Spacecraft motion and attitude control in the high elliptic orbit

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Abstract: The use of electric propulsions (EP) for spacecraft (SC) control system that should solve two basic dynamic problems: design orbit parameters keeping as well as SC required orientation securing is analyzed. For SC in high-elliptic orbit (HEO) the problem of attitude control is complicated, because in addition to orientation, associated with the mission, there appears a necessity to follow SP orientation to Sun. According to the presented analysis for the peculiarities of angular motion of a spacecraft (SC) equipped with EP subsystem (EPS) HEO, the control propulsion systems should be capable of generating corrective thrust in any direction relative to SC practically and of varying EPS thrust direction relative to SC while providing orbit correction. The EPS structure with pivoted thrusters located according to "star" circuit, at which the thrusters are located equidistantly in the same plane, and nominal thrust directions of thrusters cross the SC axis of inertia being orthogonal to this plane and the efficiency of its usage are analyzed. It is shown that such control structure appears to be more efficient, if the capability is provided for simultaneous operation of several thrusters, as well as the capability to adjust thrust of the thrusters. The proposed EPS structure allows also increasing discreteness of control action directions due to the thruster location. So, for example, with 6 thrusters used there will be 12 such directions and the angle between possible adjacent directions of thrust generated by EPS will be 30°. The use of thrusters with controllable thrust direction for the motion control allows, on the one hand, to increase the efficiency of thrust use up to 1, and, on the other hand, to generate control thrust moments both for the SC attitude control, and for unloading the SC attitude control hand wheel system. The proposed EPS makes it possible to use electric power and working body available on board more efficiently.

Nomenclature

ψ	=	thrust vector yaw angle
η	=	eccentric anomaly angle
$\xi_{p,a,1,2}$	=	a half of a boost path at eccentric anomaly in vicinity of perigee, apogee, ascending and descending paths of an orbit, respectively
ε	=	angle discrete derivation for nominal thrust direction

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α	=	permissible angle for thruster variation in the mounting plane
β	=	permissible angle for thruster variation respect to the mounting plane
γ	=	thruster deviation angle in the mounting plane
δ	=	thruster deviation angle respect to the mounting plane
P	=	nominal thrust of a single thruster
P_{SC}	=	resultant thrust of thruster subsystem
P_i	=	thrust projection on one of the axis of a connected coordinate system
P_{ij}	=	thrust projection on a plane including axis of a connected coordinate system
H	=	heeling arm of thrust respect to the longitudinal SC axis

I. Introduction

The spacecraft flight control system should solve two basic dynamic problems in the high elliptic orbit (HEO): design parameters keeping for the spacecraft orbit and securing of the required spacecraft attitude control. In the high elliptic orbit it is advisable to use electric propulsion systems (EPS), based on stationary plasma thrusters (SPT) for example, as the actuators of the spacecraft control system. Electric propulsions (EP) are characterized by high specific impulse allowing to decrease propellant mass comparing to the chemical engines, and thus to increase the spacecraft payload mass. But EP use requires spacecraft equipping with additional solar panels (SP) for the EP power supply. This makes the spacecraft control problems solving more complicated, because in addition to the attitude control associated with the execution of purpose-oriented task there appears a necessity to secure SP orientation to Sun. Problems of high elliptic orbit keeping for a spacecraft being a part of the constellation, as well as of the calculation of corrective impulses required for this were considered in [1, 2]. Arrangement of propulsion system capable of realizing spacecraft orbit correction algorithms suggested in [1, 2] is discussed in this paper. It is assumed that the spacecraft longitudinal axis should be directed to the center of Earth. Orientation problem for such a spacecraft should be solved in view of the fact that in addition to securing the spacecraft longitudinal axis direction to the center of Earth, the solar panels should be oriented to Sun for supplying electric power to the auxiliary systems and special-purpose equipment of the spacecraft and operating EPS. In the majority of cases rather high requirements are imposed on the accuracy of SP orientation to Sun. It is advisable to use flywheels for keeping necessary (highly accurate, as a rule) spacecraft attitude and to unload inertial attitude control system with the help of EPS. EPS application as actuators of the spacecraft control system is not advisable in this case, because for this purpose it is necessary to generate low thrust pulses at frequent thruster operation that being a task difficult of accomplishment. Axis of the solar panel rotation is usually orthogonal to the longitudinal axis of the spacecraft. Procedure of solar panel orientation to Sun consists of two stages: spacecraft rotation relative to its longitudinal axis and solar panel rotation relative to its axis. As is known, such rotation plan in some situations leads to high angular velocities and angular accelerations required for precise SP orientation to Sun, and this should be taken into account while considering solutions for specific tasks.

