

ANALYSIS OF PPT POTENTIALITIES IN SOLVING THE SATELLITE ORBIT CONTROL TASKS

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Introduction

The mathematical models for calculating the characteristics of propulsion sets on the basis of pulsed plasma thrusters (PPT) are studied in detail. The calculations for the PPT thrust impulse within the vast range starting from 10^4 to $5 \cdot 10^5$ Ns, resource values of 10^7 and $1.5 \cdot 10^7$, solar battery specific mass of 0.015 kg/W are made.

In accordance with the developed methodology, the mass values are obtained also for the propulsion modules in which the alternative options of rocket engines are used, gas jet propulsion nozzles and electric propulsions (electrothermal, ion and stationary plasma) including.

Comparative analysis is made for the thruster modules differing in the rocket engine type, using the power and mass criterion depending on the total thrust impulse.

Calculation model for the PPT mass

The PPT thruster set mass can be regarded as the sum of:

$$M_p = M_m + M_c + M_w + M_k + M_e, \quad (1)$$

where M_p – PPT set mass, M_m – mass of the stored propellant, M_c – mass of the capacitor battery, M_w – mass of the voltage transformer, M_k – mass of the PPT structure elements, M_e – mass of the power source. Components of the PPT mass can be presented as follows:

$$\begin{aligned} M_m &= mN, \\ M_c &= \gamma_c W, \\ M_w &= \gamma_w W f / \eta_w, \\ M_k &= M_{k_0} + \gamma_k W, \\ M_e &= \gamma_e W f, \end{aligned} \quad (2)$$

where: m – propellant mass outflow per impulse, N – PPT resource (total number of the impulses), γ_c – capacitor specific mass, W – energy stored in the

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capacitor, γ_w – specific mass of the voltage transformer, f – average frequency of the PPT operation, η_w – transformer efficiency, M_{k_0} – minimum mass of the structure elements which does not depend on energy, γ_k – structure element specific mass, γ_e – energy source specific mass, η_e – power source efficiency.

The thruster set mass may be presented in the following way:

$$M_p = M_{k_0} + mN + \gamma W, \quad (3)$$

where γ is a generalized specific mass:

$$\gamma = \gamma_c + \gamma_w f / \eta_w + \gamma_k + \gamma_e f / \eta_e. \quad (4)$$

As a result of processing a large number of experimental data the empirical correlation was found, which relates thrust efficiency to the stored energy and propellant mass per impulse, that is:

$$\eta = (K_a W / m)^{1/2} E, \quad (5)$$

where:

$$K_a = 4 \cdot 10^{-11} \text{ kg/J}, \quad E = W / (W + 20) \quad (6)$$

At the same time, thrust efficiency is related to the same parameters by the following relationship

$$\eta = P^2 / (2mW), \quad (7)$$

where P – single thrust impulse, defined through the total impulse:

$$P = P_n / N. \quad (8)$$

Relationships (5) and (7) allow to obtain the thruster set mass dependence on the amount of the stored energy.

Assuming that the total impulse (P_n), PPT resource (N) and the total specific mass (γ) are known, such value of the stored energy W^* can be defined when the mass of the thruster set M_p is minimum.

Calculations of minimum mass for the thruster sets were made for the total impulse values within the

range from 10^4 to $5 \cdot 10^5$ Ns. In this case the following values for the thruster set parameters were studied:

$$\begin{aligned} N &= (1.0-1.5) \cdot 10^7, \\ f &= 0.5 \text{ Hz}, \\ \gamma_c &= 0.015 \text{ kg/J}, \\ \gamma_w &= 0.020 \text{ kg/W}, \\ \eta_w &= 0.85, \\ M_{k0} &= 0.1 \text{ kg}, \\ \gamma_k &= 0.015 \text{ kg/J}, \\ \gamma_e &= 0.015 \text{ kg/W}, \\ \eta_e &= 0.85. \end{aligned}$$

Model for calculating the mass of other EP types

The main calculation relationships for the propulsion set mass are the following:

$$M_p = M_{db} + M_m + M_{sp} + M_c + M_w, \quad (9)$$

where: M_p – thruster set mass, M_{db} – thruster unit, M_m – propellant mass, M_{sp} – mass of the propellant storage and feed system without propellant, M_c – power source mass, M_w – power transformer mass;

$$M_{db} = mnM_d, \quad (10)$$

where: m and n are the number of thrusters operating in series and in parallel, M_d – own mass of an individual thruster.

