Modeling of Force Impact on Large-Sized Object of Space Debris by Ion Injection

IEPC-2015-66／ISTS-2015-b-66

Presented at Joint Conference of 30th International Symposium on Space Technology and Science
34th International Electric Propulsion Conference and 6th Nano-satellite Symposium,
Hyogo-Kobe, Japan
July 4 – 10, 2015

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Abstract: A method of removing a large-sized space debris (SD) object, according to which a highly collimated high-velocity ion beam generated on board a Service Spacecraft (SSC) is directed towards the SD object to modify its orbit (Ion Shepherd), may be extremely efficient, especially for the debris removal from GEO area. Efficiency of force impact by ion beam depends on the distance between SSC equipped with an ion gun (IG) and the object to be removed, on the divergence angle of the beam generated by IG, and on the geometrical parameters of such object. SSC and removable SD object form a virtual cluster and its maneuvering is controlled by an electric propulsion system (EPS) mounted on board SSC. Modeling of the ion beam impact on a SD object of technogenic nature with the known geometry allows estimating components of forces and moments acting on SD at its arbitrary orientation. The modeling has been carried out for the impact by a wedge-shaped Xenon ion beam with ion current of 0.5 A, and ion energy of 4 keV with divergence semi-angles in two mutually perpendicular directions of 3^0 and 0.3^0. The SD model with geometry typical for a communication geostationary SC with the mass of 2-3 tons has been considered. It was obtained by calculation that depending on the SD orientation the transversal component of force acting on SD can be 70 % and more of the ion beam thrust, while binormal components can amount to 30 % of this value at the adverse orientation of SD. However, in case of the disordered SD rotation around its center of mass, the average values of binormal components of forces per a turn will be low. Thus, the beam can not strongly influence the arbitrary SD rotation because average values of the moments of binormal forces per one SD turn are also low. The SD erosion rate under the ion beam bombardment was estimated by calculation. At the distance from SSC to SD of 40 m, the deposited material can comprise some hundreds of monolayers after 1000 hours of operation. With the films of such thickness, the considerable degradation of properties of optical devices and protective layers of solar panels can be observed.

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Nomenclature

IG	=	ion gun
SD	=	space debris
SSC	=	service spacecraft
a_x , a_y	=	SD rotation angles
d_x	=	ion source offset along X axis
E_0	=	ion energy in the ion beam
F	=	impulse
F_x, F_y, F_z	=	impulse components
I_b	=	total ion beam current
I_x, I_y, I_z	=	inertia momentum
j(z)	=	ion current density
L_0	=	distance between SD and SSC
M	=	SD mass
m	=	particle mass
$\vec{n}$	=	ort of the surface normal
S(z)	=	cross-section area of the ion beam
$\vec{t}$	=	ort of the surface tangent
T	=	thrust
V	=	particle velocity in epy incoming flow
U	=	potential
U_0	=	emission electrode potential
U_a	=	acceleration electrode potential
X, Y, Z	=	coordinates
Π_i	=	perveance
Δh	=	difference of altitudes
ΔV_{ch}	=	characteristic velocity
β_s	=	rotation angle of the ion source around Z axis
$\beta_\perp$	=	transverse divergence of ion beam
$\beta_{//}$	=	longitudinal divergence of ion beam
ε_x , ε_y, ε_z	=	angular acceleration components
θ	=	incidence angle
υ_0	=	Xenon ion velocity

I. Introduction

Different technical devices were proposed recently for removing SD objects to safety orbits. One of such proposals implied the use of SSC equipped with electric propulsion system (EPS) to remove SD objects from GEO region.[1,2] In particular, a method of contactless action on SD object based on the transfer of impulse to the object to be removed by an ion beam injected from the SSC («Ion Shepherd») is considered as one of the efficient methods.

Characteristic velocity required for the transfer from GEO region to the disposal orbit depends on the altitude difference Δh between the disposal orbit and GEO. For the transfer with low transversal thrust, such characteristic velocity is defined as the difference of circular velocities in the initial orbit (GEO) and final orbit (disposal orbit).

$$\Delta V_{ch} = \sqrt{\frac{\mu}{r_{GSO}}} - \sqrt{\frac{\mu}{r_{GSO} + \Delta h}} \tag{1}$$

For the orbit altitude difference Δh=300 km specified by the international requirements, calculations result in ΔV_{ch}=0.88 m/s. It is easy to obtain by assessment that by acting on a rather large SD object (of about several tons in mass) by a force of some tens of mN, it is possible to remove SD from GEO region during the period of some dozens of days. These facts allow considering such method of SD removal by ion beam as rather promising.

