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Associated Optimization of the Low-Thrust Trajectory and Parameters of the Nuclear Power Plant

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It is considered optimization of the main design parameters of the electric propulsion missions. It is supposed that onboard power source is a “Topaz”-type nuclear power plant (NPP). NPP parameters can be varied within some limits, which are defined by possibility of the modification of the developing basic NPP model NPP-25. There are considered NPP modifications that allow to enforce its output power for a different duration. This investigation concerns to coordination of the spacecraft design parameters and basic parameters of the NPP (electrical power, lifetime, mass, and size).

Use of the combined electric propulsion and chemical upper stages allow effectively deliver payloads into the geosynhronous orbits and to the celestial bodies of the Solar system[1,3,4,6]. It is supposed that launcher put on the low Earth orbit (LEO) chemical upper stage (ChUS) and spacecraft with electric propulsion module. ChUS forms “nuclear-safe” orbit (this is orbit that provides safety of the NPP running) or deliver spacecraft into the geocentric hyperbolic trajectory.

There is most expedient to use thermoionic NPP because of its compactness and possibility essential to enforce its power when electric propulsion engines are running. Optimization of the low-thrust trajectories shows that magnitude of the optimal thrust acceleration is widely varied along the trajectory if the thrust magnitude is unconstrained. Approximation of these trajectories by means of invariable low thrust engines is connected with use of different thrust levels. This requires to control electrical power. Therefore, it is interest to consider two-regimes NPP.

NPP includes[2]:

- power module, which moves away instrumental module before NPP runs;
- deployment system with electrical cables along it;
- instrumental module with automatic control system.

Power module contains reactor-converter with electric-generating channels and thermoionic converters, radiation shell, radiators, structure, elements of the power supply, control and telemetric systems. NPP launching configuration is differed with respect to working one due to unpacked structure of the radiators. This structure allows to place NPP inside the limited-volume space inside launcher fairing.

NPP mass and size are mainly defined by output electrical power and lifetime. These parameters are defined by working condition, which includes magnitude of the electrical power in the different regimes, consequences, and duration of these regimes. It should be noted that given reactor-converter “type-size” allows to provide wide enough diapason of the electrical power. So, mass and size of some service systems remain invariable. Radiation shell and radiators define main variations of the NPP mass and size with respect to variation of the electrical power and lifetime. Maximal magnitude of the electrical power is decreased if duration of the enforced regime is increased. These facts can lead to essential correlation between NPP power in the enforced regime and duration of this regime if total lifetime is fixed. Variations of the NPP mass can be negligible in this case.

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Let us consider design of the Fortuna rendezvous mission based on two-regimes NPP and electric propulsion engines with constant specific impulse (Fortuna is asteroid that belongs to the Main Asteroid Belt). There are considered two variants of the NPP:

NPP-1. Nominal output electrical power N_n equals to 25 kW, and enforced one N_e equals to 50 kW. Mission analysis is carried out to estimate variations of the optimal mission parameters (payload mass, in particularity) with respect to duration of the enforced regime.

NPP-2. The second NPP variant is more powerful and more heavy (N_n= 41.75 kW and N_e= 83.5 kW).

NPP-1

Trajectory design problem is follows. It is assumed that Russian launcher "Proton" put on the LEO (altitude H=200 km) upper stage "Block D" and spacecraft, which is equipped by NPP-1 and electric propulsion module. ChUS "Block D" delivers spacecraft into the geocentric hyperbolic orbit, which is characterized by asymptotic velocity V_∞. Further electric propulsion module provides transfer to the Fortuna and equalizing of the heliocentric velocities of the spacecraft and asteroid. There are required to determine unknown design parameters of the spacecraft, optimal trajectory and control. It is assumed that performance index is payload mass. The transfer duration is fixed and duration of the enforced regime has upper bound. There are necessary to optimize:

- mass of the propellant in the ChUS "Block D" (or magnitude of the V_∞);
- direction of the V_∞;
- launch date;
- thrust control (thrust direction with respect to time and disposition of the burn and coast arcs);
- power control (NPP output electrical power with respect to time).

