 ICES-2014-279

Improved Electrostatic Shield for Lunar Dust Entering into Mechanical Seals of Equipment Used for Long-Term Lunar Exploration

Hiroyuki Kawamoto[1]
Department of Applied Mechanics and Aerospace Engineering, Waseda University
3-4-1, Okubo, Shinjuku, Tokyo 169-8555, Japan

It has been known that the dust on the Moon can cause serious problems for exploration activities. One of the major problems is that airborne dust enters into gaps of bearings and mechanical seals; such a situation could lead to catastrophic damage. To overcome this problem, we have developed dust shield systems utilizing electrostatic force for long-term lunar surface exploration. In our earlier system, a single-phase rectangular high voltage was applied to insulated parallel plate electrodes printed on a substrate at the clearance of the mechanical sealing part. It was demonstrated that more than 70% of the dust was repelled from the gap; however, because the performance of this system was not satisfactory, we have developed two improved systems. One of the improved systems uses a double-electrode configuration. We added support electrodes outside of the main electrodes so that the improved system generates a wider electrostatic field. As a result, more than 80% of the dust was repelled from the clearance. Another improved system uses a screen electrode configuration. In addition to the parallel plate electrodes, parallel screen electrodes were added near the gap. It was demonstrated that more than 90% of the dust was repelled from the clearance. The motion of dust particles near the electrodes was observed directly with a high-speed microscope camera, and it was clarified that dust particles entering into the clearance were ejected through openings in the screen electrodes. A numerical calculation using the hard-sphere model of 3D distinct element method confirmed the observed result, and it was predicted that the cleaning performance would be further improved in the low-gravity and vacuum environment of the Moon. It was also demonstrated that the performance of this system is not reduced by the rotation of a shaft and that the power consumption is extremely low, approximately 1 mW/m. This technology is expected to increase the reliability of equipment used in long-term manned and unmanned activities on the lunar surface.

I. Introduction

THE lunar surface is covered by a regolith layer; approximately 20% of the volume of this material consists of small particles less than 20 μm in diameter.[1] Because of its small-sized particles and low lunar gravity, lunar dust can easily be lofted above the surface[2,3] with any kind of disturbance due to, for example, the rocket jets[4] or the movement of vehicles and astronauts. The lofted airborne particles are apt to adhere to exploration equipment and spacesuits[5-26] because the regolith particles are electrostatically charged by the incident solar radiation and solar wind plasma.[27-30] It has been known since the Apollo era that airborne dust on the Moon can cause serious problems for exploration activities.[12,13,20,26] There are three main concerns regarding lofted lunar dust. The first 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.[9] The second problem is that the dust covers solar panels and optical elements such as lenses and mirrors, degrading their performance.[5,6,16] The third problem is that airborne dust adheres to mechanical parts of explanation equipment coming into contact with bearings, seals, and gears; such a situation could lead to catastrophic damage.[7,8,12-14,23,24,31]

To overcome the last problem, a unique cleaning system has been developed that uses electrostatic force to remove lunar dust adhering to the surfaces of equipment used for lunar exploration. A single-phase rectangular voltage

[1] Professor, Department of Applied Mechanics and Aerospace Engineering, Waseda University, 3-4-1, Okubo, Shinjuku, Tokyo 169-8555, Japan/kawa@waseda.jp

is applied to insulated parallel electrodes printed on a flexible substrate to remove the dust using an electrostatic standing wave.[7,8,14,24] This system is suitable for dust removal from flat areas such as the door of a Pressurized Excursion Module; however, it cannot prevent dust from entering into the clearance of bearings, mechanical seals, and gears of equipment. In fact, a mechanical seal is conventionally used for this purpose. Delgado and Handschuh[11] demonstrated the performance of a spring-loaded Teflon seal in a vacuum environment. It showed good sealing ability for rotating shafts; however, a short lifetime and large braking torque are intrinsic problems with mechanical seals. Suzuki et al.[23] are developing a brush-type seal made of Teflon fibers to mitigate these issues. It has been reported that the brush seal combined with a labyrinth seal has good sealing ability against the dust with a low braking torque; however, some amount of dust accumulates between the brush and the labyrinth seal, particularly during operation in vacuum. Therefore, a short lifetime is a cause of concern for this method.