While considering efficiency of this method and definition of requirements to the SSC control system providing SD transportation, it is necessary to study peculiarities of the ion beam interaction with the SD object. SSC and the removable SD object form a virtual mated configuration, motion control of which is provided by the SSC EPS. When a SD object of technogenic origin (waste SC, for example) is considered, the object geometry is known. On the other hand, relative orientation of SSC and SD object is not known. In such a case, it is necessary to allow for a possibility of random motion of the SD object relative to its center of mass. The required (as per Eq. (1)) value ΔV_{ch} is formed during the SD object transportation by the transversal component of force acting along the motion trajectory. But during the interaction of ions with the surfaces of SD object oriented at different angles to the incident ions, the binormal components of force are formed that cause movement of the SD object center of mass in the transversal direction. As this takes place, there appear the force moments relative to three space axes influencing the SD object motion relative to its center of mass. From the motion control system point of view, the mated configuration "SSC-SD object" is unstable, and this makes the control algorithm and design of the control system more complicated.

The above discussion indicates importance of modeling the SD object reaction to the impact of high-energy ion beam that should make it possible to assess mentioned components of forces and moments and to forecast the SD object motion during transportation. Such data are necessary as initial for the development of control algorithm and system for the mated configuration "SSC-SD object" during the SD object transportation.

II. Computational model

SSC-SD object configuration is presented in Fig. 1. SSC is located in the center of the basic coordinate system. Calculations were made up to the distance of 40 m along the axis Z between SSC and SD object. The geometry of the latter is presented by the simplified drawing of the waste telecommunication SC. Simplified geometrical model of the SC (Fig. 2) comprises all basic elements (solar panels and antennas) capable of having noticeable influence on the disturbing forces and moments during the ion beam action. The design layout used is typical for the modern telecommunication SC in its unpressurized version.

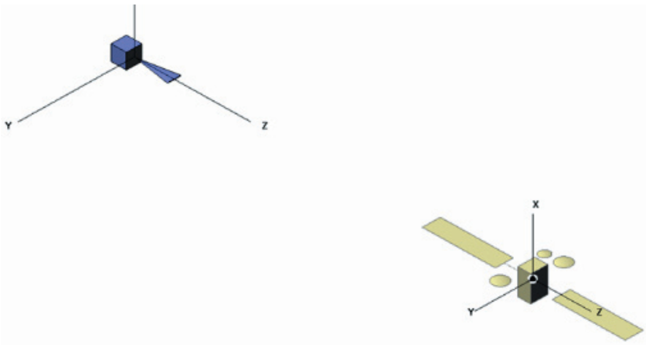

Figure 1. Computational model.

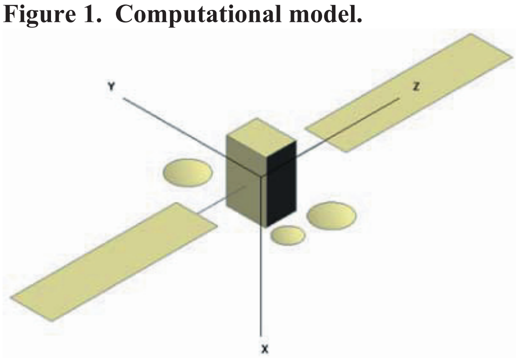

Figure 2. Geometrical model of the SD object.

The following dimensions are used in the model: for the SC body: 3400mm×2200mm×1700mm, for the solar panels: 2300mm×9200mm×30mm. Antennas indicated in the figure have the following diameters: 1380 mm, 1940 mm, and 1960 mm. The assumed geometry corresponds to the SC of 2-3 tons in mass. The SC center of mass is located at the axis of rotation of solar panels.

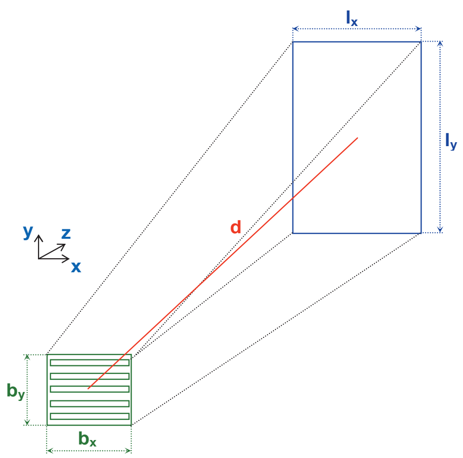

Figure 3. Geometrical model of the ion beam.

