Evaluation of Influence of Electrostatic Force Generated by Spacecraft Charging on Membrane Structure of Solar Sail

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Solar sail is a spacecraft that has a large-scale membrane to utilize the solar radiation pressure for its thrust. Hence, maintaining the membrane structure during space flight is a critical issue to keep thrust performance of the spacecraft. In this paper, we focused on the electrostatic force due to spacecraft charging on the membrane as one of the possible factor to cause the deformation of the membrane structure. We had estimated the electrostatic force via charging simulation for the IKAROS spacecraft in solar wind plasma at 1.0 AU. We had also made a structural analysis for the deployed membrane of IKAROS with the electrostatic force. The structural analysis showed that the electrostatic force could hardly affect the membrane structure in this case.

Key Words: Solar Sail, Spacecraft Charging, Electrostatic Force, Membrane Structure

Nomenclature

d_I	: thickness of an insulator, m
dx	: grid size for numerical simulation, m
E	: electric field, V/m
E_x	: X-component of the electric field, V/m
E_y	: Y-component of the electric field, V/m
E_z	: Z-component of the electric field, V/m
e	: elementary charge, C
f_n	: electrostatic force per unit area on surface n , N/m ²
f_{nx}	: X-component of the electrostatic force per unit area on surface n , N/m ²
f_{ny}	: Y-component of the electrostatic force per unit area on surface n , N/m ²
f_{nz}	: Z-component of the electrostatic force per unit area on surface n , N/m ²
f_x	: X-component of the electrostatic force per unit area on a surface, N/m ²
J_{ph0}	: current density of photoelectron for normal solar irradiation at zero potential at 1.0 AU, A/m ²
k	: Boltzmann constant, J/K
m_e	: mass of electron, kg
m_i	: mass of ion, kg
T_e	: temperature of ambient electron, K
T_{ph}	: temperature of photoelectron, K
V_I	: electrostatic potential on an insulator, V
V_s	: spacecraft potential, V
v_d	: drift velocity of solar wind, m/s

ε	: permittivity of a material, F/m
ε_0	: vacuum permittivity, F/m
ε_r	: relative permittivity of a material

1. Introduction

Solar sail is a spacecraft that utilize the solar radiation pressure for its thrust using a large-scale membrane. A large-scale membrane is necessary to maintain sufficient thrust from the solar radiation pressure (e.g. 10⁻⁶ Pa at 1.0 AU). The scale of the membrane is estimated from 10 m x 10 m to 100 m x 100 m. Typically, the membrane is made of a strong metal-coated polyimide. Reflecting solar radiation via conductive surface of the membrane, the membrane converts solar radiation pressure into the spacecraft thrust¹⁾. Solar sail, therefore, is considered to be a next-generation spacecraft that can reduce propellant during long-term space flight such as interplanetary flight.

In 2010, JAXA had launched the “IKAROS” spacecraft, the first demonstration spacecraft of solar power sail, into the Venus transfer orbit^{1,2)}. IKAROS had achieved the thrust generation by solar radiation with a large-scale membrane. The thrust was actually measured in its orbit¹⁾. Figure 1 shows the picture of IKAROS taken by its camera device in orbit. IKAROS had a large-scale membrane whose shape was a 14-meter-square when it was deployed¹⁻⁴⁾. Centrifugal force of the tip-mass at the corner of the membrane generated by spinning the spacecraft body maintained the membrane structure^{2,3)}. The structural analysis of the membrane had been performed before its launch²⁾ because maintaining the membrane structure in orbit must be critical to generate its thrust during the mission.

Meanwhile, in our former work, we had numerically analyzed the charged particle distributions and the potential structure around IKAROS in solar wind plasma at 1.0 AU to estimate the charging status of the spacecraft^{5,6)}. We considered protons for ambient ions, ambient electrons, and photoelectrons for the analysis. One of the results showed that the magnitude of the electrostatic potential was relatively high on the insulator surface of IKAROS facing the downstream of solar wind. The magnitude of the electric field on the insulator surface to the outer space was estimated to be of the order of 10 V/m⁶⁾. This was due to the charging of the ambient electrons almost without the ambient ions in the downstream region because supersonic ions form a wake structure in this region.