II. EXPERIENCE OF EP USE IN GEO

The task of securing attitude control and station-keeping by EP is being solved in geostationary Earth orbit (GEO) for about 25 years already. While 2 EPs only were used on board first spacecraft, there are spacecraft now, on board of which 8 thrusters are mounted. There are common features of control systems in GEO, namely: the use of flywheels for providing precise spacecraft attitude control, location of the solar panel axis orthogonally to the orbit plane, formation of the propulsion system corrective actions in four directions. It is necessary to note some disadvantages: SP power loss of up to 8%, and inefficiency of the thrust use with the thrusters mounted at an angle of 45° to the direction of corrective action; in this case the thrust loss is ~ 30% (geometric efficiency of the thrust use is 0.7). Above disadvantages are probably not so essential in the case of EP use in GEO, because even with not rational enough arrangement of thrusters the propellant mass saving at the liquid propellant engine substitution by EP in the correction systems is rather substantial.

III. PECULIARITIES OF EP USE FOR HEO CORRECTION

Experience of EPS use on board spacecraft for HEO correction is rather limited currently. In view of the more complicated angular motion of a spacecraft equipped with EPS in HEO than in GEO, it seems not possible to use experience of EPS arrangement and operation in GEO for HEO directly. While in GEO the angle between the direction to Sun and orbit plane does not exceed 23°, for a high elliptic orbit with inclination of ≈ 64° the angle between the direction to Sun and orbit plane will be within ± 87°. Thus, for securing orientation to Sun the solar panel axis may be rotated relative to the orbit plane by ± 87°, i.e. oriented in the orbit plane in any direction practically. According to Ref. 1,2, corrective actions are generated by the thrusters, thrust of which may have transversal or binormal direction (Fig. 1).

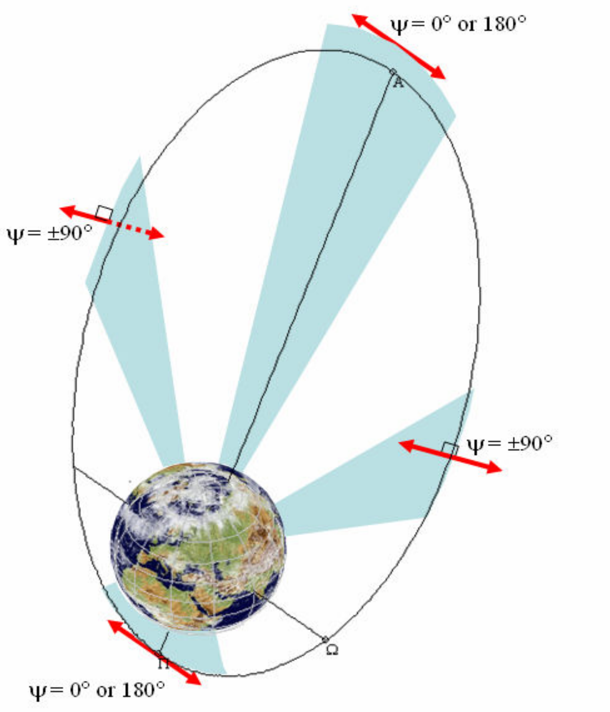

Figure 1.

Thrusters may be operated up to 4 times during one turn: near the apsidal points of the orbit and near its points, in which the eccentric anomaly η is ±90° (Fig. 2).

