 2. The sketch of a small size magnetic impulse separation system (MISS) for controllable launch of nanosatellite on a trajectory.

Let us present the calculation of such electromechanical launch system. The magnitude of force that determines the change of impulse of a separation object can be found from the condition: $dW_{\Sigma} = Fdz = dW_C - dW_H$, where dW_{Σ} is the change in energy of the system; dz is the increment of the distance between the components of the ejector; dW_C is the change of the capacitor energy; dW_H is the energy change in the magnetic field of coils. In this case, the changes of energy due to heat losses can be neglected. The energy of magnetic field of two inductively coupled coils is defined as $W_H = L_1 i_1^2/2 + L_2 i_2^2/2 - Mi_1 i_2/2 - Mi_2 i_1/2$. Inductances L_1 and L_2 do not depend on the distance z between the coils. It only affects the magnitude of mutual induction M. Therefore, the energy change of the magnetic field of coils, when the distance between them changes on the value dz, can be estimated by the formula: $dW_H = i^2 dM$. When this capacitor should develop the additional energy dW_C, because it is necessary to create the auxiliary voltage that compensates the electromotive forces (EMF) occurring in the circuits in their movement. This additional voltage dU is equal to the sum of the time derivatives of the flux linkages for the mutual induction of both coils:

$$dU = 2d(Mi)/dt = 2idM/dt,$$

where $i = \text{const}$; $dU = 2\big(i(t)\big(dM/dt\big) + M(t)\big(di/dt\big)\big)$.

The energy balance equation can be written in the following form

$$Fdz = dW_C - dW_L = 2i^2 M - i^2 M = i^2 M.$$

Therefore, the force acting on the separable satellite in a given time can be estimated by the relation $F(t) \approx i^2 dM/dz$.

It is necessary to know the dependence of mutual inductance of coils M on the distance z between them for calculation of the electromagnetic force. If we assume that the inductor coils have the same number of turns N, then $M(z)$ can be estimated using the empirically derived relationship $M = \mu\mu_0 N^2 R_{eff} f(k)$, where R_{eff} is the effective radius of the ejector coil $R_{eff} \approx R_1 + 1/2\left(R_2 - R_1\right)$. The technique of determining the form of the function $f(k)$ is specified in [10].

To provide the separation of the satellites in a given direction that is characterized by the zenith ϑ and azimuth φ angles relative to the plane of the platform, it is proposed to use a special electromechanical device (see Fig. 2).

The device for controlable injection of nanosatellites and microsatellites consists of two main parts, namely, a magnetic induction ejector (MIE) and an orientation system, which are mounted on the plate foundation *1*, related to a delivery vehicle into orbit. The orientation system consists of small-size stepper motors *2*, *18*, *20* and bevel gears *3, 19*. When the control action is applied on the motor drive *20*, it rotates in the azimuth plane of body *12* along the axis that is mounted on bearing *13*. When the control action is applied on the motor drive *2*, it rotates in the zenith plane of body *10* relative to the axis that is fixed on two bearings *16*. The MIE consists of two solenoid-type inductors, namely, “fixed” inductor *11* and “movable” inductor *8*, which are placed in the shell-type core *9*. Inductors *8*, *11* are fixed in the core and molded in pairs into cups *14* that perform additionally the role of screens from the pulses of the magnetic field. “Movable” inductor can displace along the main axis of the controllable launch system *17* of nanosatellites and microsatellites, and its movement is determined by moving guide *6*. The gland spring *7* preloads the inductance coils at the initial moment of time and serves as a damper during acceleration.