III. Ion beam model

Ion beam is generated by gas-discharge ion source (hereinafter referred to as the ion gun – IG) comprising electrostatic system for ion acceleration (hereinafter referred to as the ion extraction system – IES). A model of the wedge-shaped ion beam presented in Fig. 3 was used for calculations.

Such beam shape may be obtained using a three-electrode slotted IES (Fig. 4). Ion beam formation in the slotted IES differs by that the beam divergence angles in the transverse and longitudinal directions relative to the slot differ substantially. Transverse divergence depends on the focusing quality that can be provided based on the electrostatics laws. Longitudinal divergence depends on the ion random velocity. Its minimum value is estimated as thermal velocity. In the low-pressure discharge, the ion temperature is assumed to be close to the temperature of the gas-discharge chamber walls (about 0.05 eV). But in view of instabilities of any kind typical to gas discharge, for the energy of ions in plasma it is more realistic to use the upper-bound estimate that is equal to a half of the ion energy spread measured in the ion beam. So, measurements of the ion distribution in energy in the RF discharge of the ion thruster RIT-22 made by the electrostatic energy analyzer[3] revealed energy spread of ions in the beam of ±20 eV. We shall use this value to assess ion beam divergence along the slot.

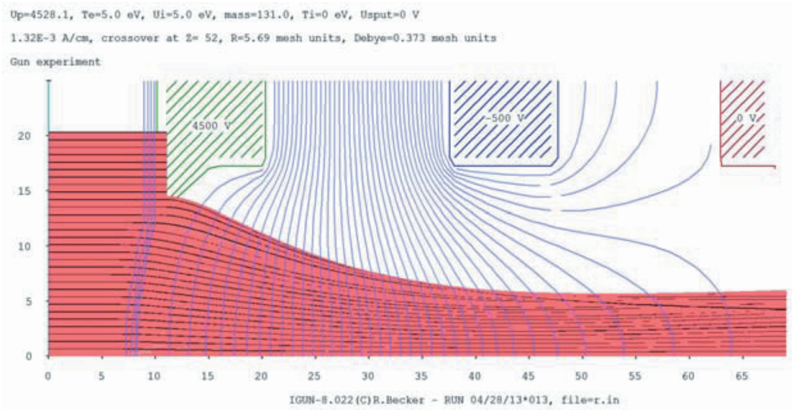

Figure 4. Ion beam geometry for the slot width of 2.5 mm and EE-AE distance of 1.7 mm.

Characteristics of the IG IES and ion beam parameters were defined by calculations using the software package IGUN[4]. Calculation results for the ion trajectories in the slotted IES with the shaped emissive electrode (EE) are presented in Fig. 4, while Fig. 5 illustrates half-angle of the ion beam divergence as a function of reduced perveance: $\Pi_i = \frac{j}{U^{3/2}}$ where j is the ion current density, $U = U_0 + U_a$ is the potential difference between EE (U_0) and accelerating electrode (AE) U_a.

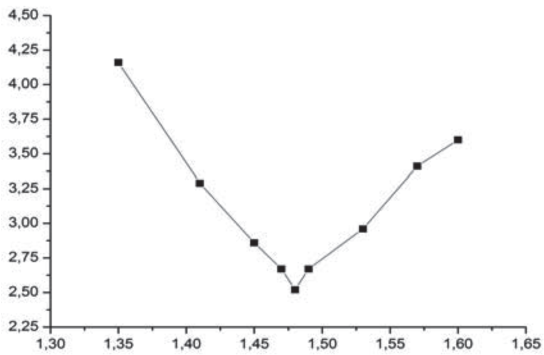

Figure 5. Ion beam divergence half-angle as a function of reduced beam perveance for the slot width of 2.5 mm and EE-AE distance of 1.7 mm.

It is obvious from Fig. 5 that the minimum of angle $\beta_\perp$ of the transverse beam divergence is extremely sharp. Minimum angle of about 2.5^0 can be obtained with $\Pi_i = 1.47 \times 10^{-8}$ A/(cm^{2}V$^{3/2}$).