The following basic conclusion may be made in view of the above: for the orbit correction the EPS should generate thrust in any direction being in the plane orthogonal to the longitudinal axis of the spacecraft. It should be noted that EPS currently used in GEO are not capable of this. Another distinction of spacecraft equipped with EPS in HEO is related to high angular rates of the spacecraft longitudinal axis rotation in the orbit plane in the perigee region, as well as in the regions of ascending and descending nodes of the orbit. For a spacecraft in GEO the angular rate of the spacecraft longitudinal axis rotation in the orbit plane is constant practically: $0.72*10^{-4}$ rad/s.

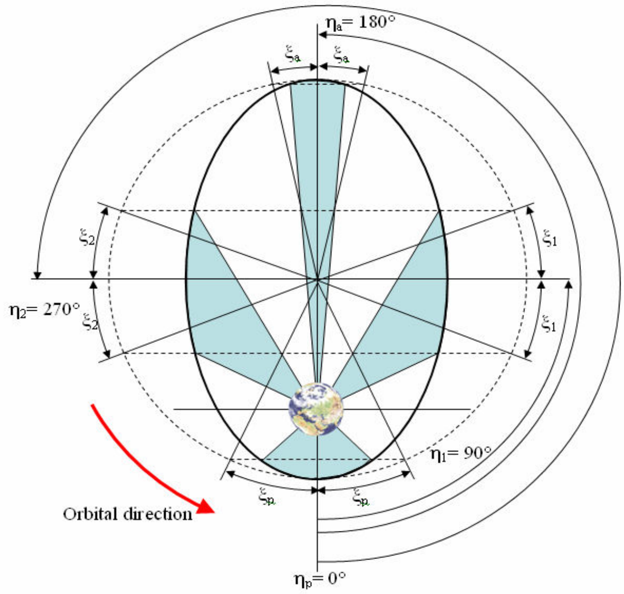

Figure 2.

For a 12-hour orbit with the perigee altitude of about 1000 km the angular rates of the spacecraft longitudinal axis rotation in the perigee region, ascending node of the orbit and apogee, respectively, are:

$$11.80*10^{-4} \text{ rad/s},$$
$$4.05*10^{-4} \text{ rad/s},$$
$$0.36*10^{-4} \text{ rad/s}.$$

In the perigee region during 300 seconds of flight the spacecraft axis will turn by 20°, and during 600 seconds - by 40°. The spacecraft longitudinal axis turn will cause necessity in the spacecraft rotation around the longitudinal axis for the solar panel re-orientation in space.

It means that in the case of relatively long orbit correction in the regions of the orbit perigee and nodes it will be required for the spacecraft to turn around the longitudinal axis by substantial angles for providing solar panel orientation to Sun, and for keeping direction of the corrective impulse relative to the orbit plane it will be necessary for EPS to change thrust direction relative to the spacecraft in the plane being orthogonal to the longitudinal axis of the spacecraft. The degree of spacecraft rotation about the longitudinal axis substantially depends on the Sun location relative to the HEO plane.

IV. REQUIREMENTS TO EPS FOR PROVIDING CONTROL IN HEO

Thus, at the formation of the electric propulsion system structure for solving problems of the motion control for the center of mass, as well as of the spacecraft attitude control in HEO it is necessary to secure the following:

- Generation of corrective impulses in any direction in the plane being orthogonal to the longitudinal axis of the spacecraft;
- Variation of the EP thrust direction relative to the spacecraft during orbit correction;
- Generation of controlling moments along all three axes for unloading inertial attitude control system.

It is possible to make a conclusion on the basis of the above that in the high elliptic orbit it is advisable to arrange thrusters in a "uniform" manner relative to the longitudinal axis of the spacecraft, and the thrusters should be provided with a capability to turn relative two axes for changing thrust direction and creating moments for unloading inertial attitude control system. As a rule, the solar panel axis crosses the spacecraft longitudinal axis, so the number of thrusters should be even: 6, 8, 10, … Exact number of thrusters is to be chosen based on the condition of efficient operation of the system as a whole. Arrangement of EPS comprising 6 thrusters operating in two thrust modes is discussed hereinafter.