The process of the nanosatellite separation is performed as follows. Parameters of nano and microsatellite launch are calculated on determining the attitude of delivery systems in the orbital coordinate system. This procedure is performed by the onboard computer of delivery system. The calculated initial data is transmitted to the microprocessor control system of the MISS launch. The nanosatellite by its base *4* is mounted on launch platform *15* by means of a robot manipulator. For creating the impulse of the electromagnetic field in the inductance coils, capacitors are used. These capacitors are pre-charged from an onboard network of the delivery vehicles into orbit or from the battery that is a part of this unit. At the initial instant of time, coils are tightly pressed to each other. At this point, the key devices are opened by pulses generated by the microprocessor and the discharge of capacitors through coils begins. Since inductors are tightly pressed to each other at the initial moment of time, energy of few joules can be stored in the volume of inductors

In designing nano and microsatellites, it is quite difficult to combine the center of mass of the spacecraft with its geometric location in the body, in any case, the center of mass is found to be displaced. This leads to the fact that as a result of separation, nanosatellites acquire the chaotic rotational motion relative to the center of mass. This will be illustrated using the 2D model (Fig. 3).

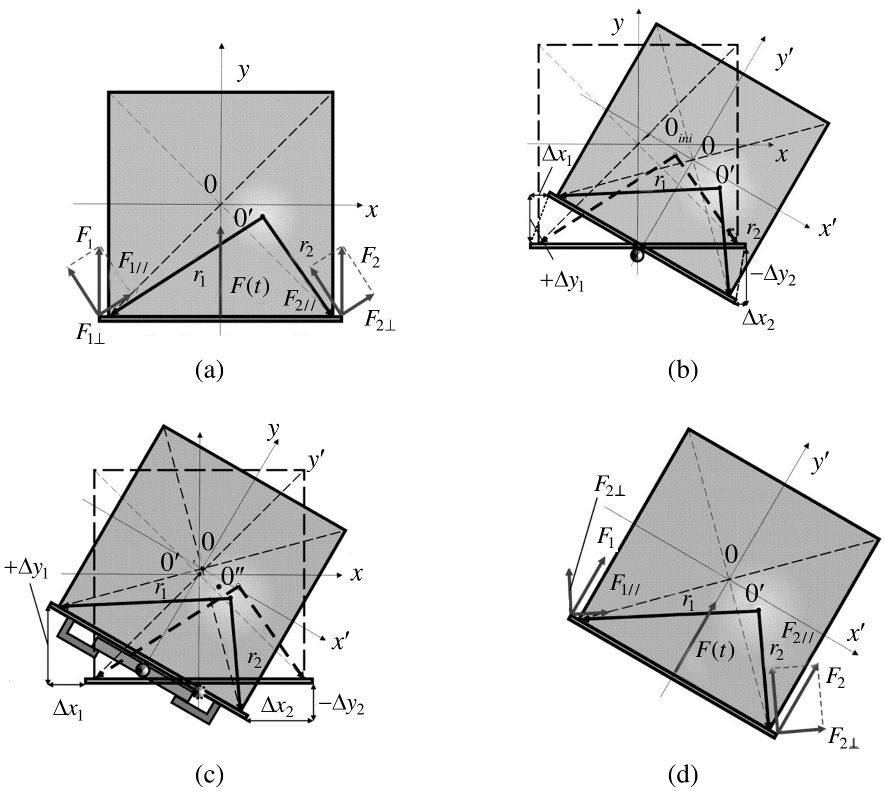

Fig. 3. Illustration of the principle of operating the magnetic induction corrector of the shifted center of mass of the nanosatellite: (a) $\vec{F} = \vec{F}_1 + \vec{F}_2 + ... + \vec{F}_4$, $\vec{M}_i = \vec{r}_i \vec{F}_i$, $0 \not\in 0'$, $\vec{M}_1 \neq \vec{M}_2 \neq \vec{M}_3 \neq \vec{M}_4$; (b) $|\Delta x_1| = |\Delta x_2| = ... = |\Delta x_4|$, $|\Delta y_1| = |\Delta y_2| = ... = |\Delta y_4|$; (c) $|\Delta y_1| \neq |\Delta y_2| \neq ... \neq |\Delta y_4|$, $\Delta t_1 = \Delta t_2 = \Delta t_3 = \Delta t_4$, $\nu_1 \neq \nu_2 \neq \nu_3 \neq \nu_4$; (d) $\vec{F}_1 \neq \vec{F}_2 \neq \vec{F}_3 \neq \vec{F}_4$, $0 \to 0''$, $\vec{M}_1 = \vec{M}_2 = \vec{M}_3 = \vec{M}_4$.