In this paper, we focused on the electrostatic force generated by spacecraft charging on the membrane of IKAROS as one of the possible factor to cause the deformation of the membrane structure. We first estimate the electrostatic force quantitatively using charging analysis software. Then, we evaluated the influence of the force on the membrane structure of IKAROA by a structural analysis.

Fig. 1. Picture of IKAROS in orbit taken by its camera device^{1,2)}.

2. Estimation of Electrostatic Force on IKAROS

In this section, we have numerically estimated the electrostatic force on IKAROS due to spacecraft charging, and have evaluated the influence of the force on the membrane structure of IKAROS by a structural analysis. We first perform spacecraft charging analysis of IKAROS using MUSCAT⁷⁾, a spacecraft charging analysis tool, to estimate the electric field on the spacecraft. The electrostatic force on the surface is estimated by the Maxwell stress tensor method. Next, we perform structural analysis for IKAROS with the electrostatic force to evaluate the influence of the force on the membrane structure of IKAROS in its orbit.

2.1. Method of computing the electrostatic force on IKAROS

We adopted Maxwell stress tensor method⁸⁾ without magnetic field to estimate the electrostatic force on IKAROS. Using this method, the force can be expressed only by the electric field on the spacecraft. Generally, electrostatic force on a finite body is described by the following equation,

$$\vec{f} = \int \vec{\sigma} \cdot \vec{n} dS \quad (1)$$

where the integral is a surface integral on the body, and dS and $\vec{n}$ are a micro-surface on the body, the unit vector normal to the surface, respectively. The Maxwell stress tensor $\vec{\sigma}$ without magnetic field is described in Cartesian coordinate as Eq. (2).

$$\vec{\sigma} = \epsilon \begin{pmatrix} E_x^2 - 1/2 E^2 & E_x E_y & E_x E_z \\ E_y E_x & E_y^2 - 1/2 E^2 & E_y E_z \\ E_z E_x & E_z E_y & E_z^2 - 1/2 E^2 \end{pmatrix} \quad (2)$$

The electrostatic force on IKAROS is computed by Eq. (1). If the surface is a conductor, we can consider a surface element as illustrated in Fig. 2 (a), and the electrostatic force per unit area normal to the surface is obtained by the following equation in the coordinate in Fig. 2 (a),

$$f_x = \epsilon_0 E_x^2 / 2 \quad (3)$$

where we use the vacuum permittivity ϵ_0 for ϵ in Eq. (2).

If the surface is an insulator, we can also obtain the electrostatic force in the same manner for the conductor surface by the following assumptions: 1) We consider single layer of an insulator on a conductor which is biased to the spacecraft ground. 2) Surface charge accumulated on the insulator is assumed to be uniform around the numerical grid. 3) We only consider electrostatic tension normal to the spacecraft surface into the insulator because we can only solve a surface potential of a spacecraft.

As shown in Fig. 2 (b), the electrostatic force per unit area on the insulator surface to the outer space can be estimated by the force balance between the forces on three layers; I) conductor, II) insulator, and III) accumulated charge on the insulator. In the figure, the force balance normal to the surface element (X -direction) is considered between the forces: 1) the force on the conductor surface, f_{1x} , 2) the force on the insulator charge to the conductor, f_{2x} , and 3) the force on the insulator charge to the outer space, f_{3x} . The magnitude of the electrostatic forces per unit area f_{1x} and f_{2x} in Fig. 2 (b) are obtained from Eq. (2) as Eq. (4),

$$f_{1x} = f_{2x} = \epsilon E_d^2 / 2 \quad (4)$$

where the electric field between the surface and the spacecraft body, E_d , is given by Eq. (5).

