Electrostatic Transport of Regolith Particles for Sample Return Mission from Asteroids

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***Abstract*—To achieve reliable and autonomous regolith sampling from asteroids in space, the authors have developed a new sampling system that utilizes electrostatic force. This system consists of electrostatic capture and transport subsystems. Regolith particles on an asteroid are captured through parallel screen electrodes activated by the application of an alternating high voltage. Captured particles are then transported to a collection capsule from side to side along the electric flux lines in a zigzag path where an alternating electrostatic field is applied. It has been demonstrated that glass and sand particles can be transported in the horizontal direction that imitates micro-gravity on asteroids. The transport rate was increased by applying a high electrostatic field of appropriate frequency. The demonstrated transport rate was approximately 3 g/min. Numerical calculation using the discrete element method predicted that the transport of particles is successful if the gravity is less than 0.02 G. The process of sampling particles on asteroids will be easier than that on the Earth, because gravity is extremely low on small asteroids, particles are assumed to be highly charged because of cosmic rays, and no air drag is exerted on the particles.**

I. INTRODUCTION

Sample return missions that are intended to bring back regolith samples from asteroids to the Earth are attracting remarkable attention because the analysis of substances from asteroids could provide critical information on the history of the solar system and the origin of life. The first sample return mission from an asteroid was completed successfully by the Japan Aerospace Exploration Agency's (JAXA) spacecraft Hayabusa (MUSES-C) in 2010.[1] Hayabusa brought back more than 1,000 small regolith particles from a small asteroid called Itokawa. The returned samples are now being studied.[2][3] Followed by the Hayabusa mission, JAXA launched a new spacecraft in 2015 for another sample return mission, the Hayabusa-2, to investigate the C-type asteroid Ryugu.[4] The regolith of C-type asteroids is considered to contain organic matter and water. Other sample return missions planned by space agencies worldwide are the National Aeronautics and Space Administration's (NASA) OSIRIS-Rex [5] and the European Space Agency's (ESA) MarcoPolo-R.[6]

Hayabusa employed a bullet firing sampling system that consisted of a series of operations: firing the bullet, crushing the asteroid surface by the bullet, and introducing the flung up regolith particles into a collection capsule through a horn. However, because of an error in the autonomous operation system, the bullet was not fired, and large samples were not captured; only some small floating particles were collected. The sampling system employed on Hayabusa-2 is similar to that of Hayabusa. Hayabusa-2 will use explosives to fire a copper impactor into the asteroid to carve an artificial crater, exposing underground pristine rocks for the probe to pick up during a touch-and-go maneuver. On the other hand, OSIRIS-Rex will use a robotic arm to pluck samples flung up by injecting nitrogen gas to the surface of an asteroid.

The sampling technique used in Hayabusa-2 is very challenging owing to the complicated firing system and operational scheme that needs to be operated autonomously. The sampling technique used in OSIRIS-Rex is also challenging, because it needs delicate mechanisms such as a gas injection system and a robotic arm. A simple sampling system that uses electrostatic force has been developed to aid existing systems.[7][8][9] High ac voltage is applied between parallel screen electrodes mounted at the end of the collection tube. During the touch-down operation, particles on the surface are agitated by an alternating electrostatic field, and some particles that are flung up are captured in the collection capsule after passing through the openings in the screen electrodes. It was demonstrated that approximately 900 mg of lunar regolith simulant FJS-1 was successfully captured in a micro-gravity environment reproduced by the parabolic flight of an aircraft with a 1-s operation time that simulated the touch-down sampling adopted for Hayabusa. In addition to the lunar regolith simulant whose diameter is 1–500 μm, it was demonstrated that large rocks (approximately 4 mm in diameter) and glass beads (2 mm in diameter) were captured in the micro-gravity environment. The system would be suitable as an optional or additional sampler, because it could automatically capture floating particles with a simple operation, even when the other sampling system does not work. The merits of this system are that it is very simple and compact, that there is no need for any mechanical drive and precise control, no contamination of impurities, very little need for power, and that it does not disturb the spacecraft's motion.