V. EP LAYOUT ON BOARD SPACECRAFT FOR THE HEO CORRECTION ("STAR" FORMATION)

EPS arrangement proposed below for controlling motion of the center of mass and spacecraft attitude control in the high elliptic orbit is based on the following principles:

- It is planned to use 6 thrusters for the orbit correction;
- Thrusters are located in the plane being orthogonal to the longitudinal axis of the spacecraft and positioned near its center of mass;
- Directions of the spacecraft thrust vectors cross its longitudinal axis, are distributed uniformly in directions (60° in between) and symmetrically relative to the plane comprising longitudinal axis of the spacecraft and solar panel axis;
- Each thruster is mounted in a two-degree-of-freedom gimbal suspension;
- Thrusters are capable of operating in two modes: with 100% thrust and 50% thrust. During the operation with the thrust of 50% of the rating the power of consumed energy is twice less than the rating.

EP layout is presented in Fig. 3.

The following aspects were taken into account during the layout determination. EP thruster location in the same plane and their uniform distribution in directions is dictated, as was noted above, by the necessity to generate corrective thrust in any direction practically that should be in the plane orthogonal to the longitudinal axis of the spacecraft. Spacecraft of "Express" series may be considered as the prototype for such thruster arrangement, but the proposed layout has some vital differences: uniform distribution of thrusters in the thrust direction, presence of two-degree-of-freedom gimbal suspensions, and thruster operation in two modes (with 100% and 50% of thrust). Choice of the rated thrust direction for the thrusters through the spacecraft center of mass is substantiated by the wish to increase reliability of control system in the case of the failure of one of

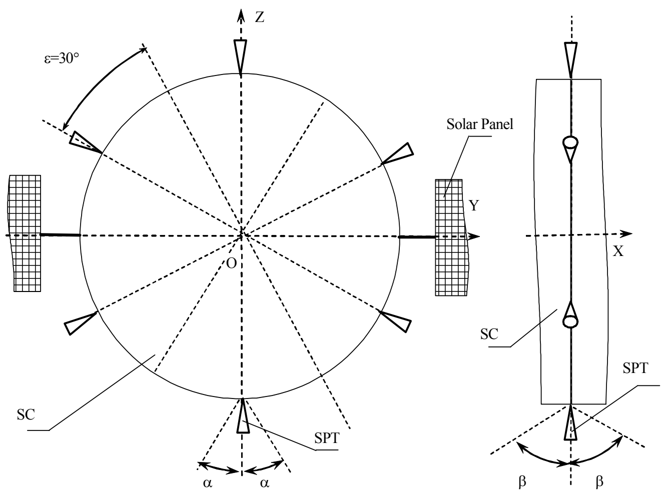

Figure 3.

the thrusters. Two-degree-of-freedom gimbal suspensions are being studied currently for the electric propulsions of SPT type, which would allow thruster rotation by up to 45° in two directions. Presence of rotating thrusters will eliminate practically all problems in the accuracy of the thrust vector direction control during the orbit correction, as well as the problems associated with the inertial attitude control system unloading. It should be taken into account that the thruster rotation angle is realized discretely with some, rather small, step. EP thrust control allows broadening for the capabilities of the proposed EPS structure. SPTs with two thrust modes (100% and 50%) are considered for illustration. The use of these modes for the HEO correction makes it possible to start several thrusters simultaneously at the specified power and thus, on the one hand, to increase the number of combinations for starting thrusters and, on the other hand, to compensate operation of control system more flexibly in the case of the failure of one of the thrusters.

VI. DISTINCTIONS OF THE PROPOSED EPS STRUCTURE

The proposed EPS structure has a number of distinctions.

A. Layout, thrust directions

First of all, this is the star-like arrangement of thrusters, according to which thrusters are located uniformly in the same plane, and rated thrust directions cross the spacecraft axis of inertia that is orthogonal to this plane. In view of the possibility for simultaneous operation of two thrusters, such layout allows to realize corrective impulse vector in 12 directions relative to the spacecraft with the discreteness ε=30°:

- 6 directions along the directions of thrust vectors of one of the thrusters;
- 6 directions along the averaged directions of thrusts for two neighboring thrusters.

