SECONDARY ELECTRON EFFECTS ON ACTIVE SPACECRAFT CHARGING

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ABSTRACT

In this paper, we investigated the secondary electron effects on active spacecraft charging by Particle-in-cell simulation. We implemented the secondary electron model for Particle-in-cell simulation constructed by G. Cheng and L. Liu. The technical implementation of the model with domain composition parallelization is also demonstrated in this paper. We performed the active spacecraft charging simulation with secondary electron emission. The secondary does not affect the potential significantly, but the spacecraft's potential becomes higher with secondary emission than without secondary emission. It is noteworthy that the returned beam electron causes almost all of secondary electron.

1. Introduction

Spacecraft can control its electric potential actively by emitting charged particle beam. Fine control of a spacecraft's potential is important in both science and engineering aspects. From the aspect of science, the spacecraft's potential affects plasma measurements because ambient plasma particles are attracted or reflected by the potential. For obtaining correct data, the spacecraft's potential should be known and controlled precisely. From the aspect of engineering, an orbital control method using electromagnetic forces is proposed recently. Charged spacecraft (or space debris) can utilize the Lorentz force and Coulomb force, which act on a charged object, for controlling their orbits. This method requires only electric power and charge sources instead of massive propellants, so it is expected as a propellantless orbital control method. For controlling the potential precisely, it is necessary to understand the behavior of the spacecraft potential under the active charging control of the spacecraft. In this paper, we report secondary electron effects on the positively active charging of spacecraft by using electrostatic particle-in-cell (PIC) simulation. In conventional active charging model, secondary electrons are ignored because almost all of them have low energy (~20eV) compared with a primary electron's energy. The secondary electrons are considered to return to the spacecraft's surface attracted by the spacecraft's potential. Then they do not contribute to a current balance of spacecraft. However, if the returned beam current is in large quantities, the returned electrons lead to the generation of massive secondary electrons. Consequently, the secondary electrons form a potential barrier around the surface and prevent the beam returning, as shown in Fig. 1. If the returning beam decreased, the spacecraft's potential rises higher than that without secondary electron emission (SEE). We performed three-dimensional electrostatic PIC simulation of the actively charged spacecraft with or without SEE. We compared the potential distribution and electron density distribution around the spacecraft and analyzed the secondary electron effects.

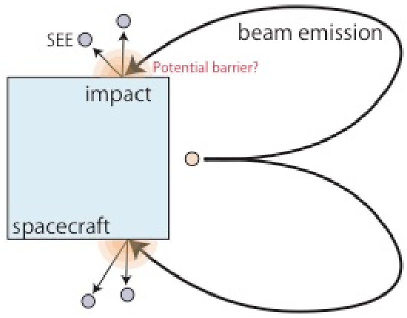

Figure 1. An illustration of Secondary electron emission of active spacecraft charging.

2. Active Charging Model: Previous studies

Spacecraft's floating potential is determined by a balance of inflow currents and outflow currents. Charged beam emission from a spacecraft changes the balance point of potential so that the potential can be controlled by the charged particle beam emission. A beam energy, that is, an accelerating potential of beam particles gives the maximum charging level [1]. When the spacecraft potential exceeds the accelerating potential V_0, emitted particles return to the spacecraft. The conventional current balance equation is given by

$$I_{e0}\left(1+\frac{eV_s}{k_BT_e}\right)^{\alpha} = I_{beam} - I_r\Theta(V_s - V_0) \qquad (1)$$

where I_{beam} is the beam current, I_r is the returning current, Θ is a Heaviside step function, V_s is the spacecraft's potential. $I_{e0} = \mu A e n_e \sqrt{\frac{k_BT_e}{2\pi m_e}}$ where A is the surface area. The multiplicative factor μ is unity on a perfect sphere and ~1.1 on an infinite cylinder. The power factor α is unity if the spacecraft is a perfect sphere and 1/2 if it is an infinite cylinder [2]. Equation (1), however, cannot solve numerically because the value of I_r is unknown and there is a discontinuity at $V_s = V_0$. Hoshi et al. proposed the active charging model which considers the velocity distribution of beam particles [3]. The model is