Propellant mass depends on the value of the specific impulse I_{sp} :

$$M_m = Pn/I_{sp} \quad (11)$$

Mass of the “dry” propellant storage and feed system depends on the propellant mass:

$$M_{sp} = C_{sp}M_m. \quad (12)$$

Masses of the solar battery and power transformer are calculated depending on the thruster power N_w :

$$M_c = \gamma_c N_w / \eta_w, \quad (13)$$

$$M_w = \gamma_w N_w, \quad (14)$$

where: γ_c , γ_w – specific masses, η_w – transformer efficiency.

Taking indexes into consideration, the mass of the thruster module with one thruster can be presented in the following form:

$$M_p = M_{db} + P_n/I_{sp}(1+C_{sp}) + N_w(\gamma_c/\eta_w + \gamma_w) \quad (15)$$

The assessments for the mass characteristics of a number of other propulsion modules, using both electric and thermal rocket propulsions (ion thrusters, thermal thrusters and gas jet nozzles) were made similarly.

Results of the comparative analysis for the mass characteristics of the propulsion module based on PPT and modules on the basis of stationary plasma thrusters (SPT), ion thrusters (IT), resistojet thrusters

(RT) and gas jet nozzles (GJN) are presented in table 1. This table shows the power and specific mass characteristics and the mass values for the elements comprising the propulsion module: thruster, propellant, propellant storage and feed system (PSFS), power processing unit (PPU) and power plant on the basis of solar panels (SP) and accumulator batteries (AB). The GJN operating with nitrogen and hydrazine decomposition products are studied as well as ammonia RT, xenon PPT and PSFS, in which the advanced tanks of composite materials are used.

As a rule, the spacecraft propulsion set consists of several thrusters for producing the thrust impulses in different directions, and for providing the required life-time and reliability for the propulsion set. For producing the required total thrust impulse the propulsion sets on the basis of pulsed plasma thrusters comprise the corresponding number of propulsion modules with several redundant elements. Propulsion sets with alternative variants of propulsions include additional thrusters. Depending on the relation of additional masses in the propulsion set the field of PPT efficient application may be somewhat broaden. But in the case of uncertainty in the total thrust pulse loss for providing the control along different directions of the spacecraft interconnected axes the efficiency of the use of propulsion set on the basis of pulsed plasma thruster decreases because of the required reserves of propellant in the propulsion module and corresponding proportional growth in the propulsion module “dry” mass.

Fig 1a shows the propulsion set mass as a function of the total thrust impulse for the case of using as a part of propulsion set of either PPT or of its most probable competitors, such as SPT M-50, ion thruster of 150...400 W in power, resistojet thruster and GJN having the parameters, realizing the minimum mass losses for the propulsion set. The plots presented allow to define the areas of the total thrust impulse, in which the PPT application provides the lowest mass losses for the jet propulsion set comparing to the options using other thruster types.

Plots, presented in Fig.1b, illustrate in linear approximation the level of characteristic velocity, realized by the propulsion set, depending on the available PS total thrust impulse and spacecraft mass, while the plots of Fig.1c show the level of characteristic velocity, required for keeping the medium altitude ($H=600...1500$ km) orbit, depending on the period of active operation and power-to-weight ratio of the satellite. In addition, Fig.1c shows the plot

for the characteristic velocity losses, required for a satellite transfer from the reference orbit, into which it is inserted by the launch vehicle, into the operational

one, and the plot for the losses required for the satellite N-S station-keeping.

Table 1.