$$E_d = \frac{V_I - V_s}{d_I} \quad (5)$$

Hence, the electrostatic force per unit area normal to the outer space (X -direction) on the insulator surface is determined by f_{3x} , and the force to the outer space, f_3 , is given by Eq. (2) as Eq. (6).

$$\vec{f}_3 = \begin{pmatrix} f_{3x} \\ f_{3y} \\ f_{3z} \end{pmatrix} = \epsilon_0 \begin{pmatrix} E_x^2 - E^2 / 2 \\ E_x E_y \\ E_x E_z \end{pmatrix} \quad (6)$$

Fig. 2. Models of the electrostatic force on the surface elements of the spacecraft: (a) conductor surface (left), and (b) insulator surface (right). Layers shown are: I) conductor, II) insulator, and III) accumulated charge on the insulator. Vectors of the electric field E_x and E_d are shown assuming a positive spacecraft body potential and a negative insulator charge.

2.2. Solar wind parameters

We used the solar wind parameters observed by the WIND spacecraft⁹⁾ as the input parameters for the charging simulations. We selected a specific data on June 14, 2010 UT when IKAROS was in orbit at 1.0 AU. In the data archive of the WIND observation, the distribution function of the solar wind plasma as a function of energy is described using Kappa distribution, although we use a Maxwellian-type distribution in the simulation. Hence, we extracted the plasma parameters from the Kappa distribution by fitting with two Maxwellian distributions for the electrons and one Maxwellian distribution for ions. The extracted plasma parameters are shown in Table 1. Typical value was used for the drift velocity of solar wind in the simulation.

Table 1. Extracted solar wind parameters used in the computation.

ion density, m^{-3}	4.05×10^6
ion temperature, eV	4.90
electron (1) density, m^{-3}	2.65×10^6
electron (1) temperature, eV	9.21
electron (2) density, m^{-3}	0.75×10^6
electron (2) temperature, eV	44.05
Plasma drift velocity, km/s	470

2.3. Numerical model of IKAROS for charging simulation

Figure 3 shows pictures of a numerical model of IKAROS. Three-dimensional geometry and major components of IKAROS¹⁾ is simplified using rectangular elements. A large-scale membrane constituting the spacecraft is assumed to be a square-shaped plate with a side length of 14 m and thickness of 0.5 m, although the actual membrane is composed of Al-coated polyimide whose thickness is 7.5×10^{-6} m. The thickness of the model is determined by the spatial width adopted in the simulation. The spatial width of 0.5 m is almost comparable to the Debye length of the photoelectrons, which is the minimum scale length of the potential shielding in the charging simulation. The conductor surface with several dielectric components (front surface) is facing upstream of the solar wind, and the insulator surface of the membrane (back surface) is facing downstream of that. All the components of the spacecraft model are electrically connected to the spacecraft ground. The material properties of the spacecraft components used in the simulation are shown in Table 2.

Fig. 3. Three-dimensional geometry of the numerical model of IKAROS. The components of the spacecraft are: 1) conductor surface of the membrane, 2) Thin-film solar cells, 3) reflection control devices, 4) solar cells, 5) spacecraft body, and 6) insulator surface of the membrane¹⁾.

Table 2. Material properties of the spacecraft surface in the simulation.

No.	Surface material	J_{ph0} , $\mu\text{A}/\text{m}^2$	Thickness, μm	ϵ_r
1	Al	40	-	-
2	Kapton	20	17.5	3.5
3	Kapton	20	25.0	3.5
4	Cover glass	15	100	7.4
5	Al	40	-	-
6	Kapton	20	7.5	3.5