If the center of mass of the nanosatellite is displaced relative to the point 0 (Fig. 3a) and it is at the point 0′, then by decomposing the force $\vec{F}(t)$ applied to the nanosatellite base into four components $\vec{F}(t) = \sum_{i=1}^{4} \vec{F}_i$, it is easy to see that the moment of forces $\vec{M}_i = \vec{r}_i \vec{F}_i$ is turned to be different, i.e. $\vec{M}_1 \neq \vec{M}_2 \neq \vec{M}_3 \neq \vec{M}_4$. This leads to chaotic rotational motion of the nanosatellite along trajectory. In order to adjust such rotational motion, it is necessary to fulfill the condition of balancing of the corresponding moments of forces: $\vec{M}_1 = \vec{M}_2 = \vec{M}_3 = \vec{M}_4$ at the moment of separating the nanosatellite from the launch platform.

This can be done by means of the launch platform displacement mechanism that provides two additional degrees of freedom in the plane parallel to the platform plane (Figs. 3b and 3c). Figure 3b illustrates the rotation of the nanosatellite in the final moment of separation at a fixed position of the $0y'$ axis relative to the unbiased position of the launch system. In this case, the increments of angle coordinates of the launch platform turn out to be the same. The presence of the mechanism of displacing the platform relative to the main axis $0y'$ (Fig. 3c) removes the conditions of fulfilling these equalities. If now the different forces $\vec{F}_1 \neq \vec{F}_2 \neq \vec{F}_3 \neq \vec{F}_4$ are applied by the platform corners, it is easy to ensure the equal corresponding moments of forces $\vec{M}_1 = \vec{M}_2 = \vec{M}_3 = \vec{M}_4$ (Fig. 3d). In order to implement this approach, a magnetic induction pulse corrector of separation is proposed. This corrector consists of four jacks that are placed at the corners of the launch platform.

Figure 4 presents the layout of the modified launch platform (a section along the A-A plane) with the magnetic induction pulse correctors of separation mounted on it.

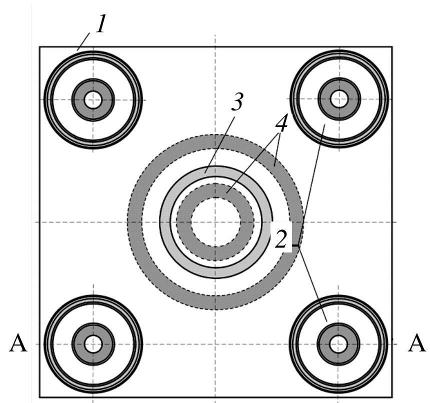

Fig. 4. Modified launch platform: (*1*) intermediate launch platform; (*2*) location of magnetic induction correctors of separation impulse; (*3*) electromagnetic NS lock; (*4*) zones of launch platform offset from the central axis.