To overcome these problems, we have developed a new electrostatic dust shield system for lunar dust as an additional countermeasure to mitigate the load on the mechanical shield and thereby improve the overall performance of mechanical equipment used for long-term lunar exploration.[32] In our earlier system, a single-phase rectangular high voltage was applied to a pair of insulated parallel plate electrodes printed on a substrate at the clearance of the mechanical sealing part. It was demonstrated that more than 70% of the dust was repelled from the gap; however, because the performance of this system was not satisfactory, we have developed two improved systems that realize high sealing performance. This paper describes the configuration and performance of the improved systems, which are expected to increase the reliability of equipment used in long-term manned and unmanned activities on the lunar surface.

II. System Configuration

The proposed system consists of a pair of insulated parallel electrodes and a power supply, as shown in the upper part of Fig. 1. It works on a simple principle. A single-phase, rectangular high voltage was applied to the parallel electrodes placed on the edges of the gap. Owing to the Coulomb force acting on the lofted particles, the particles are attracted to the electrodes predominantly along the electrical flux lines.[33] Because the application of a single-phase voltage does not generate a traveling wave, particles are not transported in one direction; rather, they are repelled from the gap.[7,8,14,15,22,24,34] An electrostatic standing wave acts as a barrier against dust on the basis of a principle similar to that of an electrostatic cleaning system developed for spacesuits[15] and the surfaces of mechanical parts.[14]

A. Electrostatic Dust-Shielding Device

We have developed three types of electrostatic dust-shielding devices, as shown in the upper part of Fig. 1. Figure 1 (a) shows the preliminary devive.[32] It consists of a pair of aluminum parallel plate electrodes that are 35 mm long, 3 mm wide, and 0.2 mm thick. In contrast, Fig. 1 (b) shows one of the improved systems, which uses a double-electrode configuration. We added support electrodes (35 mm long, 3 mm wide, and 0.2 mm thick) outside of the main electrodes (35 mm long, 1 mm wide, and 0.2 mm thick) so that the improved system generates wider electrostatic field. A single-phase rectangular voltage with twice the magnitude of that applied to the inner pair of plate electrodes was applied to the outer pair of plate electrodes. The single-phase rectangular voltage to the outer pair of plate electrodes was synchronized with that applied to the inner pair of plate electrodes. The distributions of the electric flux lines, shown in the lower part of Fig. 1 (b), calculated by the finite differential method based on the Laplace equation, show that the electrostatic shield area produced by the standing wave is wider in the double-electrode device than in the preliminary device [Fig. 1 (a)]; and thus, a better performance is expected.

Figure 1 (c) shows another improved device in which a pair of screen electrodes is added to the preliminary device. In addition to the plate electrodes, a pair of four pieces of parallel wire electrodes made of enamel wire (0.4 mm diameter) is placed near the gap. In this case, particles entering into the gap between the pair of parallel wire electrodes are expected to be repelled from the gap to the outside along the vertical flux lines shown in the lower part of Fig. 1 (c). The right-hand plate electrode and wire electrodes are grounded in this case because one side of the clearance will be a rotor in the actual application. If we apply a voltage to both sides, the power supply must have two channels, and a slip ring is necessary to apply the voltage to the electrode at the rotor side.

In all the devices, the surfaces of the plate electrodes were covered with insulating films made of polyimide (60 μm thick) to prevent insulation breakdown between the electrodes. The plate electrodes were pasted on the edges of plastic plates (35 mm long and 2 mm thick) separated by a distance of 1 mm. Note that a narrow gap is preferable for achieving high shielding performance; however, a relatively wide gap of 1 mm was used in this experiment to demonstrate the effectiveness of the system. The use of a narrow-gap configuration for a mechanical seal is expected to yield better performance than that achieved in this study.