According to calculations, the half-angles of longitudinal and transverse divergence $\beta_{//} = 0.3^0$ and $\beta_\perp = 3^0$, respectively, were used in the model of the wedge-shaped ion beam. At the exit of the radio-frequency ion beam injector (RFIBI) the lengths of the IES rectangular channel sides along and across the slots are $b_{//} = 0.2$ m and $b_\perp = 0.2$ m, respectively. It is clear that the slots are oriented along the axis Y of the local coordinate system of the RFIBI, while the axis Z coincides with the direction of beam propagation. The value of ion current density j is assumed to be constant over the beam cross-section area ("spots") and is defined by the following formula:

$$j(z) = \frac{I_b}{S(z)} \tag{2}$$

where: $I_b = 0.5$ A is the total beam current; $S(z) = l_x(z) l_y(z)$ is the beam cross-sectional area.

Whereby the law of the beam area variation is defined by the following equations:

$$l_x(z) = b_\perp + 2ztg(\beta_\perp),\ l_y(z) = b_{//} + 2ztg(\beta_{//}), \tag{3}$$

The described ion source is characterized as distributed and asymmetrical. For its mathematical description and subsequent calculation of mechanical influence, it is necessary to apply complicated computational procedures. Taking long source-SD object distance into account, we used a simplified model of equivalent point source, in which the following simplified equations define the beam area variation law:

$$\bar{l}_x(z) = \alpha_x z \,,\; \bar{l}_y(z) = \alpha_y z \qquad (4)$$

where: $\alpha_x = \frac{l_x(L_0)}{L_0}$, $\alpha_y = \frac{l_y(L_0)}{L_0}$ are the coefficients; L_0 is the distance to the SD object.

So, for $L_0 = 40$ m the sizes of the beam cross-section sides are: $l_x = 4.4$ m; $l_y = 0.62$ m, while coefficients corresponding to them are: $\alpha_x = 0.11$ and $\alpha_y = 0.0155$, respectively. Energy of ions in the beam is $E_0 = 4$ keV. With this the ion (xenon) velocity is $\upsilon_0 = 76$ km/s, and impulse (thrust) $T = 60$ mN. In such beam model the ion velocity vector in any point of the "spot" is directed from the equivalent source center.

IV. Computational model for the force impact

In general case, mechanical interaction of the beam particles with the solid body surface is characterized by coefficients of normal and tangential impulse exchange, such coefficients indicating the share of initial particle impulse transferred to the surface. Therewith the total impulse transferred to the surface is defined by the following expression[5]:

$$P = \rho V^2 \left(\vec{n} p + \vec{t}\, \tau\right) \qquad (5)$$

where: $\vec{n}$ and $\vec{t}$ – orts of the normal and tangent to surface; ρ – mass density of the incoming particle flow; V – particle velocity in the incoming flow; p, τ – coefficients of normal and tangential impulse exchange, respectively.

Exchange coefficients are the functions of the incident angle θ and particle velocity V : $p = p(V, \theta)$ and $\tau = \tau(V, \theta)$. To calculate beam interaction with surface, it is necessary to specify these dependencies as analytical relations and/or in the tabular form.

However, detailed information on the exchange coefficients is available for the rather limited number of particle-surface pairs only, therefore in many cases one must use well enough verified models of various kinds, which connect exchange coefficients with interaction parameters.

With the ion energy of 4-4.5 keV the ion-surface interaction proceeds with complete impulse absorbtion[6]. This condition was used for calculations.

The values of disturbing forces and moments acting upon the SC are calculated by integrating elementary forces and moments acting on the SD object surface over this surface taking into account the particle flow shielding by the structural elements of the technogenic SD object.

V. Force impact calculation results

To access disturbing forces and moments acting on the SD object, we made calculations, in which the following parameters were varied: SD object orientation in space that is specified by two rotation angles – a_x and a_y, "aiming parameter", i.e. the ion source central axis shift along the axis X – d_x, and the source orientation (angular deflection of the source relative to the axis Z) – β_s.

Rotation angle of the SD object a_y was varied within 0-360° with the step of 5°.

Rotation angle of the SD object a_x was specified to be equal to 0^0, 45^0, and 90^0.

The source orientation β_s that defined the aiming error was assumed to be equal to 0^0, 45^0, and 90^0.

The aiming parameter d_x was specified as 0 m, 0.5 m, and 1 m.