For realizing required direction of corrective impulse in space, it is sufficient to rotate spacecraft relative to the longitudinal axis of the spacecraft by an angle of no more than 15°. At that the solar panel power loss as a result of its rotation relative to the optimum orientation to Sun will not be more than 5% for the glass surface protected coating of a solar panel. During the operation of one thruster the thrust is generated in the direction close to the rated orientation of the operating thruster (it is meant that corrective thrust and control moments are generated simultaneously) (Fig.4).

During the operation of two neighboring thrusters the resultant thrust will be directed along the averaged direction of thrusts for these two thrusters. If thrusters are not rotated, the rated geometric efficiency of the resultant thrust will be 0.866 (cos30°), i.e. thrust loss will not be more than 13.4% (Fig.5).

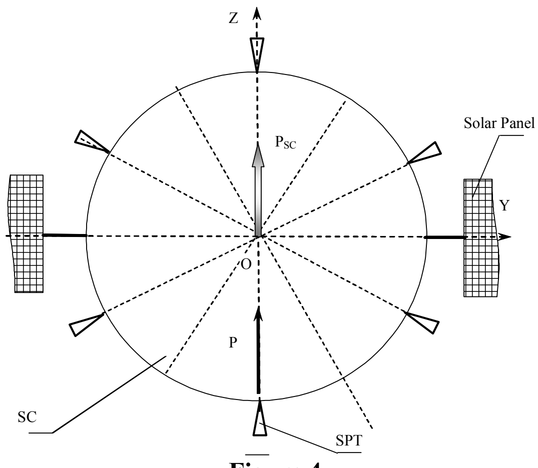

Figure 4.

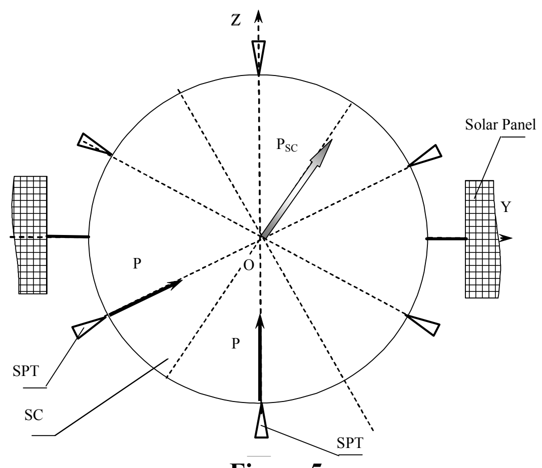

Figure 5.

As was noted above, in the case of the layout with thrusters mounted in 4 orthogonal directions the thrust efficiency with two neighboring thrusters operating is 0.7 and loss is about 30%.

B. Rotating Thrusters

Another distinction, presence of thrusters rotating in two planes, allows reducing thrust loss during the operation of two thrusters to zero. For this it is sufficient to rotate thrusters by 30° towards each other (Fig.6).

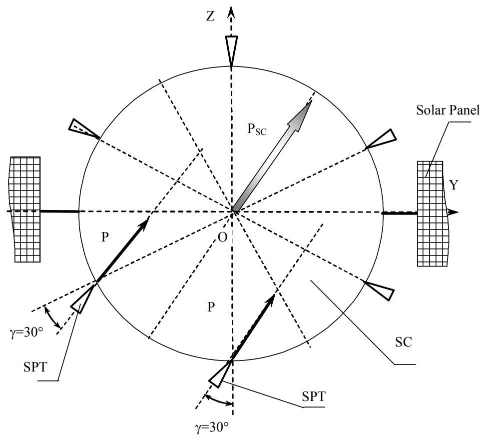

Figure 6

Besides, possibility to rotate thrusters solves the problem of the flywheel unloading. It is possible to combine the flywheel unloading with the orbit correction due to the small deviations of EP thrust directions relative to the rated ones. At the EP rotation by 10° relative to the rated direction the geometric loss of the thrust use is 1.5% only. If SPT-70 with the thrust of 0.04N is used, then, at the location of thrusters at the distance of 1 m from the main axis of inertia that is orthogonal to the reference plane, rotation by 10° will allow to obtain moment of 0.007 N×m from one thruster, that is nearly twice more than the moments generated by thrusters of "Yamal" spacecraft (Fig.7).

