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Mitigation of lunar dust adhered to mechanical parts of equipment used for lunar exploration

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ABSTRACT

A unique cleaning system has been developed utilizing electrostatic force to remove lunar dust adhered to the mechanical parts of equipment used for lunar exploration. A single-phase voltage is applied to parallel electrodes printed on a flexible substrate to remove the dust. More than 90% of adhered dust was repelled from the surface of the slightly inclined device in a vacuum, and the cleaning performance of the system would be further improved in the low-gravity environment of the Moon. This technology is expected to increase the reliability of equipment used in long-term manned and unmanned activities on the lunar surface.

1. Introduction

The lunar surface is covered by a regolith (soil) layer; approximately 20% of this material by volume consists of particles less than 20 μm in diameter [1]. Because of its small size and the low lunar gravity, lunar dust easily becomes airborne when any disturbance occurs. From the Apollo era, it has been known that the dust on the Moon can cause serious problems for exploration activities [2,3]. There are three main concerns regarding lunar dust. The first problem is that dust brought into the lunar module after moonwalks by astronauts makes breathing without a helmet difficult and particles present in the cabin atmosphere affect the astronauts' vision [4]. The second problem is that the dust covers solar panels and optical elements, such as lenses and mirrors, degrading their performance [5–8]. The third problem is that airborne dust adheres to mechanical parts of equipment coming into contact with bearings and seals; such a situation could lead to catastrophic damage.

In order to mitigate the first problem, in previous work we have developed an automatic cleaning system that utilizes alternating electrostatic force [8]. It consists of a particle-repelling device, parallel wire electrodes stitched into the insulating fabric of a spacesuit, and a power supply to generate a single-phase rectangular voltage. If the system is operated intermittently, the dust adhering to the fabric of spacesuits is removed. On the other hand, if the system is operated continuously, the dust that comes close to the fabric is repelled, and thus, the system can protect spacesuits against the adhesion of dust. To overcome the second problem, the electrostatic particle transport system was developed. The idea of transporting particles using electrostatic traveling-waves was first proposed by Masuda [9] and many investigations have since been conducted on this technology, mainly as a toner supplier of electrophotography [10–24] and recently as a cleaner of lunar dust during lunar exploration missions [5,6]. We have developed the similar system for removing lunar dust using electrostatic traveling waves generated by a four-phase rectangular voltage applied to a transparent conveyer consisting of vortical pattern transparent ITO (indium tin oxide) electrodes printed on a glass substrate [7]. It was demonstrated that more than 98% of the dust could be removed in a vacuum, and the transmission rate of light was reduced by only a few percent by the application of ultrasonic vibrations in addition to traveling waves.

This paper describes a countermeasure against the third issue: adhesion of dust to mechanical parts. To overcome this problem, we developed a barrier system that employs an alternating electrostatic field to repel and remove the lunar dust from the surface of mechanical parts of equipment. The principle of the proposed system is similar to that of the cleaning system for spacesuits [8]. That is, a single-phase rectangular voltage was applied to parallel electrodes printed on a flexible substrate. Since a traveling wave is not generated by the application of a single-phase voltage, particles

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are not transported in one direction but rather repelled from the device. An alternating electrostatic field acts as a barrier against the dust based on the same principle as the cleaning system for spacesuits [8]. This technology is expected to improve the reliability of equipment used for long-term manned and unmanned activities on the lunar surface.

2. System configuration

The cleaning system shown in Fig. 1 consists of a particle-repelling plate with parallel line electrodes printed on a substrate and a power supply used to generate a single-phase rectangular high voltage. Due to the Coulomb force and dielectrophoresis force acting on the particles on the plate, the particles turn over on the plate along the electrostatic flux lines [8].

2.1. Electrostatic particle-repelling device

The particle-repelling device consists of parallel copper electrodes, 18 μm thick and 0.3 mm wide, etched by photolithography on a flexible polyimide substrate having a thickness, width, and length of 100 μm, 150 mm, and 52.5 mm, respectively. An acrylic plate was attached to the back of the polyimide substrate as a rigid support. In actual application, the flexible substrate will be attached on the surface of the critical part where dust must be eliminated. To determine a suitable configuration of electrodes for efficient cleaning, particle-repelling devices with three different pitches were prepared: 0.6 mm, 1.2 mm, and 1.8 mm. The surface of the device was covered with an insulating film made of polyimide (12.5 μm thickness) to prevent insulation breakdown between the electrodes.