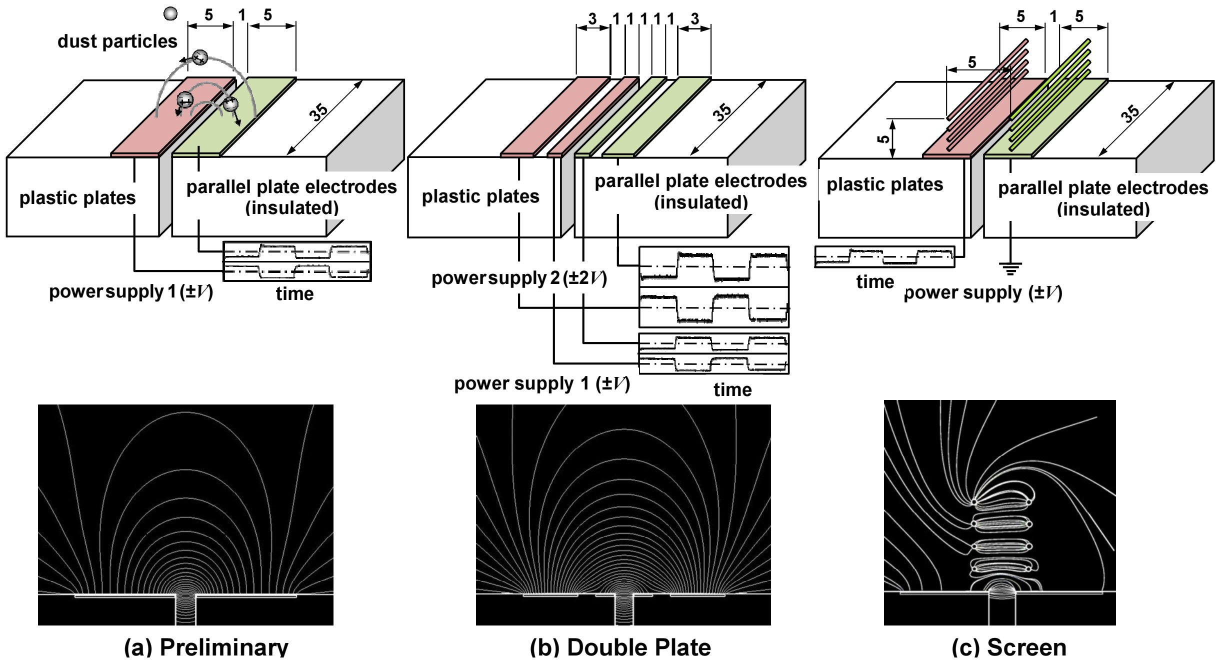

Figure 1. Configurations of three types of electrostatic dust-shielding devices (upper) and electric flux lines (lower).

B. Power Supply

We used a power supply that was originally designed and used for a cleaning system for spacesuits[15] and the flat parts of equipment.[14] A single-phase, rectangular high voltage, as shown in Fig. 1, was generated using a set of positive and negative amplifiers; the amplifiers were switched by semiconductor relays that were controlled by a microcomputer. The power supply is designed to be simple, compact, and lightweight for space applications.

C. Lunar Dust Simulant and Dust Feeder

The lunar dust simulant FJS-1 (Shimizu Corp., Tokyo),[35] which is almost identical to the popular simulant JSC-1A (Orbital Technologies Corporation, Madison, Wisconsin), was used in these experiments. The specifications, scanning electron microscopy (SEM) images, and the particle size distribution of the particles are summarized in the literature.[16]

To evaluate the system performance, dust must be fed continuously at a constant rate. This condition was realized using a vibrating dust feeder.[32] The lunar dust simulant was mounted on a sand sieve (106 μm opening) that was placed above the dust-shielding device; the sieve was then vibrated in the vertical direction using an electromagnetic shaker (Shinken Co., Tokyo, G14-818). Particles larger than 106 μm in diameter were removed by using a sand strainer. If large particles are not eliminated, cleaning rate is determined by a very small number of large particles. This disturbs the rational evaluation of the performance. Also, very large particles may be shielded easily by mechanical means such as a labyrinth seal and brush, which are used together with the electrostatic shield. Although it is assumed that large particles were not cleaned efficiently on the Earth because the large gravitational force and relatively small Coulomb force hinder their transport,[36] low gravity and high charge density of particles on the Moon will mitigate the size effect. The shielding device was isolated mechanically from the shaker. The feed rate of the dust was controlled by adjusting the magnitude and frequency of the excited mechanical vibrations. The attained repeatability of the feed rate was 7% (standard deviation). This implies that the deduced shield rate contains at least a 7% error.