$$I_{e0}\left(1+\frac{eV_s}{k_BT_e}\right)^{\alpha} = I_{beam} - I_{beam}\int_{-\infty}^{v_s-v_0}\sqrt{\frac{m_e}{2\pi k_BT_b}}\exp\left(-\frac{m_ev^2}{2k_BT_b}\right)dv \quad (2)$$

where T_b is the temperature of the beam electrons. v_s and v_0 are the velocity corresponding V_0 and V_s. With numerical approximation of improper integral of a Gaussian function in the right hand side, Eq. (2) can be solved for V_s numerically.

These active charging models do not consider the secondary electron emission. They considered the secondary electrons, which are induced by ambient electrons and returning beam electrons, do not affect the charging potential significantly because the emission energy of the secondary electrons is low compared with the spacecraft's potential (and accelerating potential). The emitted secondary electrons will be attracted by the spacecraft's potential so that they are considered to be ignorable.

However, as we mentioned in the introduction, the secondary electrons may be affected. They can contribute to the space-charge density and change the potential distribution around the spacecraft.

3. Simulation Model

In this section, we explain a simulation setup. We have performed an active charging simulation with the SEE parameters of aluminum. The detailed definition of the secondary electron (emission) model is described in the next section. The spacecraft model definition is shown in Fig. 2. We defined a conductive cube in the center of the computational domain, and the electron beam is emitted from the cube's surface. Ambient plasma parameter values are similar to that of in interplanetary space. The ambient plasma density is 10/cc, and the temperature is 12 eV of Maxwellian Distribution.

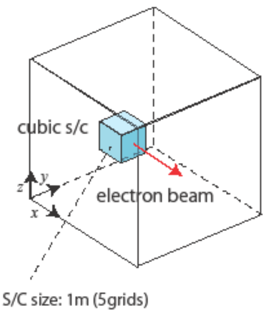

Figure 2. Spacecraft Model: A conductive cube is in the center of the domain.

3.1. Secondary Electron Model

We implemented the secondary electron model proposed by G. Cheng and L. Liu [1]. The model can treat three type of secondary electron. The 1st type is true secondary electron. The 2nd is backscattered electron. The 3rd is elastically reflected electron. Figure 3 shows the image of these three types. Each type of secondary electron has different velocity and angle distributions. The model based on emission probability of each secondary type so that the model is for Particle-based simulation. It is easy to implement the model on PIC code, and we do not explain here in detail. However, the implementation with the domain composition is somewhat difficult. Figure 4 shows the calculation procedure we implemented. Normal PIC calculation procedures are in left, and the additional procedures for SEE are in right. When the primary electron and proton impinged on the surface, the position and velocity of incident particles must be saved. The procedures are following:

1. Calculate incident position: The saved positions of incident particles are within the object so that it is necessary to calculate correct incident positions by interpolation. The incident time difference Δt_f (< 1), which shows the time difference between the true incident time and the previous calculation step, is also calculated in this step. Sometimes the correct incident positions are within another node as shown in Fig.5a. If the calculation code treats the whole object on each node, the difference between the particle's present position and the incident position is not a problem. If the code treats only parts of an object within each node, the difference may cause the problem so that an additional MPI communication is required to avoid the calculation failure.
2. Emit secondary electrons: Choose the SEE type by using random number and generate a new secondary electron particle based on the velocity distribution function of each species. The emitted particle moving are calculated from the rest of time step $1-\Delta t_f$.

3. Send secondary electrons to neighbor nodes: Sometimes the emitted electron goes to the neighbor calculation node as depicted in Fig. 5b so that it would cause the problem at the calculation of space charge. To avoid the calculation failure, we added the additional MPI communication step to send those particles to neighbor nodes.