Calculations of disturbing forces and moments were made for 27 variants of relative orientation for SSC and SD object that was specified by parameters a_x, β_s, and d_x, and for the complete rotation of SD object around the axis

Y. Calculation results for each variant in the form of functions of the SD object rotation angle around the axis Y (a_y) are presented in Figs. 6-12. Each color curve relates to specific combination of three parameters a_x, β_s, d_x.

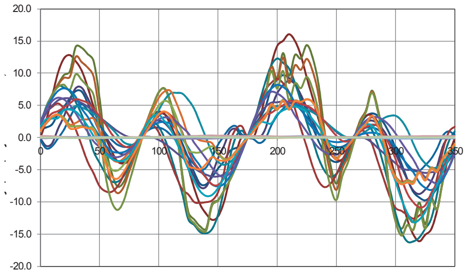

Figure 6. Disturbing force F_X as a function of rotational angle a_y

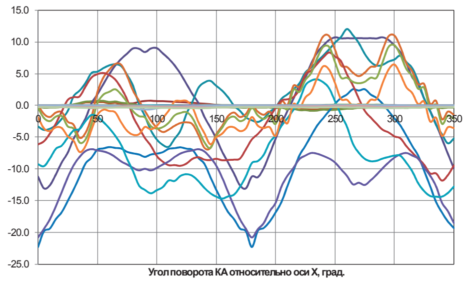

Figure 7. Disturbing force F_Y as a function of angle a_y.

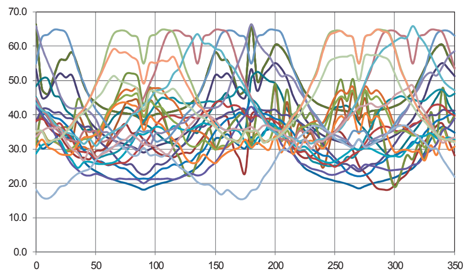

Figure 8. The force F_Z transferred by the beam in transversal direction (Z-component).

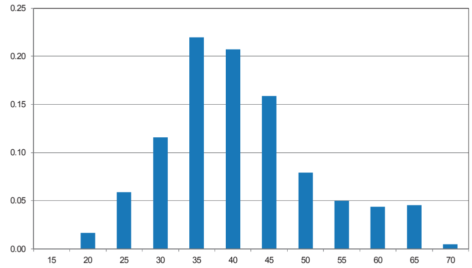

Figure 9. The force bar chart.

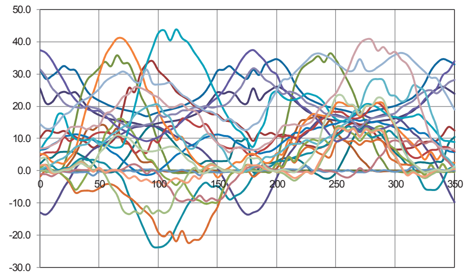

Figure 10. Disturbing moments relative to the axis X as a function of rotational angle a_y.

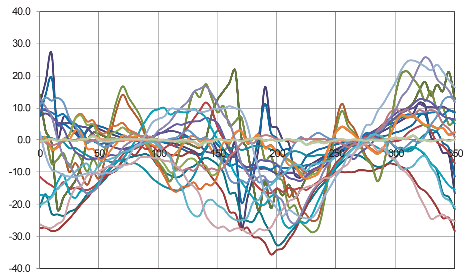

Figure 11. Disturbing moments relative to the axis Y as a function of rotational angle a_y.

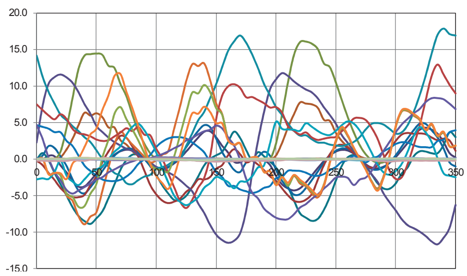

Figure 12. Disturbing moments relative to the axis Z as a function of rotational angle a_y.

Variability of components of the forces F_X and F_Y disturbing motion of the transported SD object is within ±25% of the impulse generated by ion beam. Average value of any such force over angles of SD object rotation is close to zero. The component of force F_Z acting along the SD object trajectory can be varied within broad limits, too. Average value F_Z = 43 mN was calculated based on the bar chart of Fig. 9. At that the minimum and maximum values of F_Z were 20 mN and 65 mN, respectively. If we consider average value of F_Z over angles as the average value over time (that being the case at random rotation of the SD object), the expected percent utilization of the ion beam impulse is about 65-70 %. But with this the average disturbing force components F_X and F_Y are close to zero.