III. Shield Performance

A. Effect of Applied Voltage, Frequency, Feed Rate, and Device Configuration

A plot of the measured shield rate versus the applied voltage is shown in Fig. 2. The experiments were conducted in air (20–25 °C, 1 atm, 40%–60% RH). The shield rate is determined as the weight of particles entering the gap under the applied voltage for 120 s divided by the weight of particles entering the gap in the absence of the voltage. The shield rate increased with the applied voltage; however, the shield performance reached saturation at a high voltage, and it was limited by the occurrence of corona discharge in the air at voltage higher than 4.1 kV_{p-p}. The maximum shield rate of the preliminary device was approximately 70% at a voltage of 3 kV_{p-p}, which is sufficiently below that at which corona discharge began. The performance would improve further in vacuum because corona discharge does not occur in vacuum; therefore, the voltage limit can be increased. To investigate the effect of the electrode configuration, additional experiments were conducted using an electrode width of 1 mm and electrodes separation of 2 mm.[32] The experimental results showed that the shield performance was almost independent of the electrode width and the gap between the electrodes at the threshold voltage because the applied voltage is limited by the occurrence of corona discharge. The corona onset voltage is determined by the electrostatic field. The effect of the inclination of the device was also investigated because the sealing part is not always in a horizontal position in actual operation. The shield rate when the plate was inclined at 30° was about 70% of that at a horizontal position. It was observed using a high-speed microscope camera (Photoron, Tokyo, Fastcam-max 120K model 1)[14-19,32] that some of the particles that fell on the upper plate rolled downward into the gap; this phenomenon reduced the shield rate. However, the weight of particles entering the gap when the plate was inclined is smaller than that when the plate is horizontal because the horizontally projected area of the inclined gap is narrower than that of the horizontal gap for vertically falling dust. Therefore, the horizontal position is the severest case.

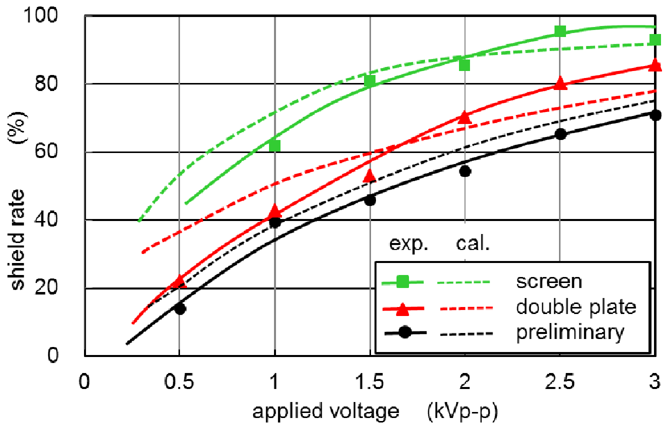

Figure 2. Measured and calculated shield rate of dust-shielding devices versus applied voltage (frequency of applied voltage: 10 Hz, dust feed rate: 5 g/s/m²).

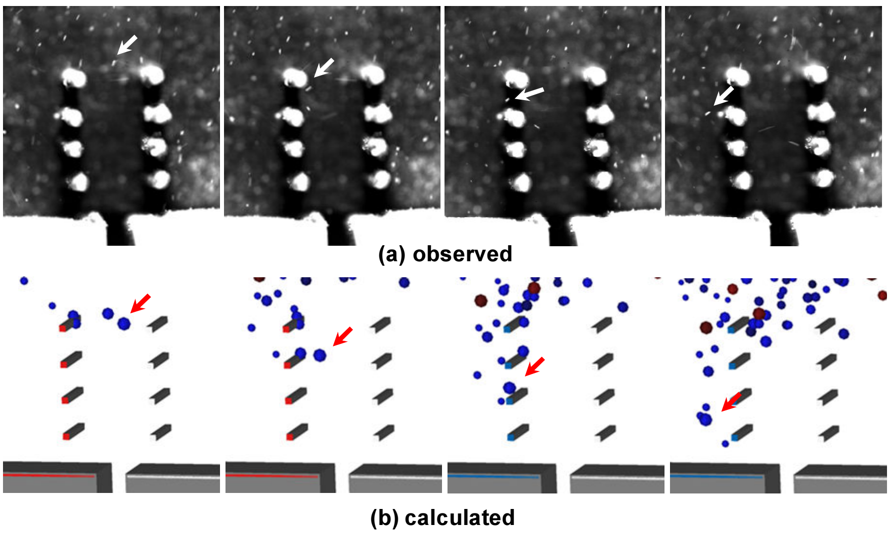

Figure 3. Snapshots of (a) observed and (b) calculated particle motion at 5 ms intervals near screen electrodes.