2.2. Power supply

We used the power supply originally designed and used for the cleaning system of spacesuits [8]. A single-phase rectangular voltage was generated by utilizing a set of positive and negative amplifiers switched by semiconductor relays that were controlled by a microcomputer. The power supply is designed to be simple, small, and lightweight for space applications.

2.3. Lunar dust simulant

The lunar dust simulant FJS-1 (Shimiz Corp) [25], which is almost identical to the simulant JSC-1A (Orbital Technologies Corporation), was used in the present experiments. The specifications of the simulant are summarized in the literature [7]. Because large particles can be easily dislodged, particles larger than 53 μm in diameter were removed from the bulk of particles by using a sand sieve. Fig. 2 shows the particle size distribution of the lunar dust simulant used in the present experiments.

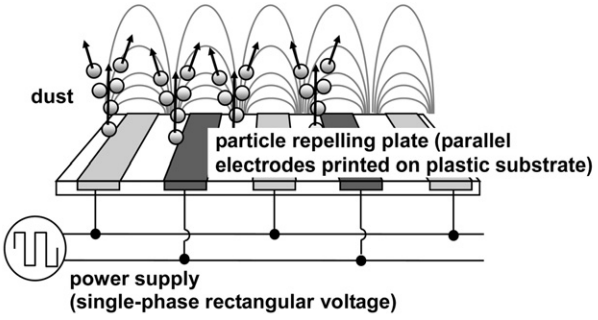

Fig. 1. Principle of electrostatic removal of lunar dust.

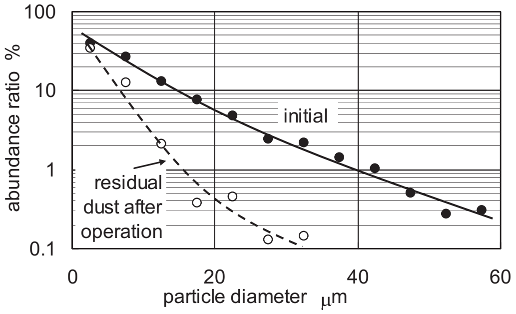

Fig. 2. Particle size distributions of lunar dust simulant used in experiments (initial) and residual dust on particle-repelling plate after operation (p = 1.8 mm, 3.0 kV_{p-p}, 10 Hz).

3. Cleaning performance

The particle-repelling plate was inclined at an angle of 40°, and a lunar dust simulant (20 mg) with a particle diameter smaller than 53 μm was uniformly scattered on the particle-repelling plate in a circular area of 30 mm in diameter (0.028 mg/mm^2). Because the dust particles used in the experiment were small, they adhered to the plate and the dust did not run off the plate even when the plate was inclined. A single-phase rectangular voltage was applied to the parallel electrodes. Particles that were repelled from the plate onto the floor were weighed on an electronic balance (SAG105, Mettler), and the cleaning rate was determined, that is, the ratio of repelled particles to the initial weight of particles. The cleaning experiments were conducted in a dry air environment (−20 °C dew point, 4.4% RH at 20 °C) created by a clean air unit (P4-QD10, IAC Co.).

3.1. Effect of electrode pitch, applied voltage and frequency

Fig. 3(a) and (b) show the cleaning rate versus the applied voltage and the frequency, respectively. The pitch of the parallel electrodes was selected as a parameter. Dust on the particle-repelling plate was removed at a threshold voltage. The cleaning rate increased with applied voltage, but saturated at high voltage. Because the applied voltage is limited by the insulation breakdown that is determined by the electrostatic field, the system performance at the voltage limit is almost independent of the electrode pitch. Electrostatic field calculation revealed that at the voltage limit the peaks of the electrostatic field at the edges of the line electrodes are approximately the same for the different pitches. This feature is the same as that of the cleaning system of spacesuits [8]. The maximum cleaning rate was about 80% at a low frequency less than 10 Hz. In conclusion, a particle-repelling plate with a long pitch is preferable for simplicity. The performance will be further improved in vacuum, because gas discharge does not take place in a vacuum, and therefore, the voltage limit can be increased.

Although a high cleaning rate was realized, not all the small particles were removed, and a small amount of particles remained on the plate. The residual particle size distribution after the operation is shown in Fig. 2. Particles smaller than 10 μm were not efficiently removed. Observation using an optical microscope after operation revealed that particles adhered on the electrode edges of the particle-repelling plate. Although it is expected that small particles can be removed more efficiently in a vacuum environment with application of mechanical vibration, a very small amount of dust will remain on the plate [7,8]. Thus, the system performance