MATHEMATICAL MODELING OF SPACECRAFT CHARGING AT OPERATION OF ONBOARD PLASMA THRUSTERS

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Introduction

The presence of periodically turned on plasma thrusters onboard a spacecraft makes the physical process of the spacecraft charging in space plasma to be more complicated because the plasma jets released by the thrusters participate in balance of electric currents flowing through the spacecraft surface at its interaction with the plasma, and in balance of currents on separate segments of the surface.

So, the plasma thruster should be included into mathematical model of the spacecraft taking into account its configuration and properties of materials used in the spacecraft construction. Locations of the thrusters, directional diagrams of the plasma jets, data on particles concentration in the jets and other necessary parameters should be defined in the model. The procedure of calculation of the electric potential distribution on the spacecraft surface and in the spacecraft vicinity includes the analysis of motion of positive ions and electrons released by the plasma thrusters in the spacecraft self electric field. The occurrence of additional currents due to operation of the plasma thrusters changes the spacecraft mean potential relative to the environmental plasma, which is determined by electric charges on the spacecraft, and also potential distribution on the spacecraft surface.

It is necessary to note that variations of the spacecraft mean potential and of the potential distribution on its surface are determined by two physical mechanisms: by variation of ratio of positive ion and electron concentrations in the plasma thruster jet, and by return of part of positive ions on the surface of the negatively charged spacecraft. The former one produces fast variations of the spacecraft mean potential at turning on and off the plasma thrusters, and the latter one makes slow variations of the spacecraft mean potential and potentials on separate elements of dielectric spacecraft surface.

In the present report, the procedure of mathematical modeling of the spacecraft charging in the case of plasma thrusters operation and the examples of calculation results are given.

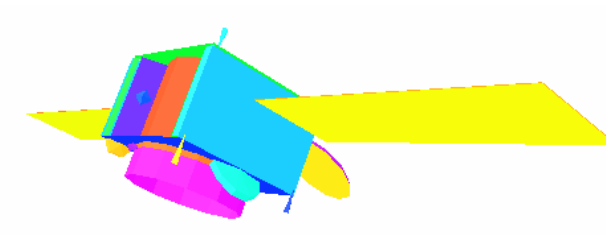

Fig. 1. Geometrical model of geosynchronous spacecraft

Build-up of the spacecraft geometrical model

The model of geometrically composite object, which a spacecraft is related to, is built as an ensemble of various 3D figures which are presented as a set of base elementary surfaces: plane, torus, ellipsoid, elliptical cylinder, elliptic cone and elliptic diaphragm with a hole. It is necessary to note that the constructed geometrical model should be set in different coordinate systems that is necessary, in particular, for taking into account orientation of the spacecraft relative to various external impact factors.

For computations, discretization of the model surface is done, i.e. a grid is constructed on the surface. Local electric currents and the electric charge densities are computed for every cell of the grid.

In fig. 1, the geosynchronous spacecraft geometrical model built according to the procedure above is shown. The various colors on the model show separate constructional elements, and material properties are set for every element.

Calculation of the electric potential distribution on the spacecraft surface and in the spacecraft vicinity

During calculation of the electric potential distribution on the spacecraft surface, the local current balance is computed, and the electric charge densities are determined for every cell of the surface. For evaluation of the primary plasma currents, the analytical description of the environmental space plasma is set which is based on two-temperature Maxwellian distribution function of electrons and ions characterized by 4 parameters: temperatures of “cold” and “hot” components of the plasma and concentrations of particles of both components [1-4]. In balance of the currents, the secondary emission currents from the surface determined by primary plasma currents, and also photoemission currents on the sunlit surface segments are taken into account. In the case of the plasma thruster operation, additional current originating due to collection of ions from the plasma jet is included into the balance of currents. In all cases, conductivity currents between separate elements and the spacecraft metal ground are included in balance.

The steady state is determined for each charging condition by iterative procedure in which the local current balance equations are solved on every step, and the charge densities are determined. Using the obtained data, the electric field in the spacecraft vicinity is constructed, and local currents for the next iteration step are computed taking into account this field. Such approach enables to obtain distribution of the electric potential on the surface and in the spacecraft vicinity for every discrete time and to investigate dynamics of charging of any spacecraft surface segment.