If inertial attitude control system is unloaded at the time moments, which do not coincide with the orbit correction, then for creating control moment it is possible to use 2 opposite thrusters operating in the 50%-thrust mode. At that the thrusters may be declined by the angles of about 30° (Fig.8).

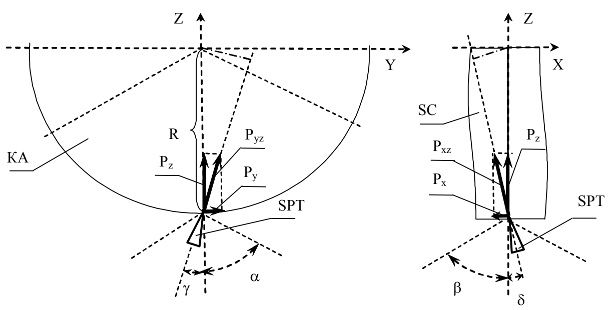

Figure 7.

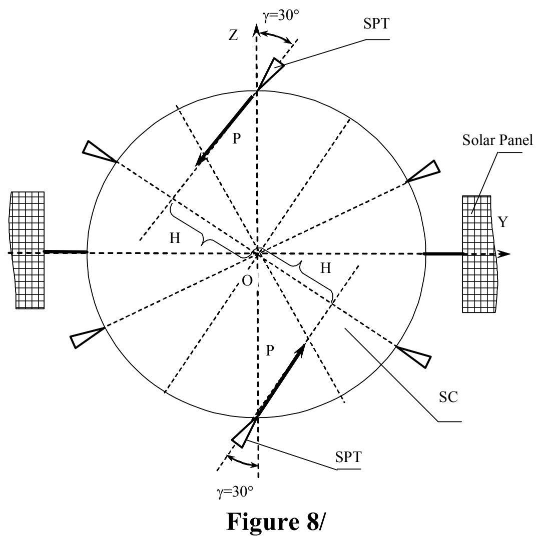

Figure 8/

It should be noted that at the orbit correction with simultaneous unloading of the inertial attitude control system the thrust direction of the operating thrusters may be arbitrary and differ from the rated directions.

C. Different thrust modes

The use of two thrust modes, 100% and 50%, allows to use available onboard energy more completely. If energy is enough for the operation of one thruster only, then at the operation of two thrusters for generating thrust in the intermediate directions they should be operated in the mode of 50% power.

If there is enough energy for the operation of two thrusters, then at the thrust generation in the intermediate direction two thrusters may be operated at full power, while at the thrust generation in the direction of thrust of one of the thrusters it is possible to use 3 thrusters: one at full power in the nominal direction, and the rest two – at 50% of power. When rotation of neighboring thrusters by 60° is used, there will be no thrust loss (Fig.9).

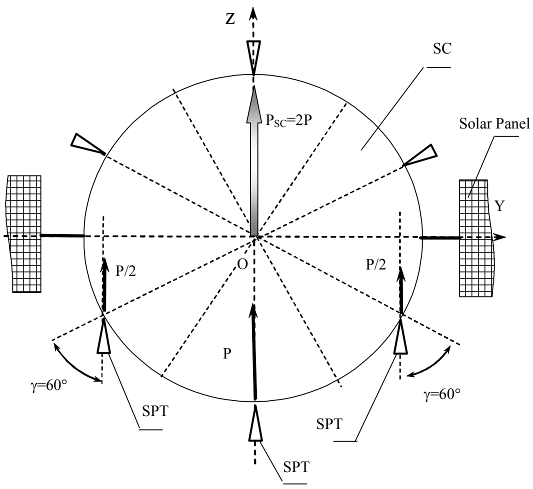

Figure 9.