Parameters of the "Block D" were given from ref.[5] There is assumed that mass of the spacecraft structure and service systems equal to 1000 kg, and specific mass of the xenon tanks equals to 0.13 (xenon is propellant of the electric propulsion module). Specific mass of the electric propulsion module equals to 10 kg/kW. There are assumed that European ion thrusters ESA-XX[6] are used in the electric propulsion module. The total thrust of the electric propulsion module equals to 84 g in the nominal regime and it equals to 156 g in the enforced one. The specific impulse is invariable and it equals to 5419 s.

Table 1 presents some results of the 650-days mission design. There are mission parameters with respect to given duration of the enforced regime T_e in this table. The follows notation is used in the table 1:

- M_o is initial spacecraft mass after separation of the "Block D";
- V_∞. is initial geocentric hyperbolic exceed of the spacecraft velocity;
- T_b is total duration of the all heliocentric burn arcs;
- M_f is final spacecraft mass in the vicinity of the Fortuna;
- M_{xe} is required mass of the xenon;
- M_{pl} is payload mass.

Table 1

Fortuna rendezvous missions parameters

T_e [days]	M_o [kg]	V_∞ [km/s]	T_b [days]	M_f [kg]	M_{xe}[kg]	M_{pl}[kg]
∞	6065	1.051	399.7	5070	995	1241.1
365	6019	1.239	408.2	5053	966	1227.4
200	5953	1.473	535.2	5005	948	1187.8
100	5740	2.053	584.1	4843	897	1026.4
50	5560	2.459	597.0	4702	858	890.5
0	5314	2.936	636.0	4462	853	651.1

NPP mass variation of the enumerated variants is negligible. So, it is assumed that NPP mass is invariable and it equals to 2200 kg.

Analysis of the investigation results shows that use of NPP enforcing allows essentially to increase payload mass.

Fig. 1 presents optimal dependencies of the NPP electrical power with respect to time for all 6 trajectories, which are presented in the table 1.

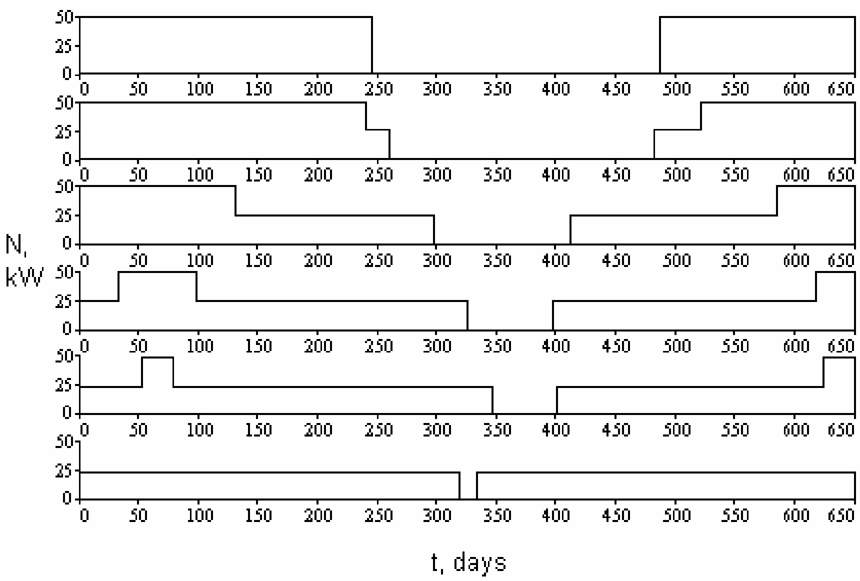

Fig. 1. Optimal NPP-1 power control of Fortuna rendezvous mission

The upper chart corresponds to unlimited duration of the enforced regime. Optimal magnitude of the electrical power equals either N_e or 0 in this case. The bottom chart corresponds to the nominal NPP power without ability of enforcing. The rest charts correspond to restrictions T_e=365, 200, 100 or 50 days. These restrictions were found essential ones, so as duration of the enforced regimes is equal to limit magnitudes. On the other hand, total duration of the burn arcs was found less than NPP lifetime on the optimal trajectories.