When the double-plate configuration was adopted, the shield performance increased to approximately 85% at 3 kV_{p-p}. To investigate the dynamics of dust in the standing wave field, the motion of the particles was observed from the lateral side of the device using the high-speed microscope camera. It was confirmed, as expected, that the dust particles approaching the gap were apt to fly away to a great distance; thus, higher performance was realized by the device with the double-plate electrodes. This phenomenon was confirmed by observing the distribution of accumulated dust on the substrate after operation. The dust on the double-plate device was distributed in a wider area than that on the preliminary device. Although the performance is sufficiently improved, the system has a disadvantage in that it needs two sets of power supply equipment.

The shield performance was further increased to more than 90% at 3 $kV_{p\text{-}p}$ by adding the screen electrodes to the plate electrodes. It was clarified by direct observation that dust particles entering into the clearance were ejected through the openings of the screen electrodes, as shown in Fig. 3 (a), which shows snapshots of the observed particle motion taken with the high-speed microscope camera at 5 ms intervals (refer to particle motion designated in arrows). Additional experiments to investigate the effect of the height of the screen electrodes revealed that the shield rate is increased by increasing the number of wires, and therefore the height of the screen electrodes; however, it saturated at a pair of four wires (5 mm in total height of four wires above the gap). The device with a pair of four wires appears to be practically most appropriate for the actual application.

Figure 4 shows the experimentally measured shield rate at different frequencies of the applied voltage for the three electrode configurations. The shield performance was high at low frequencies, and it was highest at 10 Hz in all cases. Direct observation showed that the motion of the dust synchronized with the electrostatic standing-wave field at low frequencies, but it did not follow the change in polarity during high-frequency operation. It was confirmed that the asynchronous motion of dust at high frequencies reduced the shield performance. In contract, shielding is possible even when the frequency of the applied voltage is zero; however, under application of a DC voltage, the shielded dust accumulates on the electrodes, and it is not repelled from the surfaces of the electrodes. Therefore, the application of a low-frequency voltage is indispensable for long-term operation.

The shielding rate was also evaluated in terms of the feed rate of dust normalized by the gap area (1 mm × 35 mm). As shown in Fig. 5, the shield rate decreased slightly with increasing feed rate but was almost independent of the rate when the rate was less than 15 g/sm^2.

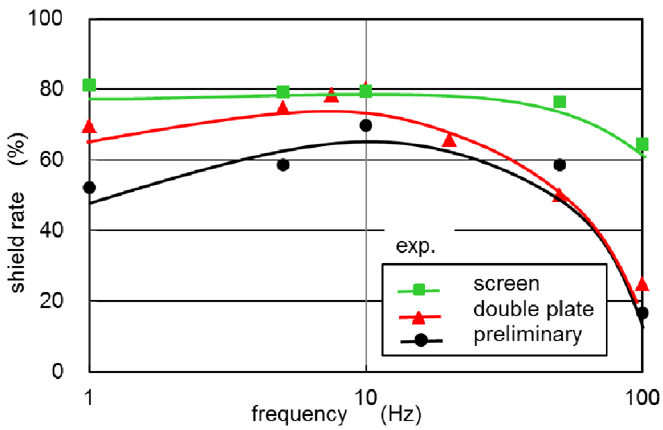

Figure 4. Measured shield rate of dust-shielding devices versus frequency of applied voltage (applied voltage: 2 $kV_{p\text{-}p}$, dust feed rate: 5 g/sm^2).