Ion

Propulsion set parameters	Resistojet thruster		Pulsed thruster		Gas jet nozzle		Stationary plasma thruster	Pulsed plasma thruster
Specific impulse, s	270...290		3000		70...100		1500	1300
Single thruster mass, kg	0.5		1.5		0.2...0.4		1.0	0.5
Thruster power, W	50...450		150...400		-		300	-
PSFS specific mass	0.15		0.15		0.7...0.2		0.15	-
PPU specific mass, kg/kW	-		5		-		5	5
Power set specific mass, kg/kW	15		15		-		15	15
Power set mass, kg	0.75...6.75		2.25...6		-		5.0	2.0
PPU mass, kg	-		0.75...2.0		-		1.2	0.7
Total thrust impulse, kNs	10	50	50	100	5	10	50	50
Propellant mass, kg	~4	~20	1.85	3.7	7.8...5.5	15.7...11	2.5	3
PSFS mass, kg	~0.6	~3	0.5	0.6	5.46...1.1	11...2.2	0.3	-
Propulsion module mass, kg	5.85 ...	24.25 ...	6.65 ...	8.8 ...	13.46 ...	26.9 ...	13.4	15.6
	11.85	30.25	11.65	13.8	7	13.4		

As follows from Fig.1a, the propulsion sets on the PPT basis provide the lowest mass losses comparing to the propulsion sets on the basis of SPT M-50 and 150...400 W ion thrusters for the total impulse range of less than 60 kNs, practically independently on the power set specific mass. In some cases, complete or partial use of the power set, supplying the payload, is possible for supplying the jet propulsion set. For the total impulse of less than 3...5 kNs the pulsed plasma thruster is the second in mass after the propulsion sets on the basis of gas jet nozzles and thermal thrusters.

Characteristic velocity losses for keeping the orbit for a satellite operating in medium altitudes of 600...1500 km are mainly conditioned by the compensation of errors during the insertion stage with the required level of characteristic velocity of about 10 m/s and of the disturbances, caused by the light pressure and aerodynamic drag, at the characteristic velocity losses

from 2 to 10 m/s per year and at the satellite power-to-weight ratio of 1...5 W/kg. The level of required total thrust impulse within the range of 10-60 kNs is characteristic for correcting the orbit of a satellite of up to 1000 kg in mass, operating in medium altitudes of 600...1500 km during 6...10 years for keeping the track of an Earth remote sensing satellite or keeping the structure for a low-orbit communication satellite constellation.

Realization of the final part of the satellite insertion into the operational orbit using the propulsion set comprising the electric propulsions allows to increase the mass of the payload inserted into this orbit. Fulfillment of this operation using the propulsion set based on PPT with a total impulse of up to 60 kNs provides the orbit altitude variation within the limits of 300...500 km for a satellite of 500...250 kg in mass at a transition duration of up to 7.5 months.

Station-keeping for a geostationary communication satellite with an active lifetime of 5...10 years is a power consuming task and requires high losses of characteristic velocity of 2.5...5 m/s per year for a longitudinal correction (W-E) and of about 50 m/s per year for N-S station-keeping. Propulsion set with a total impulse of up to 60 kNs provides the N-S station-keeping for a satellite of up to 250 kg in mass during 5 years.

W-E station-keeping during 5-6 years may be acceptable for the geostationary satellites designed for the Earth remote sensing, meteorological satellites in particular, and is provided by a propulsion set on the basis of pulsed plasma thruster with a total impulse of less than 60 kNs for a satellite of up to 1000...1500 kg in mass.

From the mass losses point of view the use of PPT as a part of propulsion set with a total impulse of 60 kNs is comparable to a propulsion set on the basis of SPT-50, 150...400 W ion thruster and resistojet thruster with a minimum power of about 50 W, while their efficient use may be conditioned by other criteria, in particular, by the simplicity, reliability, low cost, etc.

Propulsion set on the basis of PPT with a total impulse of 20 kNs requires the mass loss at a level of 5...7 kg, that being by 50% (93...5 kg) less comparing to a propulsion set based on SPT-50, IT and RT at minimum power losses for the power supply and by 80% (20 kg) less comparing to the propulsion sets b