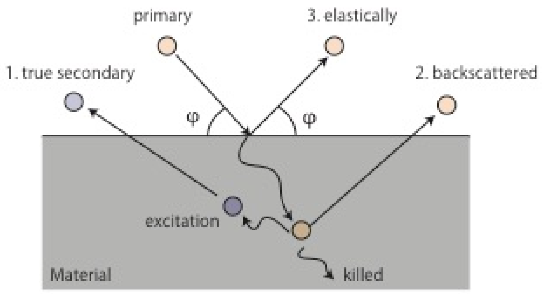

Figure 3. Three types of secondary electron.

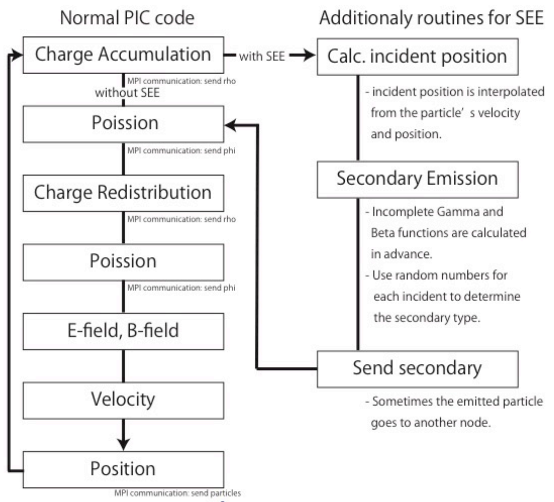

Figure 4. Calculation procedure: Normal PIC procedures are in right. Additional calculation procedures for SEE are in right.

4. Results

Figure 5 and 6 show the result of PIC simulation. The potential rises due to electron beam emission. When the spacecraft's potential exceeds V_0 at t = 10 μs, the beam current begins to decrease. When the beam current is almost similar to the ambient electron current, the potential and currents become stable. The potential at the end of the calculation is 66.2V. The beam current is 35.8 μA, and the ambient electron current is -35.5 μA without secondary electron emission. With the secondary emission, the potential is 66.9V. The beam current is 32.5 μA and the ambient electron current is 35.9 μA. The secondary current is 3.70 μA. The potential becomes slightly higher with SEE. The beam current becomes slightly less with SEE. These results indicate that the beam electrons may be slower with SEE than without SEE so that more beam electrons return to the surface.

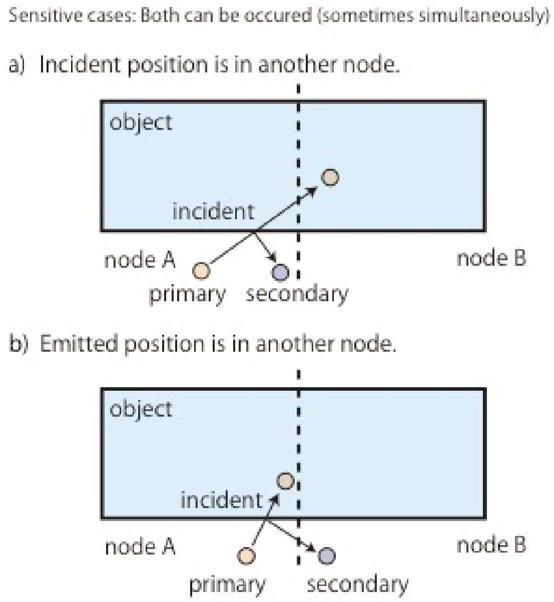

Figure 5. Sensitive cases for SEE with the domain decomposition method. a) Incident position may be within another node. b) Emitted position (new position of a secondary electron) may be within another node. Additional MPI communication is required to avoid the calculation failure.

On the contrary, the net current emission (Beam electron + Secondary electron) is 36.2 μA, and it is slightly larger than without SEE (35.8 μA). As a result, the potential becomes higher. The decrease of the beam current (35.8 μA to 32.5 μA) is about 9.22 %. A secondary current to beam current (without SEE) ratio is 10.3%. The values may change on other conditions. So we do not conclude that the spacecraft potential always becomes higher with SEE.