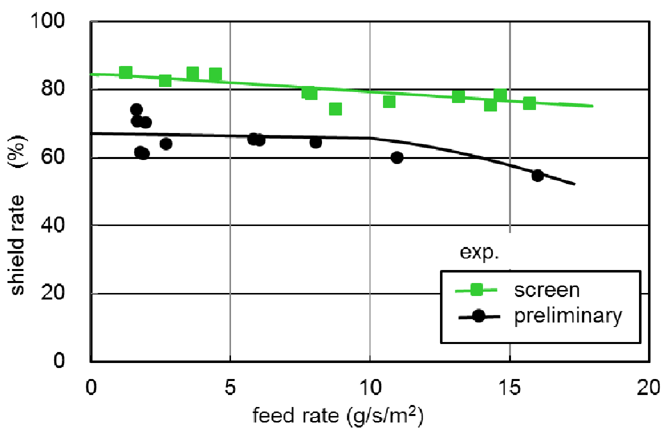

Figure 5. Measured shield rate of dust-shielding devices versus feed rate of dust (applied voltage: 2 $kV_{p\text{-}p}$, frequency of applied voltage: 10 Hz).

B. Performance on the Moon

Numerical calculations were conducted using a three-dimensional hard-sphere model in the distinct element method[16,37] to predict the performance of this system on the Moon. Details of the numerical method and experimental procedure to determine the critical parameters such as adhesion force and distribution of charge density of particles are reported in the literature.[16,37] Before calculating the performance of the system on the Moon, we confirmed the validity of the numerical method by comparing experimental and numerical results on the Earth. The calculated results, represented by the broken curves in Fig. 2, are clearly in reasonable agreement with the measured results not only qualitatively but also quantitatively. Furthermore, the calculated motion of particles shown in Fig. 3 (b) was compared with the observed motion shown in Fig. 3 (a). We confirmed that the calculated and observed motions are in qualitative agreement; thus, the present numerical method can be used to predict the performance of the device under conditions that differ from those considered in this study. Then, we estimated the performance of the system on the Moon by simulation. The gravity was reduced to $g/6$ and the air drag was eliminated in the calculation for the lunar environment. In addition, the charge density of particles was altered in the calculation because dust on the Moon is generally assumed to be electrostatically charged by photoelectric emissions caused by radiation from nearby sources, or by electron/ion collisions via sticking or secondary electron emissions, and the charge of particles is not discharged in vacuum.[27-30] Therefore, the charge density of the dust particles on the Moon would be much higher than that we measured on the Earth. It was assumed in this calculation that the charge density of the dust on the Moon is -0.01 ± 0.1 μC/g, which is 5 times that on the Earth. The calculated result suggests that the dust forms a cloud at altitudes of several millimeters, and virtually no particle will enter the gap. Thus, extremely high shielding performance on the Moon is predicted. However, we also predicted by numerical calculation that the shield performance is substantially reduced if the speed of particles that enter the gap is greater than 1 m/s. Because it is not possible to achieve complete shielding in all situations, combing the proposed shielding device with other devices such as a mechanical seal and/or brush seal will increase the reliability of equipment used in long-term manned and unmanned activities on the lunar surface.

C. Power Consumption

The power consumption of the dust-shielding device was measured. Because the transient current flowed immediately after voltage was switched, the power loss is proportional to the frequency. On the other hand, the power loss is proportional to the square of the applied voltage if insulation breakdown does not occur.[16] The measured power consumption is approximately 1 mW/m for the preliminary and screen devices, where it is assumed that the power loss is proportional to the sealing length. The power consumption of this system is extremely low.

IV. Concluding Remarks

An electrostatic shield system for lunar dust has been improved to prevent the dust from entering into the bearings, mechanical seals, and gears of equipment used for long-term lunar exploration. It was demonstrated that more than 90% of the dust was repelled from the clearance by adopting the combination of plate and screen electrode configuration. Direct observation of the motion of dust particles near the electrodes revealed that dust particles entering into the clearance were ejected through openings in the screen electrodes. A numerical calculation using the hard-sphere model of 3D distinct element method confirmed the observed result, and it was predicted that the cleaning performance would be further improved in the low-gravity and vacuum environment of the Moon. We believe that the system is suitable for space applications because it is simple and lightweight and also because it does not have moving parts and requires extremely low power.

Although high performance was demonstrated and numerical calculations predicted further improvement in the low-gravity and vacuum environment of the Moon, it is not possible to achieve complete shielding, as small amounts of dust can still enter into the gaps. However, combining the proposed shielding device with other devices such as a mechanical seal and/or brush seal will increase the reliability of equipment used in long-term manned and unmanned activities on the lunar surface.

Acknowledgments

The author expresses his gratitude to Ippei Tsushima, Hayato Hoshino, Noriaki Tajima, and Shyta Inari (Waseda University) for their support in conducting the research. Part of this work was supported by JSPS KAKENHI Grant Number 23360116.