Components of force moments relative to the axes X and Y are equally variable. Beam interaction with solar panels is one of the reasons of the so wide variations of the force components and moments. Maximum disturbing forces and moments are with solar panels turned in such a way that the beam influences their end sections.

At continuous action of the disturbing binormal force the velocity of SD object motion in lateral direction reaches $V = \frac{F}{M}t = 8.64$ m/s in 10 days. This is comparable with characteristic velocity of the SD object transfer to the disposal orbit. It is clear that this factor should be taken into account while calculating motion trajectory and specifying requirements to the SSC control algorithm. But based on Fig. 6 and Fig. 7 the probability of such unfavorable orientation of the SD object relative to SSC is about 0.03. In view of the sign-variable nature of the beam disturbing action on the SD object, real velocity of binormal motion can be lower substantially. Nevertheless, the possibility for continuous shifting movement of the SD object during some time interval, duration of which is rather difficult to forecast, should be taken into account when developing motion control system for the mated configuration SSC - SD object.

The moment of inertia I_z for heavy SC (of 2-3 tons in mass) is about 50000 N×m^2 along the axis of rotation of solar panels (moment I_y) and about 500000 N×m^2 transverse the axes of rotation X and Z (moments I_x and I_z, respectively). With the disturbing moment of 20 mN×m (Fig. 10 and Fig, 11), we obtained the following values of angular acceleration along the above axes: $\varepsilon_{x,y} = \frac{M}{J} = 0.4 \times 10^{-6}$ rad/s^2; $\varepsilon_z = 4 \times 10^{-8}$ rad/s^2. With the SD object transfer period of 10 days, the maximum angular spin rate (at continuous action of the moment) is 3.264 rad/s (about one turn per second).

But continuous action of the force moment maintaining rotation of the SD object is possible only with continuous action of the force causing origination of such moment, i.e. with the constant SD object orientation. If such object is rotating, the binormal force components and moments are averaged over one turn and have weight-average estimate close to zero. This statement is valid when the axis of SD object rotation has constant direction in space, but this does not follow from the general pattern of disturbance of the SD object motion around its center of mass. Nevertheless, total action of the binormal forces and moments during the entire period of the SD object transportation will be considerably lower than the peak values.

The above discussions do not have any influence on the conclusion that the efficiency of the beam impulse use for the formation of transversal force component is not higher than 65-70 %.

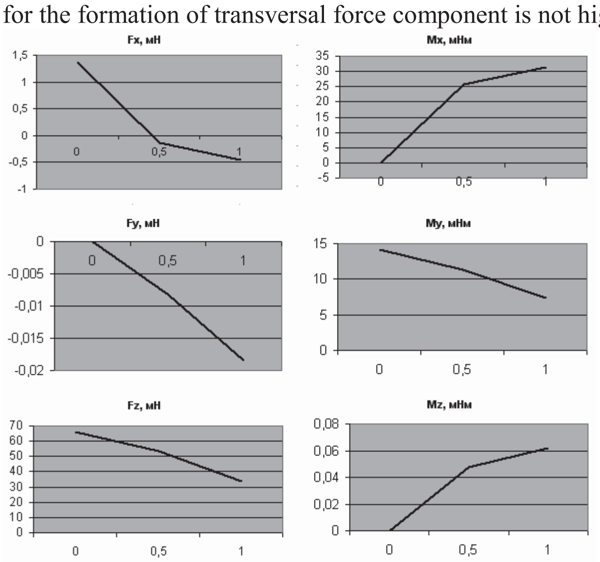

Figure 13. Forces and moments of the beam action on SD object depending on the aiming parameter at the following SD object orientation: $a_x = 0^0$, $a_y = 0^0$**.**