It is noteworthy that the secondary current has a peak at 15 μs, and the maximum secondary current is about to 5.32 μA. The data indicate that the secondary current is mainly caused by the beam electron, not ambient electrons. We show the electron densities at the end of the simulation in Figure 7. Figure 7a is beam electron density and Fig. 7b is secondary electron density. Almost all of the secondary electrons are emitted from the beam-emission surface. This figure also indicates that beam electron causes the secondary electron.

5. Conclusion

We have investigated the secondary electron effects on active spacecraft charging by Particle-in-cell simulation. We have implemented the secondary electron model for Particle-in-cell simulation constructed by G. Cheng and L. Liu. The technical implementation of the model with the domain composition method is also demonstrated in this paper. We performed the active spacecraft charging simulation with secondary electron emission. The secondary does not affect the potential significantly, but the spacecraft's potential becomes higher with secondary emission than without secondary emission. The potential difference is about 1% with V_0 = 50 V. It is noteworthy that the returned beam electron causes almost all of secondary electron.

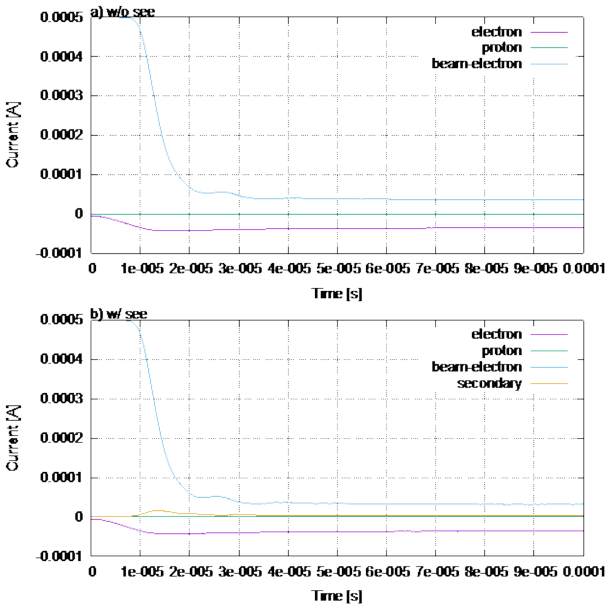

Figure 5. The current history of active charging simulation

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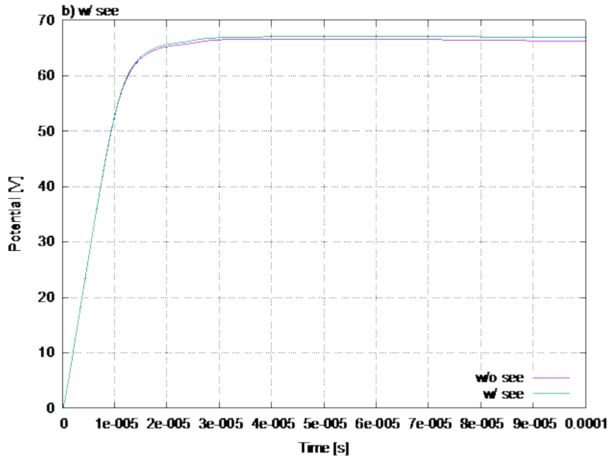

Figure 6. The potential history of active charging simulation: The green line is the case with secondary emission. The purple line is the case without secondary emission.

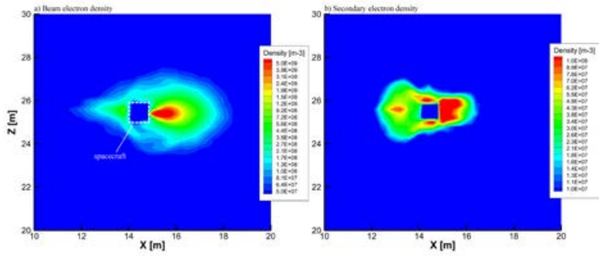

Figure 7. Electron densities: a) beam electron density, b) secondary electron density