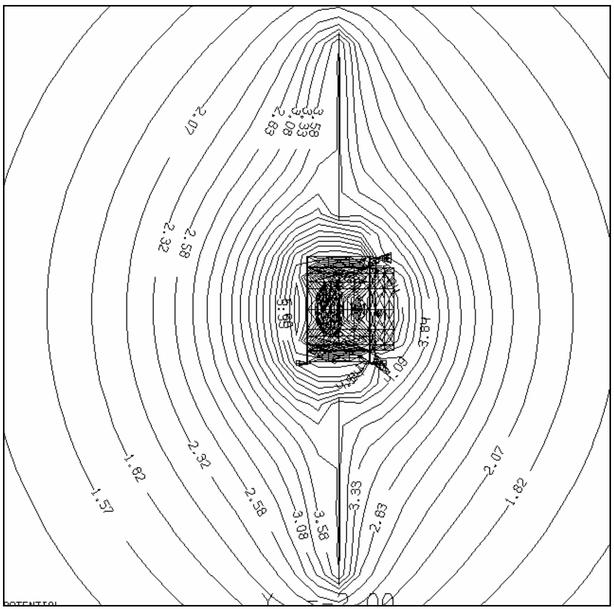

Fig. 2. Equipotential curves of electric field in spacecraft vicinity in the case of differential charging in plasma with temperature of “hot” component 3.55 keV

In fig. 2, the results of calculation of structure of electric field in the spacecraft vicinity are shown for spacecraft charging in plasma with “hot” component temperature 3.55 keV. In this figure, numbers on equipotential curves indicate the value of electric potential in kilovolts. Equipotential curves nearest to the spacecraft surface give information on potentials on the surface. Note that structure of equipotential curves is determined not only by features of the spacecraft surface configuration, but by peculiarities of the spacecraft differential charging, i.e. potential distribution on the surface.

The calculation data presented in fig. 2 were obtained for spacecraft charging in the Earth’s shadow when there is no photoemission from the surface, so the highest negative potentials arise on the surface. In usual flight conditions, the spacecraft is irradiated by the Sun on one side. In this case, the spacecraft mean potential reduces, and (that is even more essential) brightly expressed asymmetry in the electric structure occurs.

In fig. 3, results of the electric field structure computations in the case of partial illumination of the spacecraft surface are presented.

Generally, process of fast recharging of the spacecraft at plasma thruster turning on produces the fast drop of the spacecraft mean potential. In limiting case, the mean potential may be reduced up to zero value, and differential spacecraft charging can be maintained.

The degree of difference of the spacecraft charging before and after plasma thruster turning on significantly depends on character of the potential distribution on the surface, and on magnitudes of potentials of various surface elements at before plasma thruster turning on. Intensity of plasma currents determined by collection of ions on the surface from area of the plasma thruster nozzle play important role too.

In fig. 4, the structure of electric field near the spacecraft which originally was charged differentially up to steady state in plasma with temperature 3.55 keV (see fig. 2) is shown for the case when plasma thruster were turned on. The case is considered when the plasma thruster turning on reduces the spacecraft mean potential up to zero value.

Comparing fig. 2 and fig. 4, we may see that the plasma thruster turning on has produced significant modification of the spacecraft differential charging character and consequent modification of the electric field structure in the considered case.

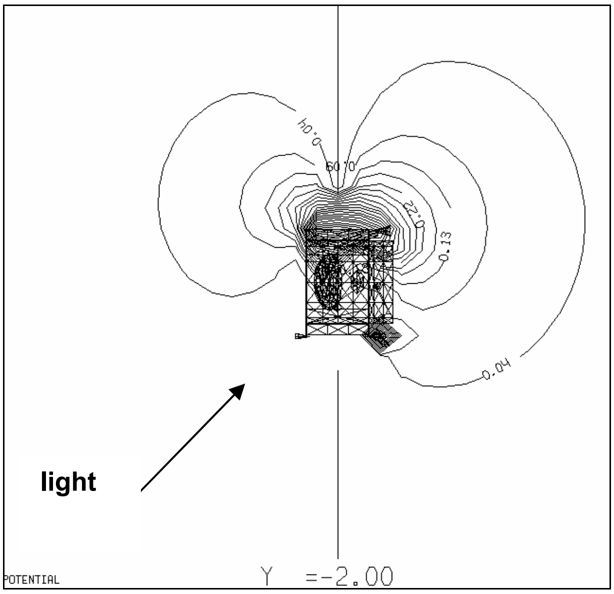

Fig. 3. Equipotential curves of electric field in spacecraft vicinity in the case of illumination of the surface

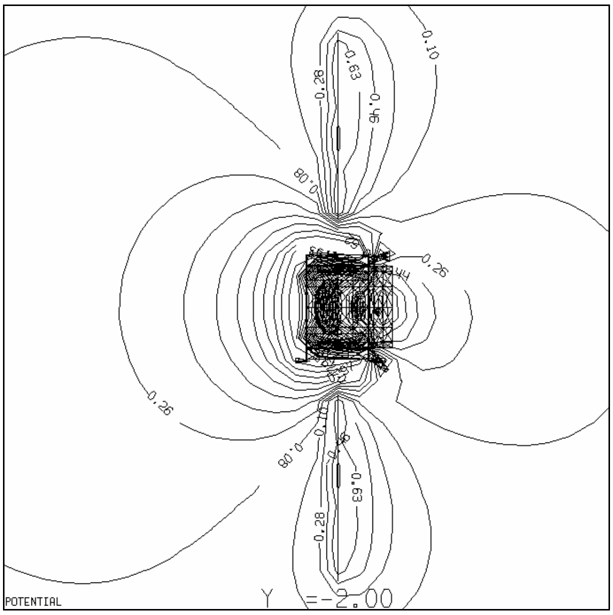

Fig. 4. Equipotential curves of electric field in spacecraft vicinity after plasma thruster turning on

