Abstract

Consideration has been given to the problems of complex optimization of electrojet propulsion systems [EJPS] used in control systems (CS) of geophysical observational spacecraft (GHOSC). Analysis of the requirement to propulsion systems (PS) for correction and orientation systems of GHOSC of different generations has been carried out and the structure of determining quantities and parameters has been developed.

Efficiency criteria for EJPS has been chosen. The stationary plasma thrusters (SPT) can be considered as the promising types of engines for GHOSC control systems.

The ways of increasing the effectiveness of EJPS operation with SPT has been determined:
- improvement of dynamic characteristics due to engine stabilization;
- increase of reliability due to improvement of launch characteristics and use of malfunction control and diagnostics.

The problems of integration and characteristics of EJPS interaction with the on-board systems (solar batteries, radio engineering systems) and SC structure have been considered.

Nomenclature

\[ F = \text{thrust}; \]
\[ \Delta F = \text{thrust instability}; \]
\[ I_\Sigma = \text{summary (total) thrust impuls}; \]
\[ M_{ps} = \text{propulsion system mass}; \]
\[ \tau = \text{build-up time}; \]
\[ J_{ri} = \text{residual impuls}; \]
\[ N_n = \text{nominal power consumption}; \]
\[ p = \text{number of engines}; \]
\[ n = \text{number of start-ups}; \]

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ms = subsystem mass;
Nns = subsystem power consumption;
\eta_t = total thruster efficiency;
\dot{m} = propellant flow rate (per second);
U_a = anode voltage;
I_a = anode current;
N_d = discharge power;
V_d = discharge voltage;
I_a = discharge current;
I(t) = instant value of a current;
I_0 = stabilized current;
N(t) = instant value of power;
N_0 = stabilized power;
K_f = coefficient of thrust instability;
K_y = accuracy coefficient;
\dot{\phi} = angular velocity of rotation;
t = time;
T(t) = time-dependent temperature.

The geophysical observational spacecraft form a class of unmanned spacecraft which provide the receipt from space and the transmission to the Earth of various information about Earth and its atmosphere for the operational geophysical use, the research of Earth natural resources and the control of the environment.

The receipt of geophysical information is achieved by using information systems, measuring the Earth and atmosphere emission in the subspectral bands of electromagnetic radiation.

To achieve correction, orientation and stabilization of the spacecraft one uses the control systems which includes the propulsion system. The complicated set of requirements to propulsion systems, as executive elements is being formed on the basis of the analysis of tasks to be handled by the SC control system.

Propulsion systems are used:
- for initial correction;
- for SC orbit control;
- for location targeting and its maintenance;
- for orbit transfer (longitudinally) or for SC phase rearrangement as part of a system;
Selection procedure for a proper propulsion system includes intricate trade-offs of its operational characteristics. As a basis for this hierarchical trade-off formulation a specific mission or its alternatives are to be analyzed.

For EJPS of correction and orientation systems of GHO spacecraft of different generations ("Meteor-Priroda" 1-st and 2-st generations, Resource-O, Electro-1 - 3-st generation, Electro-2 - 4-generation) the structure determining values and parameters includes in myself on the first (highest) level:

- necessary summary (total) thrust impulse of engines \( I_\Sigma \) with the break-up on the thrust directions \( I_{\Sigma_1}, I_{\Sigma_2}, I_{\Sigma_k} \) etc.;
- engine thrusts \( F_i \) in each control channel and for each stage of the SC correction manoeuvre;
- thrust instability of engines \( \Delta F_i \);
- engines build-up time \( r \);
- residual impulse \( I_{ri} \);
- propulsion system mass \( M_{ps} \);
- nominal power consumption \( N_m \).

At the subsystem level (second level): number of engines for each thrust direction \( P_i \);
- number of start-ups on each control channel and for each correction manoeuvre \( n_i \);
- each subsystem mass \( m_s \);
- kind (sort) of propulsive mass \( p.m. \);
- specific impulse of engines \( I_{sp} \) (for calculation of the necessary propulsive mass reserve);
- each subsystem nominal power consumption \( N_{ns} \);
- characteristics of the EJPS and SC interaction (integration of EJPS with the spacecraft).

At the elements level (third level) all basic values, which correspond to the basic data of higher levels and characterized by constructive and parameter realization of each PS element.

By choice of EJPS parameters of GHO SC correction systems with limited power supply it is advantageous to minimize duration of the SC putting into operation and losses of special information, because of the correction procedures during operational life of SC with proper mass limitations.
In EPS multipurpose application in the geostationary GHO SC (Electro 1,2) correction and orientation systems as the criterion of optimization it is advantageous to use a minimum of propulsion system total mass in adhering to energetic restrictions and preserving the required control efficiency.

The problem of optimization of EJPS application in spacecraft control systems is most complex and implies formulation of efficiency indexes and criteria of operation efficiency.

As efficiency indexes for geophysical observational spacecraft of third generation (Resource-O) the following parameters may be adopted:
- periodicity of global information collection, i.e. time interval during which the target observation is performed;
- stabilization of observation conditions (orbital altitude, illumination, route repeatability for fourth generation spacecraft (Electro-2);
- continuity of survey of one and the same region of the Earth surface.

