Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 185 (2017) 304 – 311

Procedia Engineering

www.elsevier.com/locate/procedia

6th Russian-German Conference on Electric Propulsion and Their Application

Analysis for Feasibility of Spitzer's Schemes Complication for Spacecraft Final Insertion into Geostationary Orbit by Electric Propulsion

Mikhail Konstantinov[a]*, Victoria Svotina[b]

[a]*Professor, RIAME Leading Researcher, 5 Leningradskoe sh., Moscow, 125080, Russian Federation*
[b]*RIAME Head of Laboratory, 5 Leningradskoe sh., Moscow, 125080, Russian Federation*

Abstract

In the mid-90s of the past century Arnon Spitzer offered a flight scheme comprising an elliptical synchronous equatorial orbit for the SC injection into geostationary orbit (GEO). The advantages of such scheme were related to the SC control simplicity during its transfer from the elliptical synchronous orbit into GEO. The main advantage of Spitzer's scheme is the possibility of observing spacecraft from Earth using a limited number of ground stations along the entire trajectory of the SC flight from an intermediate orbit into GEO. Some flight schemes, which preserve the main advantage of the Spitzer's scheme, are analyzed. The inclination and the eccentricity of the intermediate synchronous orbit are optimized. Several variants of the yaw angle control are analyzed. Numerical analysis was carried out for a space transportation system based on the launch vehicle "Angara-A5", chemical upper stage "KVTK", and electric propulsion system comprising four thrusters SPD-140 with the specific impulse of 1700 s.

Peer-review under responsibility of the scientific committee of the 6th Russian-German Conference on Electric Propulsion and Their Application

Keywords: Spacecraft; Electric Propulsion; Geostationary Orbit; Intermediate Synchronous Orbit; Spitzer's Scheme

Introduction

Spitzer [1-3] proposed the scheme of SC injection into GEO that had the following advantages: the possibility of observing spacecraft from Earth using a limited number of ground stations along the entire trajectory of the SC flight from an intermediate orbit to GEO; and the possibility of a permanent electric propulsion system (EPS) thrust vector orientation control in inertial space during the entire flight from an intermediate orbit to GEO (for the equatorial intermediate orbit option).

Such scheme is actively used, for example, for final injection of space platform Boeing-702 by XIPS (Xenon Ion Propulsion System) into the GEO. The possibility to raise the SC injection efficiency (by shortening the time for SC injection into GEO or increasing the SC mass inserted into GEO) has not been sufficiently studied yet, due to some complications of the flight scheme. It was attempted to analyze some flight schemes which preserve the main advantage

---

* Corresponding author. Tel.: +7-916-095-0218; fax: +7-499-158-0367.
E-mail address: mkonst@bk.ru

Peer-review under responsibility of the scientific committee of the 6th Russian-German Conference on Electric Propulsion and Their Application
doi:10.1016/j.proeng.2017.03.308

of the Spitzer's scheme (see above). SC mass injected into GEO vs. injection time is the criterion for assessing the modified scheme efficiency. The results of efficiency numerical analysis are presented for the following space transportation system: launch vehicle injected into the base low-Earth orbit (200-km circular orbit with 630 inclination) - 24-tons SC; chemical oxygen-hydrogen upper stage (specific impulse of 470 sec, final detachable mass of 3.3 tons); EP system with four operating thrusters with specific impulse of about 1700 sec and total thrust of 1.16 N.

Modification of the Spitzer's scheme is based on the following ideas:

- Introduction of the inactive legs into the trajectory (at such legs, the EPS thrust changes osculating orbit elements during the EPS operation relatively non-effectively).
- Modification of the structure of flight control law from one trajectory pass to another for a SC with EPS operation.
- The use of non-zero yaw angle at any part of trajectory pass for changing osculating orbit inclination during the flight with EPS operation (in order to vary orbit inclination and eccentricity simultaneously).

Analysis for the flight control laws for a SC with EPS resulted in the absence of perturbation of the osculating orbit semi-major axis (osculating orbit period has no secular perturbations, it equals to one sidereal day). Analysis for the SC with EP motion was conducted using the model of Newton's gravitation field of the Earth and in case of EPS thrust effect. The second zonal harmonic influence on the SC with EPS trajectory was analyzed.

1. Mathematical model for the motion of SC with EPS

Equations for the osculating orbital elements can be conveniently represented as a function of eccentric anomaly (E). EPS thrust P components for the orbital coordinate system axes are defined by pitch φ and yaw ψ angles as $S = P\cos\psi\sin\varphi;\ T = P\cos(\psi)\cos(\varphi);\ W = P\sin(\psi)$. Yaw angle is the angle between the thrust vector and the osculating SC motion plane [-90°…+90°]. The pitch angle is the angle between the transversal and thrust vector projection on the SC motion plane [-180°…+180°].

Let's consider that some parts of the SC trajectory pass with the constant yaw angle ψ=*const* and operating EPS. An eccentric anomaly of this trajectory part varies from E_o up to E_K ($E_K>E_o$). Let's choose such pitch angle, with which the thrust projection onto the osculating plane of the SC motion is perpendicular to the apsidal line of the orbit, while in the orbit perigee such projection is opposite to the local transversal. At this, in the orbit apogee the thrust projection onto the osculating plane will be directed along the local transversal. Then the pitch angle will relate to the true anomaly υ of the current orbital point as $\varphi=\upsilon+180°$, and the components of reactive acceleration in the orbital axes have the following form: $S = -P\cos(\psi)\dfrac{\sin(E)\sqrt{1-e^2}}{1-e\cos(E)};\ T = P\cos(\psi)\dfrac{e-\cos(E)}{1-e\cos(E)};\ W = P\sin(\psi)$ (e – orbit eccentricity). Let the reactive acceleration and the orbit elements along the considered part of the orbit are constant. Then the secular drifts of the orbit elements under the influence of the disturbing reactive acceleration have the following mathematical formulas where: a – semimajor axis, p – focal parameter, ω - perigee argument, i – inclination, Ω – longitude of ascending node, μ - gravitation parameter of Earth, m – SC mass.

These relations will be used for the analysis of motion of a SC with EPS for the flight schemes presented hereinafter.

$$\begin{aligned}
&\Delta a = \frac{-2P}{\mu m} a^3 \cos\psi\left(\sin E_k - \sin E_o\right);\\
&\Delta p = \frac{2P}{\mu m}\cos\psi \frac{p^3}{\sqrt{\left(1-e^2\right)^5}}\left[\frac{3e}{2}\left(E_k - E_o\right) - e^2\left(\sin E_k - \sin E_o\right) + \frac{e}{4}\left(\sin 2E_k - \sin 2E_o\right) - \left(\sin E_k - \sin E_o\right)\right]; \qquad (1)\\
&\Delta e = \frac{-P}{\mu m} a^2 \cos\psi\sqrt{1-e^2}\left[\frac{3}{2}\left(E_k - E_o\right) + \frac{1}{4}\left(\sin 2E_k - \sin 2E_o\right) - 2e\left(\sin E_k - \sin E_o\right)\right];
\end{aligned}$$