References

[1]McKay, D. S. et al., *"The Lunar Regolith." Lunar Sourcebook*, Heiken, G., Vaniman, D., and French, B. M. Eds., Cambridge University Press, Cambridge, 1991, pp. 285-356.

[2]Colwell1, J., Robertson, S., Horányi, M., Wang, X., Poppe, A., and Wheeler, P., "Lunar Dust Levitation," *J. Aerospace Eng.*, Vol. 22, Issue 1, 2009, pp. 2-9.

[3]Stubbs, T. J, Vondrak, R. V., and Farrell, W. M, "A dynamic fountain model for lunar dust," *Advances in Space Research*, Vol. 37, Issue 1, 2006, pp. 59-66.

[4]Metzger, P. T., Immer, C. D., Donahue, C. M., Vu, B. T., Latta, R. C., and Deyo-Svendsen, M., "Jet-Induced Cratering of a Granular Surface with Application to Lunar Spaceports," *J. Aerospace Eng.*, Vol. 22, Issue 1, 2009, pp. 24-32.

[5]Calle, C. I., et al., "Dust Particle Removal by Electrostatic and Dielectrophoretic Forces with Applications to NASA Exploration Missions," *Proc. ESA Annual Meeting on Electrostatics*, ESA, Minneapolis, 2008, O1.

[6]Calle, C. I., Buhler, C. R., McFall, J. L., and Snyder, S. J., "Particle removal by electrostatic and dielectrophoretic forces for dust control during lunar exploration missions," *J. Electrostat.*, Vol. 67, Issue 2-3, 2009, pp. 89-92.

[7]Calle, C. I, Immer, C. D., Ferreira, J., Hogue, M. D., Chen, A., Csonka, M. W., Suetendael, N. V., and Snyder, S. J., "Integration of the Electrodynamic Dust Shield on a Lunar Habitat Demonstration Unit," *Proc. ESA Annual Meeting on Electrostatics 2010*, 2010, Paper D1.

[8]Calle, C. I., Chen, A., Immer, C. D., Csonka, M., Hogue, M. D., Snyder, S. J., Rogriquez, M., and Margiotta, D. V., "Dust Removal Technology Demonstration for a Lunar Habitat," *AIAA SPACE 2010*, Anaheim, CA, 2010.

[9]Cooper, B. L., McKay, D. S., Taylor, L. A., Kawamoto, H., Rifrio, L. M. and Gonzalez, C. P., "Extracting respirable particles from lunar regolith for toxicology studies, *Proc., 12th Int. Conf. on Engineering, Science, Construction, and Operation in Challenging Environment, Earth & Space 2010*, ASCE, Honolulu, 2010, pp. 66–73.

[10]Christoffersen, R. et al., "Lunar dust effects on space suit systems: Insights from the Apollo spacesuits," NASA/TP-2009-214786, National Aeronautics and Space Administration, Houston, 2009.

[11]Delgado, I. R., and Handschuh, M. J., "Preliminary Assessment of Seals for Dust Mitigation of Mechanical Components for Lunar Surface Systems," *Proc. of the 40th Aerospace Mechanism Symposium*, NASA/CP-2010-216272, NASA Kennedy Space Center, 2010.

[12]Gaier, J. R. "The Effects of Lunar Dust on EVA Systems during the Apollo Missions," NASA/TM-2005-213610, NASA Glenn Research Center, Cleveland, Ohio, 2005.

[13]Gaier, J. R., Siamidis J., and Larkin, E. M. G., "Effect of Simulated Lunar Dust on the Properties of Thermal Control Surfaces," *J. Spacecraft and Rockets*, Vol. 47, No. 1, 2010, pp. 147-152.

[14]Kawamoto, H., and Miwa, T., "Mitigation of Lunar Dust Adhered to Mechanical Parts of Equipment Used for Lunar Exploration," *J. Electrostat.*, Vol. 69, Issue 4, 2011, pp. 365-369.

[15]Kawamoto, H., and Hara, N., "Electrostatic Cleaning System of Lunar Dust Adhered to Spacesuits," *J. Aerospace Eng.*, Vol. 24, Issue 4, 2011, pp. 442-444.