However, in the experiment for electrostatic capture in the micro-gravity environment, we observed that some glass beads adhered to the inner surface of the sampling tube, probably owing to the electrostatic adhesion force, and were not captured in the collection capsule. Because nobody knows how much the regolith is charged in space, a method is necessary for transporting the captured regolith particles into the capsule even if the particles are highly charged and extremely high adhesion force is applied to the particles.

To overcome this issue and to assure the electrostatic sampling of asteroid regolith in space, the authors have developed a unique regolith transport system that uses electrostatic force and is compatible with the electrostatic capture system. This study investigated the configuration and performance of the transport system that is expected to increase the reliability of the sampling system.

II. System Configuration

Fig. 1 shows a schematic illustration of the system and photographs of a zigzag path for transporting regolith particles. The system has two primary functions: capture and transport of particles. When a rectangular two-phase high voltage is applied between the parallel screen electrodes attached to the lower end of a sampler, the resultant Coulomb force and electrophoresis force [10] act on particles near the electrodes, and some agitated particles pass through the openings of the screen electrodes. The captured particles are introduced into the zigzag path where an alternating electrostatic field is created by ac voltage applying to the electrodes placed along the zigzag path. Particles are transported from side to side along the electric flux lines, designated by green arrows in Fig. 1. Both positively and negatively charged particles are transported by the Coulomb force because an alternating electric field is applied. The regolith is generally assumed to be electrostatically charged by photoelectric emissions caused by radiation or by electron/ion collisions via sticking or secondary electron emissions, and the particles are not discharged in vacuum.[11][12] In the micro-gravity environment, particles would be transported to a collection capsule attached at the upper end of the zigzag path without dropping down. A single-phase rectangular voltage was generated with a set of positive and negative amplifiers switched by semiconductor relays controlled by a microcomputer.[13]

In the experiment, we used two kinds of small transporting paths as shown in the right hand side of Fig. 1; one is a narrow path (10 mm pitch) and the other is a relatively wide path (15 mm pitch). Plate electrodes made of aluminum are arrayed in frames made of epoxy resin. The total path length is 125 mm.

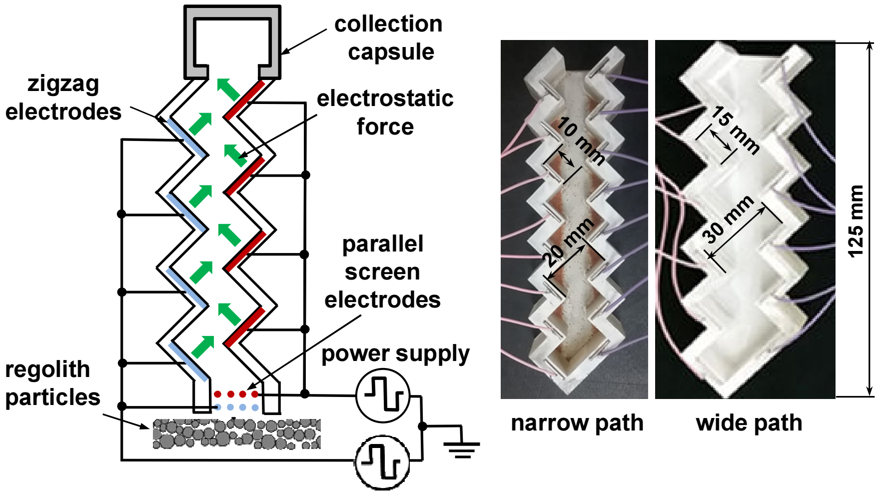

Fig.1. Schematic illustration of the sampling system (left) and photographs of the zigzag path for transporting regolith particles (right).

Because the characteristics of particles present on an asteroid surface are unknown, the following four kinds of particles were used in the experiments. The scanning electron microscopy (SEM) images and particle size distributions are shown in Fig. 2.