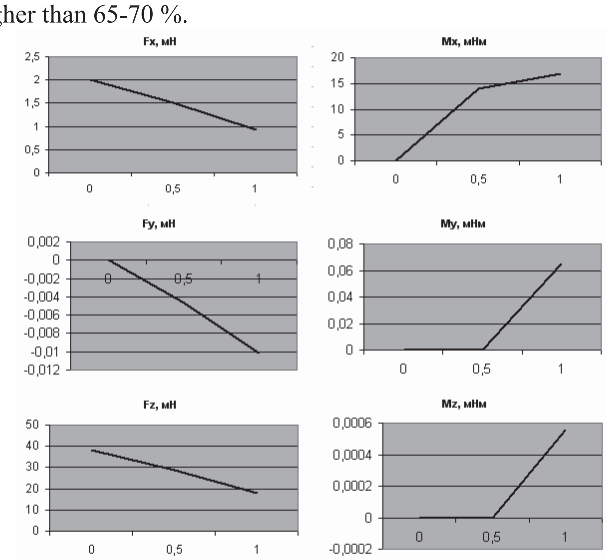

Figure 14. Forces and moments of the beam action on SD object depending on the aiming parameter at the following SD object orientation: $a_x = 0^0$, $a_y = 90^0$**.**

Position of the central beam axis relative to the center of mass of the SD object (precision of aiming) can define values of binormal forces and moments to a considerable degree. Deflection of aiming can be of random nature, but could be used to control the SD object motion around its center of mass and to increase control efficiency for the mated configuration 'SSC - SD object". It is necessary to control dynamics of the SD object rotation to control "aiming point". For this, visual means should be used to observe the SD object position and dynamics of rotation, as well as recognition algorithm capable of providing information required for the operation of EPS control system.

SD object has complicated shape, and dependencies of forces and moments on the "aiming point" position are not obvious. Variations of force components and moments depending on the aiming point (in meters) are presented in Figs. 13-15 as an example; they represent qualitative pattern of the beam action on the SD object of the above mentioned configuration for three different locations of the SD object.

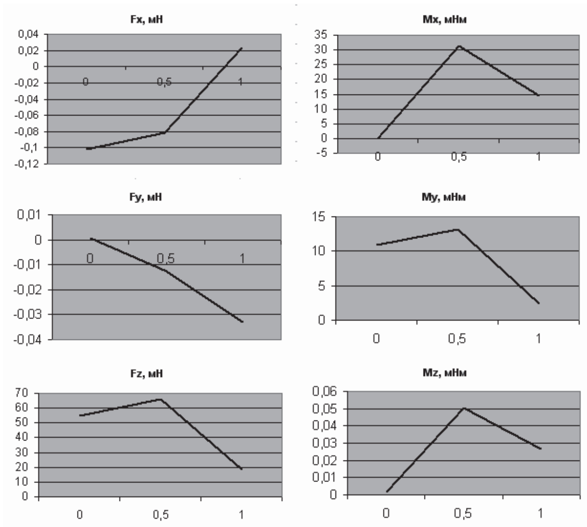

Figure 15. Forces and moments of the beam action on SD object depending on the aiming parameter at the following SD object orientation: $a_x = 90^0$, $a_y = 0^0$.

Complicated nature of force and moment dependencies along all three axes is evident from the plots. It is defined by the SD object geometry. There are force projections on plane being orthogonal to the beam direction, and moments even at nominal aiming, when solar panels are located symmetrically relative to the beam.

VI. Conclusion

Principal instability of the system "SSC – SD object" is one of the problems of the Ion Sheppard implementation. Under the ion beam action on the SD object, in addition to the force acting along the SD object motion direction, there appear the disturbing forces normal to this force. According to the results of modeling for the force impact of wedge-shaped ion beam, the peak values of disturbing forces can comprise as much as 20 % of the impulse generated by beam. With this, the impulse use factor may be about 70 %. Besides the disturbing forces, the ion beam produces moments of forces relative to the SD object center of mass that cause uncontrollable rotation of the SD object. Modeling was made for 27 variants of relative orientation of SSC and SD object at different aiming errors. Results obtained can be used for the development of motion control algorithm for the mated configuration "SSC - SD object".

Acknowledgments

This work was supported by the grant No. NSh-895.2014.8 of the Russian Federation President for the state support of the leading scientific schools of the Russian Federation; by the grant of the Russian Federation Government No. 11.G34.31.0022 for the state support of researches conducted under the supervision of the leading scientists at the Russian educational institutions of the higher professional education; with the state support for complex projects on creating high technology industries implemented with the participation of higher education establishments, agreement No. 02.G25.31.0072; with government support for applied research and development aimed at the creation of products and technologies under the Agreement No. 14.577.21.0101, which are gratefully acknowledged.

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