As the criterion of efficiency it is advantageous to use a minimum value of EJPS mass on condition that the required total thrust pulse and the accuracy of corrective manoeuvres are provided and the controlling forces are created.

For the real use in the SC control systems, the following types of EJE are primarily considered: hydrozine heat, ammonia electrothermal engines and xenon stationary plasma thrusters [1].

The promising type of electric propulsion engines to be used in control systems of GHO spacecraft are stationary plasma thrusters (SPT). SPT besides high rate of full flow (up to 100km/s), makes it possible to control not only the rate but also the position of the thrust and unlike ion engines can adequately operate with both small \((1-3) \times 10^{-2} \text{N}\), and large \((\geq 1 \text{N})\) thrusts at sufficiently high efficiency \((\geq 50\%)\).

Moreover, as SPT operates with low-temperature plasma at relatively low control voltage (hundreds of volts) [2] there can be provided high reliability and long lifetime \((\geq 5000 \text{ hours})\). When using xenon as fuel, SPT becomes ecologically pure system and the possibility to use simple and reliable supply system is secured.

At present SPT are already capable to implement the practical objectives of the perspective geophysical observational spacecraft. Advancement of EJPS with SPT for correction and orientation systems of GHO spacecraft calls for the following problems to be solved: increase of lifetime up to \((5-7) \times 10^3 \text{ hours}\), decrease of power-thrust ratio up to \((10-12) \text{W/mN}\), increase of specific impulse up to \(2.5 \times 10^4 \text{ Ns/kg}\), increase of the number of start-ups up to \(10^5\) and increase of its self-sufficiency due to the use of the on-board controlling systems.
SPT is advisable to use in precision altitude control systems of high-orbit GHO SC (R orbit ≥ 15'10^3 km) to provide stable control moments (not less then ±5-10%) at (1.5-3)10^-2 N level. SPTs are nicely complemented with motor-flywheels and gyroscopes which are used to dump angular momentum due to relatively low thrust value (<0.05N) and its high stability (not more then 3-5%). In what follows we will consider the ways of increasing the effectiveness of EJPS with SPT in the GHO SC control systems.

To perform the definite SC correction manoeuvres it is necessary to obtain the rated thrust impulse, which can be practically provided either by starting of SPT with stabilized thrust for a given period or by comparison of the results of integrated thrust values of unstabilized thrust which is followed by EJPS shut down at the moment of their equality. The practical realization of the second method involves some difficulties as there are no reliable low-thrust sensors. The other methods to perform SC manoeuvres, as a rule, require an additional power and fuel consumption, as well as additional EJPS start-ups. The thrust instability decrease from 25% to 10% for GHO SC Resource-O allows to decrease the total time of the initial correction by 1,2-1,35 times. In this case the number of radio controls of orbit (RCO) is decreased and their duration is reduced by 1,4-1,5 times. As applied to this SC class to keep the orbit correction intervals from 22 to 25 days it is necessary that the EJPS thrust instability were ≤5% (at average level of solar activity about 150W/m^2 Hz).

As can be seen from the high-orbit GHO SC "Electro" orientation and stabilization accuracy characteristics, the maximum value of angular velocity of SC rotation around the mass center at the motor-flywheels unloading, max^\dot{A}(t), is proportional to the engine thrust and a sum of K_f+K_y, where K_f = \delta F/F is a coefficient of thrust instability, and K_y is an uncertainty about flywhell inertia moment value.

For example, stabilization accuracy of the GHO SC "Electro-1" is provided at limitation on thrust value up to (0.05-0.07)N and K_f ≤ 10%. SPT thrust instability can reach the value of 20% compared to nominal value and depends on the supply parameters according to a formula:

\[ F = (2U_a I_a^2 \cdot A)^{1/2} \]  \hspace{1cm} (1)

Where U_a and I_a are SPT anode voltage and anode current, respectively; A - is the inverse value of SPT anode current rate of change versus propellant flow rate, m, and is equal to A = d\dot{m}/dI_a, and \eta_f is SPT thrust efficiency.
If SPT thrust instability is expressed in terms of anode current and anode supply voltage instability, complete differential function $F(U_a, I_a)$ is found and it is assumed that $A$ and $\eta_t$ are constants within the operating range of $U_a$ and $I_a$ variation, then one can obtain:

$$\frac{dF}{AU_a} = \frac{A}{2U_a} (I_a dU_a + 2U_a I_adI_a) (2I_a + 2I_a \cdot \eta_t)^{1/2} \quad (2)$$

If the expression (2) is divided by (1) and finite small increments are used instead of differentials, then the expression of the thrust instability takes the following form:

$$\frac{\Delta F}{F} = \frac{1}{2} \left( \frac{\Delta U_a}{U_a} + \frac{\Delta I_a}{I_a} \right) \quad (3)$$

Therefore, to stabilize SPT thrust it is necessary to stabilize its anode current and supply voltage. Realization of this approach allows to decrease SPT thrust instability up to 3-5%.