(1) Glass beads: Spherical, 100 μm in diameter, insulator.

(2) Lunar regolith simulant: FJS-1 (Shimizu Corp.,Tokyo),[14], highly irregular shape, insulator.

(3) Namibu sand: Sand particles collected from Namibu desert, irregular shape but relatively round compared to the lunar regolith simulant, insulator.

(4) Aluminum beads: Spherical, 300–600 μm in diameter, conductor.

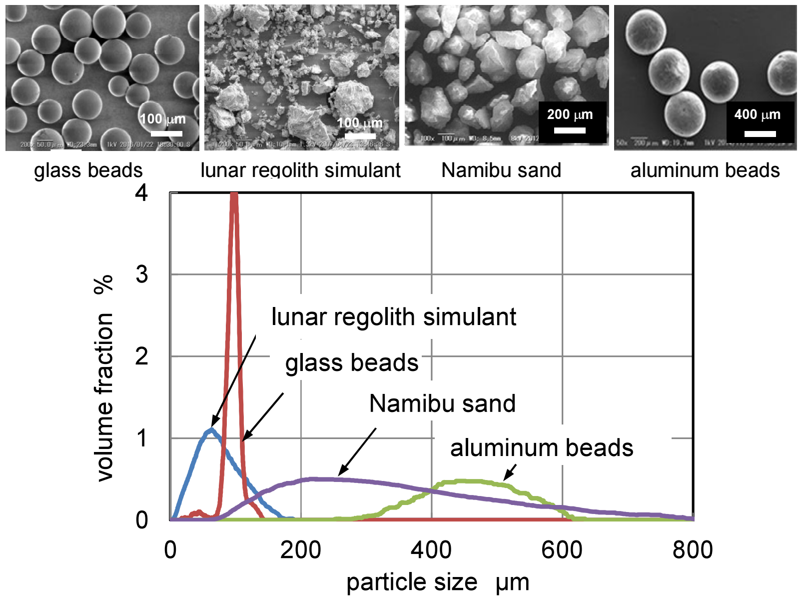

Fig. 2. SEM images of particles used for experiment and their particle size distributions.

III. Results and Discussion

If the path is arranged vertically, almost all the particles fall down before they reach the top of the path because of Earth's gravity. Therefore, the path was set as horizontal to imitate micro-gravity on asteroids, and particles were fed from a vibration feeder by dropping the particles at one end of the path. The feed rate was maintained constant at 3 g/min by controlling the vibration acceleration of the feeder. A high ac voltage was then applied between the electrodes to transport the particles. The transported particles at the other end of the path were weighed using an electronic balance (SAG105, Mettler Toledo International, Tokyo). The experiments were performed in air (20–25 ℃, 101,000 Pa, 60–70% relative humidity).

Fig. 3 shows the effect of the applied ac rectangular voltage. The experiments were conducted three times under the same condition, and the averaged transport rates were plotted in the figure. Spherical aluminum beads were used for the experiments. Particles did not move at a voltage lower than the threshold voltage because the adhesion and friction forces to the wall of the path are higher than the electrostatic driving force. With the application of a voltage higher than 4 $kV_{p\text{-}p}$, however, particles were successfully transported. The transport rate was increased by applying a high voltage, but this was limited by the electrical insulation breakdown. This voltage was 9 $kV_{p\text{-}p}$ for the narrow path. The transport rate of the narrow path is higher than that of the wide path at the same voltage because the electrostatic field is higher for the narrow path if the applied voltage is the same. However, the maximum transport rate is almost the same for both paths at the limiting voltage.