Calculation of trajectories of positive ions and electrons in the self electric field of the charged spacecraft

As it was noted above, for analysis of influence of plasma thruster operation on the spacecraft charging processes, it is necessary to include into the current balance on the surface components determined by collection of the charged particles from the thruster nozzle area. Computation of these additional currents is done on the basis of results of modeling of trajectories of ions and electrons in self electric field of the charged spacecraft. At modeling, the same spatial grid as was used for computation of distribution of electrical potential in the spacecraft vicinity was constructed. The additional local currents for separate surface segments are determined by summing of trajectories of the charged particles hitting the considered segments.

In fig. 5, the trajectories of positive ions going out from the plasma thruster nozzles are shown in case of the spacecraft differential charging. It is visible, that the considerable portion of ions is returned to the spacecraft surface.

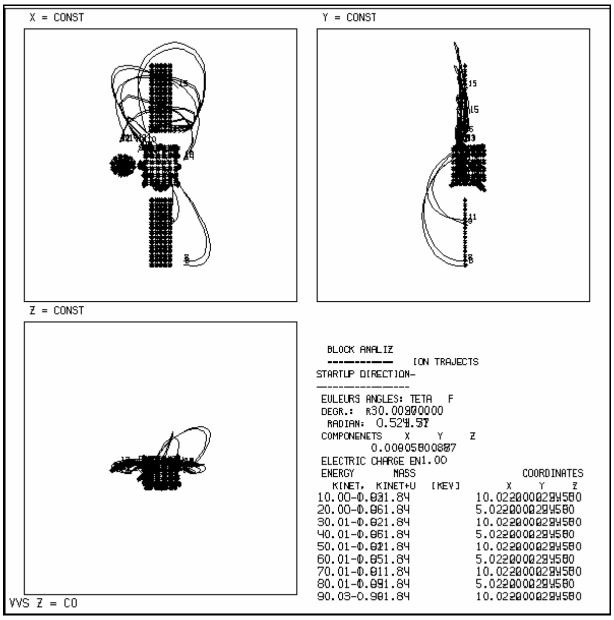

Fig. 5. Configurations of trajectories of the positive ions going out from four plasma thruster nozzle areas in the case of the spacecraft differential charging

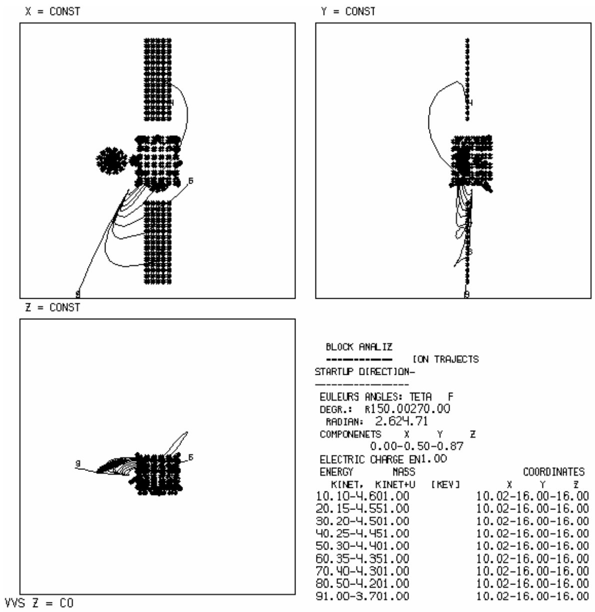

Fig. 6. Trajectories of the positive ions in the electric field of differentially charged spacecraft before plasma thruster turning on