<u>NPP-2</u>

This variant supposes N_n=41.75 kW and N_e=83.5 kW. Use of the ChUS was found inexpedient in this case. Modern and prospective ChUS can put on the geocentric parabolic orbit mass nearly 6 tons if launcher “Proton” is used. This initial mass does not allow to deliver appropriate payload mass to the Fortuna. So, it is expedient use powerful NPP-2 and electric propulsion to achieve geocentric parabolic velocity.

The problem formulation is follows. It is assumed that “Zenith”-type launcher put on the LEO (H=200 km) spacecraft and ChUS. The ChUS is used to raise orbit up to 800 km (“nuclear-safe” altitude), and then it is separated from the spacecraft. Then NPP and electric propulsion module are switched on in the enforced regime, and spacecraft moves along spiral-like trajectory around the Earth to achieve parabolic velocity. The thrust direction is assumed transversal one in this arc of the trajectory. It was found that duration of this arc equals to 310 days.

It was assumed that duration of the enforced regime must not exceed T_e=1.2 years. The exceed of duration of the enforced regime with respect to duration of the geocentric spiral-like motion is used in the heliocentric arc of the trajectory to optimize NPP power control. It was found that initial spacecraft mass M_o at the beginning of the heliocentric arc equals to 10000 kg.

There should be found unknown mission parameters, trajectory and optimal thrust and power control, which are provide maximal payload mass. It is supposed that duration of the enforced regime should not exceed given magnitude.

There are necessary to optimize:

- launch date;
- thrust control (thrust direction with respect to time and disposition of the burn and coast arcs along the trajectory);
- NPP power control.

It is assumed that ion thrusters ESA-XX are used. Total thrust of the electric propulsion module equals to 142.8 g in the nominal regime and it equals to 285.6 g in the enforced one. Specific impulse is assumed invariable and it equals to 5419 s. Specific mass of the electric propulsion module equals to 10 kg/kW. NPP mass equals to 3000 kg. Mass of the spacecraft structure and service systems equals to 1000 kg. Specific mass of the propellant tanks equals to 0.13. It is assumed that duration of the heliocentric arc equals to 850 days.

The optimization demonstrated that optimal mission parameters are follow:

- final spacecraft mass in the vicinity of the Fortuna equals to 8043 kg;
- propellant mass, which it is required in the geocentric and heliocentric parts of the trajectory, equals to 3369 kg;
- payload mass equals to 2770 kg;
- total duration of the burn arcs equal to 1042.5 days.

Fig. 2 presents optimal NPP power control.

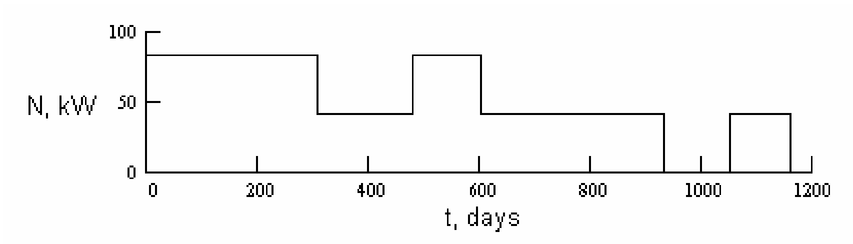

Fig. 2. Optimal NPP-2 power control of Fortuna rendezvous mission

The carried out investigations demonstrate expediency to use two-regimes NPP. The duration and sequence of these regimes should be optimized taking into account flight conditions and design restrictions. It is shown that more powerful and more heavy NPP is more efficiency if more appropriate launcher is used, and electric propulsion module is used instead of ChUS to achieve geocentric parabolic velocity. It can be provided essential increasing of the payload mass in this case. Analysis, which was carried out, contributes to determination rational NPP parameters and ways of the expedient NPP modification.

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