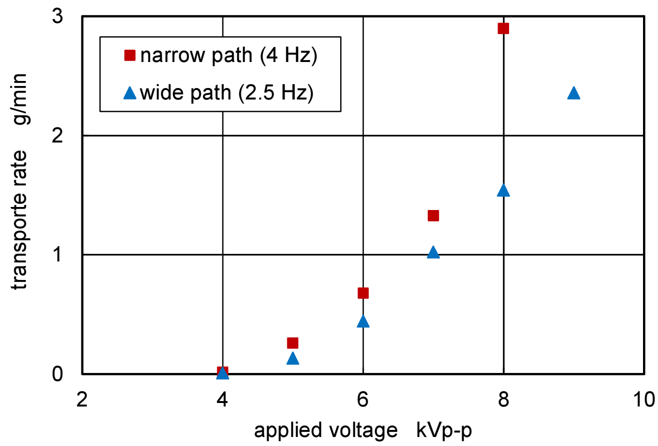

Fig.3. Transport rate of particles with respect to the applied voltage (aluminum beads, 8 kV_{p-p}).

Fig. 4 shows the effect of the frequency for the 8 kV_{p-p} rectangular voltage. Aluminum beads were used for the experiments. The transport rate increased linearly at low frequency because the motion of the particles was almost synchronized with the frequency at low frequency. However, the transport rate saturated and decreased at high frequencies because particle motion could not follow the polarity change at high frequencies owing to inertia. The optimal frequencies were approximately 4 Hz for the narrow path and 2.5 Hz for the wide path. Because it takes a long time to move particles from one side of the electrodes to the opposite side in the wide path configuration, the optimal frequency for the wide path is lower than that for the narrow path.

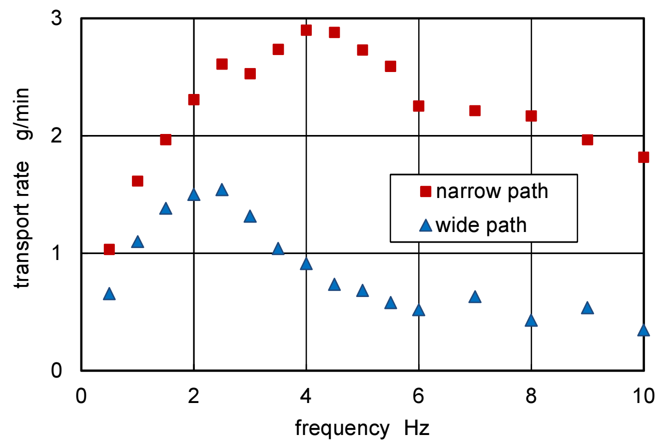

Fig. 4. Transport rate of particles with respect to the frequency of applied voltage (aluminum beads, 8 kV_{p-p}).

Fig. 5 shows the effect of particle characteristics. It was confirmed that both conductive (aluminum beads) and insulating (Namibu sand) particles can be transported using this system. Because Namibu sand is not spherical but irregular in shape and the average diameter is smaller than the aluminum beads, the adhesion and rolling friction forces would be relatively larger than in aluminum beads, resulting in lower performance. In fact, the glass beads and lunar regolith simulant were hardly transported because of the relatively high adhesion force owing to their small size. In the case of the lunar regolith simulant, in addition to the adhesion, the high rolling friction owing to its irregular shape disturbs the electrostatic manipulation of regolith particles. However, it is expected that the process of sampling particles on asteroids in space will be easier than that on the Earth, because gravity is extremely low on small asteroids, particles are assumed to be highly charged because of cosmic rays, and no air drag is exerted on the particles. This assumption was confirmed by the numerical calculation based on the modified hard sphere model of the distinct element method (DEM).[15] Fig. 6 (a) shows the calculated weight of the transported particles in 0.01 G and vacuum with respect to the frequency of applied voltage in the narrow path upon the application of 8 $kV_{p\text{-}p}$ rectangular voltage. Two thousand aluminum beads (500 μm in diameter, total 0.36 g) were initially placed at the lower end of the narrow path, and the number of beads that reached the upper end of the path was counted after application of the voltage for 10 s. Because the computational load is high for the DEM calculation, the calculation was stopped after 10 s. Therefore, particles did not reach the top at a low frequency of less than 1.5 Hz. The number of particles reaching the top increased linearly at 2–4 Hz, and then, it decreased at higher frequency. The optimal frequency was approximately 4 Hz. These fundamental characteristics are the same as the experimental result on Earth, shown in Fig. 4. Fig. 6 (b) shows the calculated effect of gravity. It suggests that the transport of particles is possible if the gravity is less than 0.02 G, which is much smaller than Itokawa's gravity.