As was noted above, for securing required direction of correcting thrust in space it is necessary to rotate spacecraft relative to the longitudinal axis by no more than 15° at the initial time moment. In the case of the long-term orbit correction process and necessity in the variation of the spacecraft roll angle for providing solar panel orientation to Sun, the rotation in roll should be made discretely by successive spacecraft rotations relative to its longitudinal axis by 30° and by variation in the composition of operating thrusters with this.

D. Redundancy

The proposed EP layout is characterized by high reliability. If by these or those reasons it is necessary to generate thrust in the direction of the failed thruster, this task may be solved by the neighboring thrusters, though at that the efficiency of resultant thrust may be and will be lower. As the nominal relative angle between the directions of thrusts of the thrusters located in the neighborhood of the failed thruster is 120°, the efficiency of resultant thrust without the thruster rotation will not be lower than 0.5 (cos 60°). (Fig.10)

If solar panels do not prevent thruster rotation by 60°, there will be no resultant thrust loss (Fig.11).

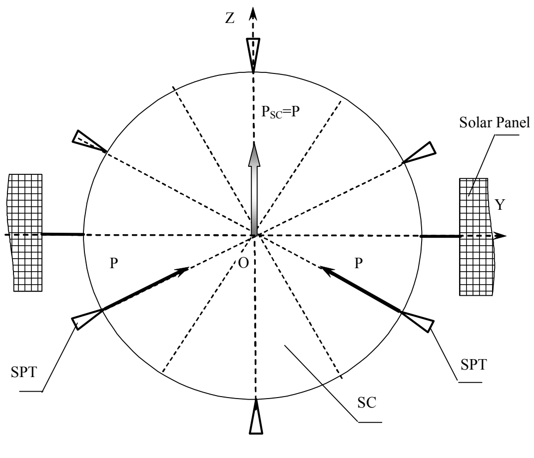

Figure 10.

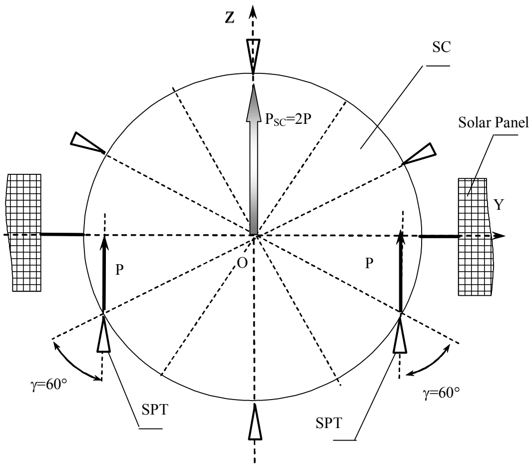

Figure 11.

VII. APPLICATION OF THE PROPOSED EPS STRUCTURE

The proposed structure of electric propulsion system may be efficiently used for solving control tasks as applied to the motion of the center of mass and to the spacecraft attitude in the high elliptic orbit. In principle, such structure might be used for the GEO also. It should be noted that realization of the proposed EPS structure requires availability of reliable two-degree-of-freedom gimbal suspensions for the electric propulsions. The presence of solar panels imposes constraints on the angles of rotation for the thrusters located close to the solar panel axis, because the thruster plume may reach solar panel during the rotation. It is possible to soften these constraints by selecting appropriate geometry of the solar panels, location of the solar panel axis at some distance from the EP mounting plane, reduction for the number of thrusters or the use of spatial deflection for the EP thrust direction outward the solar panel axis.

VII. CONCLUSION

EPS structure is considered, the thrusters in which are rotating and have star-like arrangement, i.e. the thrusters are located uniformly in the same plane, while the nominal directions of their thrusts cross the axis of inertia of the spacecraft that is orthogonal to this plane.

The proposed EPS structure allows simultaneous efficient solving for the problems of high elliptic orbit correction and spacecraft attitude control.

This structure makes it possible to increase discreteness for the possible directions of thrust generated by propulsion system, raise efficiency of the thrust use and improve reliability of the propulsion system as a whole.

References

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