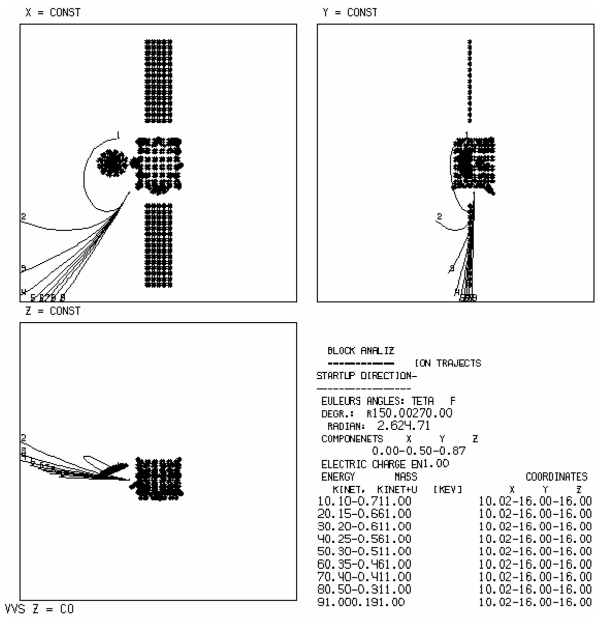

Fig. 7. Trajectories of the positive ions in the electric field of differentially charged spacecraft after plasma thruster turning on

The sharp drop of the spacecraft mean potential after the plasma thruster turning on produces, as it was shown above, strong modification of the spacecraft differential charging character. Accordingly, the trajectories of positive ion moving from the plasma thruster nozzle area suffer essential modification. This modification is illustrated by fig. 6 and fig. 7, on first of which the trajectories of ions going out from one of plasma thrusters nozzle area in the electric field of differentially charged spacecraft before plasma thruster turning on are shown, and on the second – trajectories of ions in the spacecraft electric field after plasma thruster turning on. In both cases, the trajectories of ions with energies 0.1–1.0 keV are shown.

Comparing fig. 6 and fig. 7, we see that trajectories of ions change essentially after plasma thruster turning on: the notable portion of ions leaves the spacecraft vicinity. The feature corresponds to physical process of drop of the spacecraft mean potential to zero value.

Dynamics of spacecraft charging and influence of the plasma thruster operation on the charging processes

The computation procedure used enables to analyze the time variations of potentials on every spacecraft surface segments in the case of the spacecraft charging in space plasma with plasma thrusters turned off, as far as in the case of the thruster operation [5]. In fig. 8, the results of calculation for the composite configuration spacecraft model in the case of spacecraft differential charging are presented.

The calculation starts at an initial state, when there are no charges on all spacecraft elements, and accordingly potentials of all elements relative to the environmental plasma are equal to zero. At the starting time, the spacecraft illuminated by the Sun on one side falls in hot magnetospheric plasma. The curves in fig. 8 show dynamics of variation of the electric potential on four cells on the surface (location of the cells is indicated in the figure caption). It is seen that differential charging of spacecraft occurs under impact of natural external factors during time interval 0–750 seconds.

At time $t = 750$ s, the plasma thruster is turned on for 50 seconds. It is seen from fig. 8 that there is fast change of the negative potential for all four considered cells after the plasma thruster turning on. Accordingly, the spacecraft mean potential relative the environmental plasma drops too. However, differential charging of the spacecraft surface is maintained during the plasma thruster operation. After thruster turning off, the process of the spacecraft differential charging under impact of the external factors continues, and the process goes faster in comparison with charging before plasma thruster turning on due to the fact that initial state is essentially different.

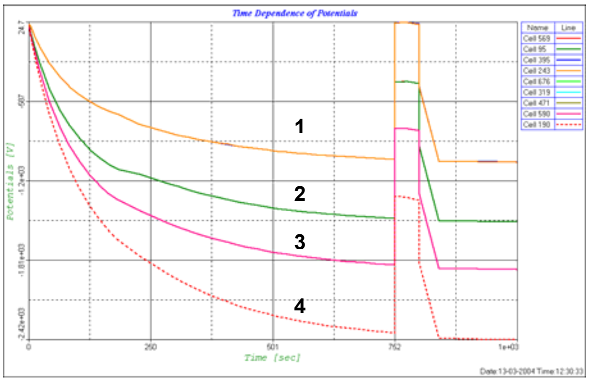

Fig. 8. Time variations of potential of four various cells on the spacecraft model surface: 1 – sunlit cell at centre of solar array; 2 – sunlit cell at centre of the upper spacecraft panel; 3 – shielded cell at centre of antenna; 4 – cell on dielectric side opposite to side with antenna

Conclusion

1. The plasma thruster operation onboard the spacecraft makes significant influence on the spacecraft charging process.
2. There are two physical mechanisms determining the influence: variation of ratio of positive ion and electron concentrations in the plasma thruster jet, and return of part of positive ions on the surface of the negatively charged spacecraft.
3. The physical and mathematical models developed enable to investigate the influence of plasma thruster operation on charging of spacecraft having complex configuration with nonuniform surface.

4. Distributions of electric potential on the spacecraft surface, electric fields, positive ion and electron trajectories in the spacecraft vicinity, dynamic characteristics of processes of charging of various spacecraft design elements evaluated in the paper yield quantitative estimations of the plasma thruster influence on the spacecraft charging processes.

References

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