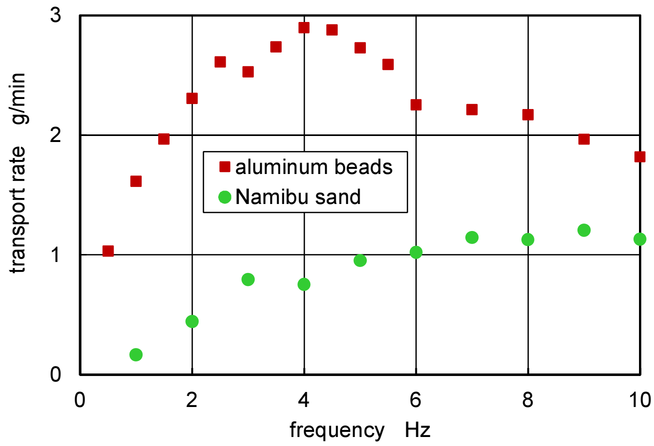

Fig. 5. Transport rate of particles with respect to the frequency of applied voltage (narrow path, 8 $kV_{p\text{-}p}$).

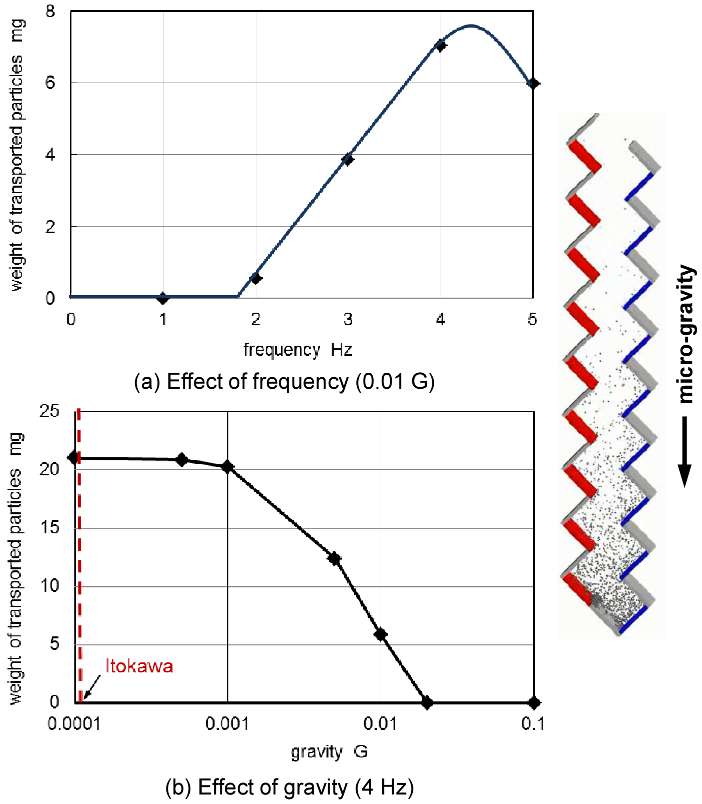

Fig. 6. Calculated performance in space (narrow path, 8 $kV_{p\text{-}p}$). The figure on the right shows a calculated snapshot of particle transport in micro-gravity and vacuum environment.

IV. CONCLUSION

The authors have developed a unique particle transport system that is compatible with an electrostatic particle capture system. The experimental result and numerical calculation predicted that potentially reliable transport is possible on an asteroid in space using a zigzag path where alternating electrostatic field is applied.

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