One of the methods of increasing the EJPS effectiveness is to improve SPT launch characteristics.

At present, heating of the SPT cathode-compensator (CC) during the specified time interval is an adopted way of launch moment readiness. As a rule, the time interval is found experimentally. But to achieve high reliability for a large number of start-ups ($>10^4$) is difficult enough with the above mentioned technique.

The use of the way of determination of SPT launch momentum readiness directly in terms of emission current from CC allows to increase of EIPS operation reliability. Requirement of EJPS build-up time decrease necessitates the use of speed up heating of the cathode-compensator, which leads to overheating or underheating.

With that, the power feeding by stabilized voltage of its usual method a power feeding of CC starting heater (SH). Use of "mixed" method of power feeding to CC starting heater by stabilized current and then by stabilized voltage allows to decrease of maximum values power and current by more than 1.6 and 2.3 times accordingly and simultaneously to decrease temperature growth rate at its operating point approximately by 1.4 times [3]. Theoretical dependence of CC temperature growth rate and its current values, power and current of starting heater on heating time in different methods of power feeding, have been presented on the Fig. 1, 2 and 3.
Putting into the structural scheme of system transformation and control (STC) the devices of automatic control and malfunction diagnostics is one of the ways of increasing the effectiveness of EJPS.

The availability of the anomalous operations in the SPT and different transient times in the EJPS units call for an additional diagnostics of possible deviations by method of tests (switching-off and repeated star-ups of engine), and also by their duration.

The problems of integration of EJPS on the basis of SPT with on-board systems and SC structural elements have been considered (including the characteristics of its interaction).

The investigation of solar battery (SB) panels resistance to prolonged action of jet and thermal radiation of SPT in the laboratory conditions has also been conducted.

**Parametrs of SPT:**

Operation 1 - discharge power \( N_d = 400 \text{W} \) (\( U_d = 160 \text{V}; \ I_d = 2.5 \text{A} \))

Operation 2 - \( N_d = 19.5 \text{kW} \); \( U_d = 500 \text{V}; \ I_d = 39 \text{A} \). The small change of volt-amper characteristics (VAC) of SB (in the limit of measurement errors) has been obtained for operation 1 for 50 hours of SPT operation with current density on the panel surface 1-5A/m^2.

The appreciable degradation of SB VAC (23...50) % has been detected for equal time for operation 2 basically by action of the heat flow. The action of thermal radiation had been determined with the discharge power \( \geq 5 \text{kw} \) for the specific geometry of SB panels and SPT on the spacecraft [4].

The information about jet and SPT thermal radiation have been used to choose the relative geometry of SB panels and SPT on the GHO SC "Electro-2", which secures its long operational time.

The investigation of electromagnetic compatibility (EMC) of EJPS with SC radioengineering systems has been conducted. For first generation of GHO SC SPT jet in the frequencies 40...200 MHz can attenuate radio signals by up to 10-20 dB, lead to parasitic LF modulation of signal by up to 10-20% worsen signal/noise ratio on the airborne receiver inputs of radio command link by more than 10 times. Jet efflux from SPT (power 400..500w) into space leads to the increase of the average electromagnetic field intensity near SC up to \( 10^{-1} \text{V/m} \) (frequency range 5-20Hz; up to \( 5\cdot10^{-3} \text{V/m} \) (0.8-1.5MHz); up to \( 5\cdot10^{-6} \text{V/m} \) (200-250MHz) [5].

The characteristics of intensity and directivity of electromagnetic radiation in wide frequency range permit to choose the relative position of SPTs and airborne receivers, which guarantees reliable radio communication with GHO SC of different generations. Also
measurements of the characteristics of interaction SC "Meteor" and "Meteor-Priroda" with environment has been carried out by mass spectrometer.

The results show the absence of visible influence of SPT operation on the spacecraft and so it seems that there is no necessity to take special measures to control the long joint operation of SC GHO and EJPS. The abovementioned problems can become more severe once SPT power reaches 10kw or exceeds it.

Conclusion

The problems of complex optimization of EJPS control systems of geophysical observational spacecraft have been discussed. The structure of determining values and parameters of EJPS have been developed. The efficiency indexes and the criteria of efficiency for use of EJPS have been proposed.

The ways of increasing the effectiveness of EJPS operation with SPT have been considered, including thrust stabilisation, improvement of launch characteristics, control and malfunction diagnostics.

The characteristics of interaction of EPS with SB panels, radioengineering systems and structural elements have been defined.

Reference


Fig 1 The dependence of SH power and CC temperature growth rate on heating time:
1 - with stabilized power,
2 - stabilized voltage,
3 - stabilized current,
4 - optimum operation of power feeding.

Fig 2 The dependence of CC temperature on heating time:
1 - with stabilized power,
2 - stabilised voltage,
3 - stabilised current,
4 - optimum operation of power feeding.

Fig 3 The dependence of SH current on heating time:
1 - with stabilized power,
2 - stabilized voltage, 3 - stabilized current, 4 - optimum operation power feeding.