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Evaluation of the efficiency of propulsion systems usage with energy accumulation at spacecraft

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Abstract

The problem of cooperative optimization of trajectory and main design parameters of spacecraft, equipped with propulsion systems with energy accumulation, during low Earth orbit formation and correction in non-central gravitational field is considered. The working principle of these propulsion systems is a periodic cycle of energy accumulation from the energy source at the passive stages of orbital transfer, and its discharge to supply power to the engine during the active stages of orbital transfer. The special characteristics of propulsion systems with energy accumulation is limited operation time per one switching, which determines by the energy, stored in an accumulator. For design-ballistic analysis, the mass model of the spacecraft with an uncontrollable power-limited engine with energy accumulator is used. The general problem is separated into dynamic and parametric parts. Using averaging mathematical models of motion and Pontriagin's maximum principle, the calculation method of the ballistic characteristics of approximately-optimal orbital transfer is obtained. The method of design-ballistic optimization is obtained as an iterative procedure. It was found, that inclusion of an energy accumulator in a propulsion system provides an increasing of orbital transfer efficiency.

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Keywords: spacecraft; propulsion system with energy accumulation; design model; averaging method; optimal control program;

1. Introduction

One method of increasing orbital transport operation efficiency, for spacecraft transferring from injection to working orbit or orbital correction, is to use engines with high specific impulse. Specific impulse can be increased by using new working fluids or an additional thermal or electrical energy supply. Widely used electric jet engines (EJE) of a low-thrust, can provides a significant increase in payload mass or enable the spacecraft to be equipped with a lighter rocket. At same time, EJE have the disadvantage of a significantly longer duration of orbital transfer.

Nowadays, perspective propulsion systems with energy accumulation devices are being designed, characterized by a thrust order of about dozens of Newton and specific impulse which average between EJE and liquid engines (LE). At the Keldysh Research Center, a solar thermal propulsion system (STPS) with heating of the working fluid is being designed. The operational principle of STPS is next. During the sunlit portion of an orbital transfer, solar panels can be used to transfer solar energy to heat energy, which can be stored in a thermal accumulator (TA).

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Before fuel (hydrogen) supply to the engine, it is heating in TA that increases specific impulse. STPS can operate at LE mode with cold components (oxygen - hydrogen). The special characteristic of this propulsion system is limited operation time per one switching, determined by the TA working capacity, and the higher thrust order, that allow the orbital transfer duration to be decreased.

2. Problem statement

The main optimization problem in spacecraft dynamics is the maximal payload mass m_{PL} transferring to working orbit for determined boundary conditions, initial spacecraft mass m_0 and orbital transfer duration T . For problem solving, the design model of a spacecraft, equipped with an uncontrollable power-limited engine with energy accumulator [2] is used. It is assumed that propulsion system operates in two modes. Firstly, the engine is switched-on, thrust P and exhaust velocity c are constants and the energy accumulator is discharged with constant power N_E . Secondly, the engine is switched-off, parameters P and c are equal to zero and the energy accumulator is charged from solar panels with constant power N_S . For analysis, a spacecraft mass model is introduced, as a sum of spacecraft components mass:

$$m_0 = m_{PL} + m_C + m_E + m_S + m_{en} + m_{wf} + m_{fs} ,$$

where m_{PL} – payload mass, m_C – spacecraft structural mass, m_E – mass of TA, m_S – solar panel mass, m_{en} – engine mass, m_{wf} – working fluid mass, m_{fs} – fuel storage and fuel transfer system mass.

The components mass can be written as functions:

$$m_C = \mu_C m_0 , \ m_E = \gamma_E E_0 , \ m_S = \gamma_S N_S , \ m_{en} = \gamma_{en} P , \ m_{wf} = \frac{P}{c} T_m , \ m_{fs} = \beta_{fs} m_{wf} ,$$

where E_0 – maximal energy, stored in the accumulator (accumulator operational capacity), N_S – solar panel power, P – engine thrust, c – exhaust velocity, T_m – duration of active areas of orbital transfer, μ_C , γ_E , γ_S , γ_{en} , β_{fs} – respectively specific mass characteristics, assumed as constant values.

For payload mass, we can write:

$$m_{PL} = m_0 \left(1 - \mu_C\right) - \gamma_E E_0 - \gamma_S N_S - \gamma_{en} P - \left(1 + \beta_{fs}\right) m_0 \left(1 - \exp\left(-\frac{V_x}{c}\right)\right), \quad (1)$$

where V_x – characteristic velocity of orbital transfer.

The vector of optimized design parameters contained engine thrust, solar panel power and TA operational capacity: $\boldsymbol{\psi} = \left(P, N_S, E_0\right)$. If we fix the design parameters, the maximum of payload mass m_{PL} correspons to minimal characteristic velocity V_x . The main variational problem is divided into dynamic and design parts.

The dynamic problem involves determining the optimal control program, which minimizes characteristic velocity, taking into account limitations to control vector $\boldsymbol{u}$ and state vector $\boldsymbol{x}$:

$$\boldsymbol{u}_{opt}\left(t\right) = \underset{\boldsymbol{u} \in \boldsymbol{U},\, \boldsymbol{x} \in \boldsymbol{X}}{\arg\min} \left[V_x \left(\boldsymbol{u}, \boldsymbol{x}_0, \boldsymbol{x}_k, T\right) \ \middle| \ T = fixe, \boldsymbol{x}_0 = fixe, \boldsymbol{x}_k = fixe \right].$$

The design part is formalized in the following equation:

$$m_{PL} = \underset{\boldsymbol{\psi} \in \boldsymbol{\Psi}}{\arg\max}\, m_{PL} \left(\boldsymbol{\psi} \middle| \ V_x = V_{x\min} \left(\boldsymbol{\psi}, \boldsymbol{x}_0, \boldsymbol{x}_k, T\right)\right).$$

3. Calculation method of approximately-optimal ballistic characteristics of orbital transfer