2.4. Electrostatic force estimated by charging simulation

For the charging analysis using MUSCAT, the IKAROS model shown in Fig. 3, and the solar wind parameters in Table 1, and material properties in Table 2 are used. Numerical parameters are also shown in Table 3. The IKAROS model is installed in the center of the numerical domain. The flow direction of the solar wind is normal to the surface of the membrane from negative- to positive-X direction in Fig. 3. Solar cells on the model generate electricity of +70 V to the spacecraft ground to simulate the actual spacecraft in orbit. A single Maxwellian photoelectron emitting from the front surface with the temperature of 1.5 eV is included in the

Table 3. Numerical parameters for charging simulation.

mass ratio (m_i/m_e)	1836
Numerical domain, 0.5m x 0.5m x 0.5m	128 x 128 x 128
Size of solar sail, 0.5m x 0.5m x 0.5m	1 x 28 x 28
Grid size dx , m	0.5

simulation. Calculating the charging status of IKAROS, we had only updated the net current onto the spacecraft without considering the space charge effect of the charged particles in the numerical domain. It is, however, almost appropriate to estimate the electric field on the back insulator surface because the magnitude of the wake potential is small enough to affect the electric field on the insulator surface⁶⁾.

Figure 4 shows a snapshot of the surface potential at 57.8 s on IKAROS obtained by the simulation. This time, we could achieve the charging simulation up to 57.8 s although the largest time constant for charging in this simulation is expected to be as large as minutes by the hot ambient electrons on the back insulator surface¹⁰⁾. The surface potential on the front surface is shown in Fig. 4 (a), and that on the back surface in Fig. 4 (b). We can recognize the positive potential on the front surface in Fig. 4 (a), and the negative potential on the back insulator surface in Fig. 4 (b). The positive potential of 2-5 V shown in Fig. 4 (a) agrees well with the theoretical one that is of the order of kT_{ph}/e on the spacecraft surface where photoelectron current is dominant for charging¹¹⁾. The body potential of the spacecraft is obtained as +4.8 V by the

simulation. The negative potential shown in Fig. 4 (b) has its maximum absolute value of 18 V at the outer corner of the membrane, which is still increasing. The saturation value is theoretically estimated to be several times of kT_e/e for charging by hot electrons¹¹⁾.

Meanwhile, we can recognize the asymmetric potential on the front surface in Fig. 4 (a). This is considered due to the robust accumulation of the charge for the incoming or outgoing particles on the dielectric materials in this simulation. Note that the robustness is determined by the time step to update the surface potential in the MUSCAT simulation. On the front surface, the accumulation was calculated among ambient ions, ambient electrons and photoelectrons, although it was done only by the ambient electrons on the back surface. Hence, we consider that ununiformity of the surface potential on the dielectric surface is more recognized on the front surface than on the back surface.

Figure 5 shows the electrostatic force with the electric field on IKAROS obtained by the simulation. The electrostatic force is computed from Eq. (3) for a conductor surface, and from Eq. (6) for an insulator surface. The electric fields to

Fig. 4. Numerical results of the surface potential on the surface of IKAROS at 57.8 s, (a) front surface, and (b) back surface. Contours show the surface potential in V. Block arrows indicate the direction of the solar wind flow.

Fig. 5. Numerical results of the electrostatic force with the electric field on the surface of IKAROS at 57.8 s, (a) front surface, and (b) back surface. Vectors show the electrostatic force per unit area, and contours the X-component of the electric field in V/m. Block arrows indicate the direction of the solar wind flow.

calculate the electrostatic forces in both Eq. (3) and Eq. (6) are obtained by the MUSCAT simulation. Vectors in Fig. 5 show the electrostatic forces per unit area. Contours in the figure show the X -component of the electric field, E_x , on the surface. The solar wind flows in the direction of the positive X in the figure indicated by block arrows. Figure 5 (a) shows the results on the front surface facing to the upstream of the solar wind, and Fig. (b) those on the back surface facing to the downstream. In Fig. 5 (b), we can recognize remarkable electrostatic forces per unit area on both inside and outside edges of the back insulator surface on the membrane. The maximum magnitude of the force per unit area is of 1.0×10^{-8} N/m² at the outside corner of the membrane. We can also recognize in Fig. 5 (a), on the other hand, no remarkable electrostatic force is recognized in the same scale on the front surface including on the insulator. The maximum magnitude of the force per unit area on the front surface is of the order of 10^{-11} N/m². Comparing the numerical results shown in Fig. 4 (b) and Fig. 5 (b), we can recognize that the electrostatic force on the outer edge of the membrane corresponds to the local charging on the outer edge.