This platform consists of a case (base) (*1*) (Fig. 5), in which the measuring part of the system for correcting the pulse of the satellite separation is located. Each corrector contains the force and measuring systems, which are designed by the unified modular principle. The measuring module of each corrector contains a set of neodymium ring magnets *3*, which are pressed into cup *2* made of magnetic material that screens the magnetic fields. Measuring coil *4* is located inside this compound cylindrical magnet. It is pressed onto rod *6* that can move in the vertical direction through bushing guides *5*. Fixation unit *7* serves for fixing the launch platform on the MISS movable rod (Fig. 2) instead of platform *15* (Fig. 5). Boards of radioelements of the correction system *8* are mounted into the housing. The intermediate launch platform is located on the top cover, it consists of a thrust bearing *9* of the ball bearing with the rigidly fixed ball *10*. Power modules are installed on it coaxially with the measuring modules and they consist of ring neodymium magnet assembly, which are placed into cylindrical bodies *11*. The power elements are high current solenoids *12*, which in the discharge "of its own" capacitor creates the additional launch pulses $\Delta P_i = F_i dt$, the magnitude of which is determined by the discharge time of each *RLC* circuit controlled by the microprocessor. Thus, different forces, which compensate for the inequality of the angular momentum caused by the shift of the center of mass from its geometric location, are applied to platform *13*, onto which the launchable nanosatellite *14* is mounted. Spherical bearings *5* (Fig. 2) mounted on the movable rods enable the external platform *15* (Fig. 2) occupy a certain position in space within some solid angle, which requires the condition of moment compensation. Mechanisms *16, 17, 25* compensate for the platform "extensions" in its tilting. They are plain washers having the ability to move in the plane inside the cylindrical ferrule *24* of larger diameter. For rigid fixation of the separation nanosatellite on platform *13*, electromagnet *18* (Fig. 5) controlled by the microprocessor is applied that fixes the satellite base, when the current is applied on it. The ring of ferromagnet *22* is preinstalled on the satellite base. Electromagnet *18* is placed in cylindrical case *23*, guide *19* is installed in its center that serves as a bearing for rod *20*. Stretched spring *21* is put axially on the rod, therefore, platform *13* takes the necessary position when high current solenoids are cut off.

The corrector of the separation impulse works as follows. After that the nanosatellite is rigidly fixed on platform *13* by the controlled electromagnet *18*, platform *13* and measuring coils *4* under the impact of spring *21* are in the initial position (see Fig. 4). When equal impulses of current are fed to all four high-current solenoids (see Fig. 4) that are able to almost compensate for the spring force due to the fact that the center of mass of the nanosatellite is offset from its geometric location, the high-current and measuring solenoids pass different distances inside "their" assembly of ring magnets for the same time interval.

The amplitude and duration of the impulse generated by the measuring solenoids are "inversely" proportional to the moments of impulse created by impulses of forces at the expense of impulses of current excited in high-current solenoids. In fact, measuring coils register the EMF $\varepsilon_i = -\vec{B}(z)\left(d\vec{S}/dt\right)$. In accordance with the geometry of the system (Fig. 4), we can write an expression for the EMF generated in each loop of the measuring coil $\varepsilon_i = -B_\perp(z)\left(dS/dt\right)$, where $dS = dl\left(v(t)dt\right)$, or $\varepsilon_i = -B_\perp(z)v(t)\left(\int\limits_{\pi D_i} dl\right)$, i.e. $\varepsilon_i \sim v(t)$, $\int\limits_0^{\Delta t} v_i(t)\,dt = \Delta z_i$. Here Δt is the duration of the discharge pulse (the same for all correctors). Thus, if at the end of the launch impulse, which is determined by the current pulse in the main magnetic induction ejector (Fig. 2), to apply current pulses of corresponding duration on the high-current solenoids of correctors (Fig. 4), then it is possible to compensate the dispersion of the corresponding moments of forces caused by the shift of the center of mass of the nanosatellite.

The design of the launch platform for the separation device is presented in Fig. 5. Figure 6 presents a block diagram of the separation device control.

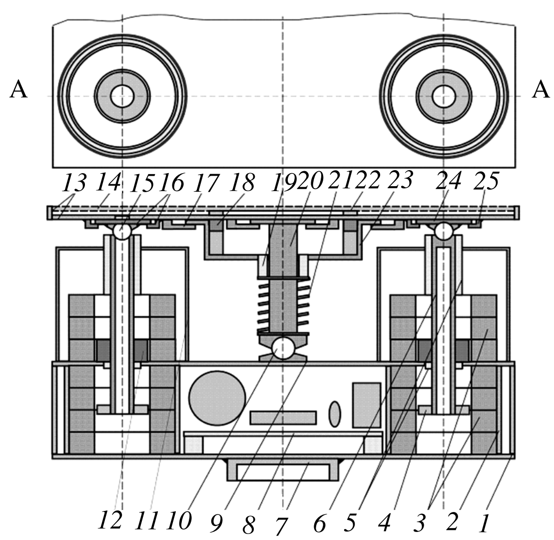

Fig. 5. Design of the launch platform.