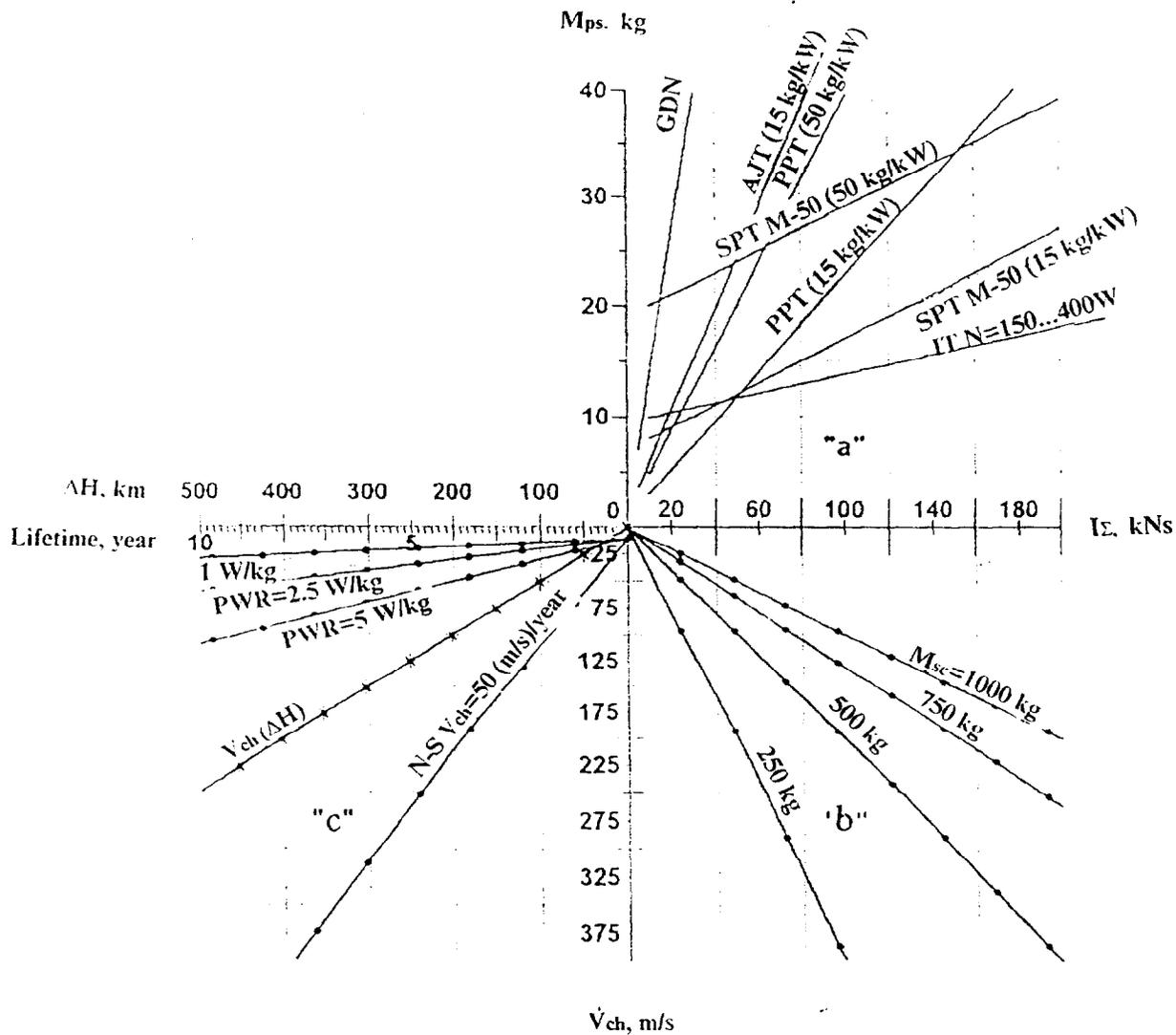
ased on the most perspective gas jet nozzles.

Conclusion

A comparative analysis is made for the mass characteristics of propulsion module based on pulsed plasma thrusters and a number of perspective propulsion modules using SPT, IT, GJN, RT. It is shown that the propulsion module based on PPT has advantages in mass comparing to the above-mentioned propulsion modules within the total impulse range of up to 60 kNs.

Reduction of losses for a propulsion set based on PPT may be used for decreasing the mass of a satellite in total or for increasing the payload mass/satellite active life-time while keeping the satellite mass.

ANALYSIS FOR THE EFFICIENCY OF PPT APPLICATION FOR DIFFERENT ORBITAL SPACECRAFT MISSIONS



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- Propulsion set mass
 - *— V_{ch} losses for the orbit altitude variation
 - V_{ch} losses as functions of spacecraft mass, life-time, power-to weight ratio and mission
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