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Joint optimization of the trajectory and the main parameters of an electric propulsion system

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Abstract

The problem of joint optimization of the trajectory of a spacecraft with an electric propulsion system and for the main parameters of electric propulsion and power supply systems is considered. It is well known that for every space transportation operation there is an optimal value of specific impulse of electric propulsion corresponding to the minimum total mass of the system, the power supply system ensuring electric propulsion operation, and the propellant. It is easy to show that there is also an optimal value of electric power of an electric propulsion system, associated with the growth of the required characteristic velocity with the thrust decrease. Optimal specific impulse and electric power can be found only by joint optimization of the trajectory and design parameters of electric propulsion. A simple spacecraft mass budget model and the maximum principle are used for optimization. The necessary optimality conditions for the specific impulse and electric power of electric propulsion system are derived. Numerical examples of the joint optimization of interplanetary trajectory, electric power and specific impulse of electric propulsion systems are presented.

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Keywords: electric propulsion system (EPS); heliocentric trajectory; Pontryagin maximum principle; continuation technique.

1. Introduction

The use of electric propulsion systems (EPS) with a high specific impulse compared to traditional chemical rocket engines can considerably increase the efficiency of space transportation operations by a significant reduction in the propellant mass. This leads to the prospect of using electric propulsion for performing orbital and interplanetary missions. The number of completed projects of the spacecrafts (SC) using EPS as the main propulsion systems has grown since the 1990s when the first practical experience of real space transport operations was obtained. These completed projects include a series of geostationary satellites and interplanetary spacecraft.

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Nowadays several new projects for near-earth and interplanetary spacecraft with electric propulsion systems are being prepared for realization. Moreover, the use of electric propulsion for flights to target orbits, or for interplanetary flights, is regarded as one of the most promising options for the majority of the spacecraft under design. The effectiveness of the use of electric propulsion for performing space transportation operations is stipulated by the level of technology being used and by the optimal choice of the main design parameters of electric propulsion.

When considered from the point of view of space transportation problem analysis, the level of technology is defined by the total efficiency of EPS η - the ratio of the mechanical power of the plasma beam to the electric power consumed by EPS; specific mass of the power supply and propulsion unit (PSPU) γ - the ratio of the total mass of the electric propulsion system and its onboard power supply system (PSS) to the electrical power consumed by the electric propulsion system; the relative mass of the propellant storage and feeding system (PSFS) a_t - the ratio of the final mass of PSFS to the propellant mass consumed by the electric propulsion system. The main design parameters of the electric propulsion system are thrust T, specific impulse c and power consumption P. Although the acceptable range of the main design parameters of the EPS has technical constraints, the calculation of their optimal values is required to justify the choice of the type, the operational mode and the number of thrusters in the main EPS and the PSS parameters of the spacecraft under design. In addition, optimization of the main design parameters for typical space transportation operations is the basis for the choice of their values in the design of new thrusters.

So far a typical approach to optimizing the main parameters of the EPS has consisted in solving a number of problems of optimization of spacecraft trajectories with different values of these parameters. To a certain extent, this approach is associated with the tradition to divide the optimization problem into the dynamic (trajectory) and parametric (design) problems. The purpose of this paper is, on the contrary, the combined optimization of the trajectory and the main design parameters of the EPS. To solve this problem, an indirect approach based on the maximum principle is used and necessary conditions of optimality of the main design parameters of the electric propulsion system are derived [1]. Optimization of a nuclear electric propulsion mission to Jupiter is presented as a numerical example of the approach applying to the space mission design.

Nomenclature

EPS	electric propulsion system
SC	spacecraft
PSS	power supply system
PSPU	power supply and propulsion unit
PSFS	propellant storage and feeding system
$\mathbf{x}$	position vector
$\mathbf{v}$	velocity vector
m	mass
t	time
Ω	force function
δ	thrusting function
$\mathbf{e}_T$	unit vector along thrust direction
μ	gravity parameter
$V_{\infty 0}$	hyperbolic excess of velocity
P	EPS electrical power
T	EPS thrust
c	EPS specific impulse
γ	PSPU specific mass
η	EPS efficiency
a_t	ratio of PSFS dry mass to filled propellant mass
J	cost function
H	Hamiltonian
ψ	switching function
$\mathbf{p}$	adjoint vector
ε	small regularization parameter
τ	continuation parameter