3. Structural Analysis of the Membrane

We have obtained the electrostatic force on IKAROS generated by spacecraft charging via charging simulation. Evaluating the influence of the electrostatic force on the membrane structure of IKAROS, we made structural analysis for the deployed membrane in orbit via numerical simulation. We considered a simple polyimide membrane of 7.5×10^{-6} m thick to simulate the membrane of IKAROS. The size of the unit structural mesh adopted was 0.5 m x 0.5 m corresponding to the numerical grid used in the charging simulation. Table 4 shows the material properties considered in the simulation.

Figure 6 shows the numerical results of the structural analysis of the membrane of IKAROS with the electrostatic force and a centrifugal force. The initial state is shown in Fig. 6 (a) and the steady state in Fig. 6 (b). The scale of the deformation is also shown in Fig. 6 (c). The centrifugal force is additionally considered in the simulation assuming that the square-shape membrane is rotating at 0.5 rpm. The deformation of the membrane shown in Fig. 6 (b) and (c) is magnified by 20000 times; the maximum deformation of the 14-meters-square membrane is estimated to be 0.22 mm by the simulation. We consider that the wave-like deformation of the membrane in Fig. 6 (b) and (c) is caused by a numerical instability in this simulation because the scale of the unit structural mesh is relatively large to that of the membrane. The structural analysis shows that the electrostatic force generated by spacecraft charging hardly causes the deformation of the membrane in the solar wind plasma.

Table 4. Material properties of the membrane model.

Thickness, 10^{-6} m	7.5
Mesh size, m x m	0.5 x 0.5
Young's Modulus, GPa	3
Poisson's ratio	0.3
Density, kg/m ³	1420

Fig. 6. Numerical results of the structural analysis of the membrane of IKAROS with the electrostatic force and a centrifugal force: (a) initial state, (b) steady state, and (c) the scale of the deformation shown by a contour graph. The deformation of the membrane in (b) and (c) is magnified by 20000 times. The block arrow in (a) indicates the direction of the solar wind. Abaqus/Standard was used for this analysis.

4. Conclusions

We had numerically estimated the electrostatic force on IKAROS due to spacecraft charging in solar wind plasma at 1.0 AU in order to evaluate whether the force could cause the deformation of the membrane structure of IKAROS that was critical for its thrust performance. MUSCAT, a spacecraft charging analysis software, was used to obtain the charging status and to compute the electric field on IKAROS. The electrostatic force on IKAROS was calculated by Maxwell stress tensor method using the electric field obtained by the charging simulation.

Although we had not obtained the saturation value of the surface potential on IKAROS, the charging analysis showed that the highest absolute value of the electric field was recognized on the outer edge of the back insulator surface of the membrane corresponding to the remarkable charging. The maximum magnitude of the electrostatic force per unit area was estimated as 1.0×10^{-8} Pa in this case using the actual plasma parameters observed by the WIND spacecraft. The

magnitude value corresponded to 1% of the solar radiation pressure at 1.0 AU. Estimation of the saturation value of the surface potential on IKAROS is ongoing.

The structural analysis of the membrane with the electrostatic force using a simplified membrane model showed that the electrostatic force hardly causes the deformation of the membrane in this case. However, it is possible that the electrostatic force on the membrane per unit area of the order of 1% of solar radiation pressure could affect the attitude control of IKAROS, because IKAROS did prove that we can perform attitude control by solar radiation pressure using its reflection control device²⁾.

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