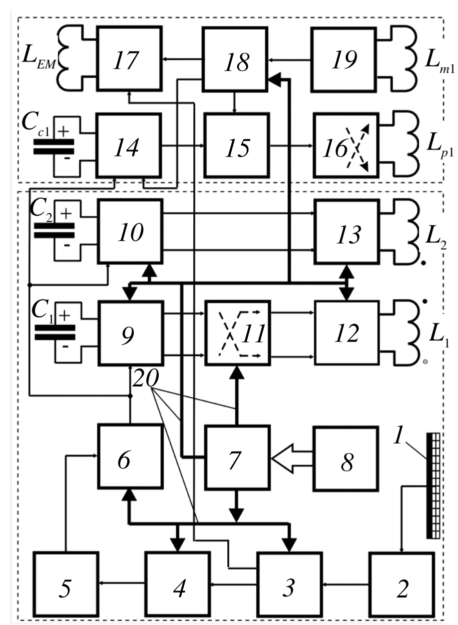

Fig. 6. The control unit of the small-size system of nanosatellite separation.

Microcontroller *7* generates control signals to the actuating parts of the magnetic induction ejector (Fig. 2) and it is connected with the onboard computing system of a delivery vehicle by the communicator *8*. The control unit includes a power system (solar panel *1*, controller *2*, voltage converter *3*), battery unit *4* and voltage stabilizer *5*.

To control the electric motors *2, 20* of the drive (Fig. 2), the engine drive is used, which receives the commands from the microcontroller. The charge of the capacitors C_1 and C_2 of the ejector module is made by means of charge control unit *6*.

After the necessary charge is generated in the capacitors, they discharge through the inductor coils L_1, L_2. At the same time during 10–40 μs, the coils L_1, L_2 are switched on so that the "winding direction" of them coincides. Then the coils L_1, L_2 are turned "counter". This is realized via the switch of the winding terminals *11* that is connected to the "stationary" inductance coil L_1 and the key charge devices of capacitors *9*, *10* and their discharge (units *12*, *13*) through the inductances L_1, L_2. The basic pulse that is required to launch a nanosatellite with the given initial velocity is generated in the initial interval of time.

The correction impulse for each of the four correctors is generated due to the interaction of the magnetic fields of the solenoid L_{p1} and the magnetic field of assembling the ring magnets upon application of the current impulse into the winding. The parameters of this current impulse are calculated by microprocessor *18*, which in turn receives the input data from the corresponding measuring solenoid L_{m1}. The windings of measuring solenoids are connected to the microprocessor via the digital data shapers *19*. The necessary energy for generating the current pulse is accumulated in capacitors C_{c1}, which are charged via the key charge devices *14* under control of the microprocessor. The discharge pulse is generated by using key *15*. Commutator *16* switches the direction of current in the winding of the solenoid L_{p1}. To control the time of switching on the electromagnet, unit *17* connected to the microprocessor *18* is used.

Capacities of 10000 μF (100 V) were used in the layout of this system. The coils of ejector contains 48 turns of wire with a diameter of 1 mm. The energy stored in each capacitor is about 50 J, the energy that can be concentrated in the ejector is approximately 3 J. The charging time of capacitors is 1–20 s. The dimensions of the device are 0.1×0.1×0.1 m^3, the mass is 2.9 kg.

CONCLUSIONS

The system developed for separation of nanosatellites is designed for launch into necessary orbits with the required parameters (initial speed, direction) of both separate nanosatellites with masses from 1 to 3 kg and their groups. The correction system of launching impulse eliminates the occurrence of rotational motion of the nanosatellite relative to its center of mass after separation.

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