[16]Kawamoto, H., Uchiyama, M., Cooper, B. L., and McKay, D. S., "Mitigation of Lunar Dust on Solar Panels and Optical Elements Utilizing Electrostatic Traveling-Wave," *J. Electrostat.*, Vol. 69, Issue 4, 2011, pp. 370-379.

[17]Kawamoto, H., "Cleaning Device for Lunar Dust Adhering to Spacesuits Utilizing Magnetic and Electrostatic Forces," *MAGDA2011: The 20th MAGDA Conference in Pacific Asia*, Kaohsiung, Taiwan, 2011, pp. 458-461.

[18]Kawamoto, H., and Inoue, H., "Magnetic Cleaning Device for Lunar Dust Adhering to Spacesuits," *J. Aerospace Eng.*, Vol. 25, Issue 1, 2012, pp. 139-142.

[19]Kawamoto, H., "Electrostatic Cleaning Device for Removing Lunar Dust Adhered to Spacesuits," *J. Aerospace Eng.*, Vol. 25, Issue 3, 2012, pp. 470-473.

[20]National Aeronautics and Space Administration (NASA) Manned Spacecraft Center, "Apollo 12 preliminary science report," NASA SP-235, Scientific and Technical Information Division, Office of Technology Utilization, Washington DC., 1970.

[21]Hyatt, M. J., and Suraka, S. A., "The Dust Management Project: Characterizing Lunar Environments and Dust, Developing Regolith Mitigation Technology and Simulants," *AIAA 40th International Conference on Environmental Systems*, Barcelona, 2010, E-17351.

[22]Qian, D., Marshall, J. S., and Frolik, J., "Control analysis for solar panel dust mitigation using an electric curtain," *Renewable Energy*, Vol. 41, 2012, pp. 134-144

[23]Suzuki, M., Matsumoto, K., Nishida, S., Wakabayashi, S., and Hoshino, T., "Experimental study on a brush-type seal in air and in vacuum as a candidate for regolith seal applications," JSASS-2010-4522, 2010.

[24]Sun, Q., Yang, N., Cai, X., and Hu, G., "Mechanism of dust removal by a standing wave electric curtain," *Science China, Physics, Mechanics & Astronomy*, Vol. 55, No. 6, 2012, pp. 1018-1025.

[25]Taylor, L. A., Schmitt, H. H., Carrier, W. D., and Nakagawa, M., "The Lunar Dust Problem: From Liability to Asset," *1st Space Exploration Conference*, AIAA, 2005, pp. 2005-2510.

[26]Wagner, S. A., "The Apollo Experience Lessons Learned for Constellation Lunar Dust Management," NASA, TP-2006-214726, 2006, pp. 34-40.

[27]Abbas, M. M., Tankosic, D., Craven, P. D., Spann, J. F., LeClair, A., and West, E. A., "Lunar dust charging by photoelectric emissions," *Planetary and Space Science*, Vol. 55, Issue 7-8, 2007, pp. 953-965.

[28]Abbas, M. M., Tankosic, D., Craven, P. D., LeClair, A. C., and Spann, J. F., "Lunar Dust Grain Charging by Electron Impact: Complex Role of Secondary Electron Emissions in Space Environments," *The Astrophysical Journal*, Vol. 718, Issue 2, 2010, pp. 795-809.

[29]Ding, N., Wang J., and Polansky, J., "Measurement of Dust Charging on a Lunar Regolith Simulant Surface," *IEEE Trans. Plasma Science*, Vol. 41, No. 12, 2013, pp. 3498-3504.

[30]Forward, K. M., Lacks, D. J., and Sankaran, R. M., "Triboelectric charging of lunar regolith simulant," *J. Geophysical Research*, Vol. 114, Issue A10, 2009, A10109.

[31]Anderson, G. A. and Iacomini, C., "The Design and Operation of a Lunar Dust Seal Testing System," *Aerospace Conference*, IEEEAC, 2010, paper #1435.

[32]Kawamoto, H., "Electrostatic Shield for Lunar Dust Entering into Mechanical Seals of Equipment Used for Lunar Exploration," *J. Aerospace Eng.*, Vol. 27, Issue 2, 2014, pp. 354-358.

[33]Jones, T. B., *Electromechanics of Particles*, Cambridge University Press, New York, 1995, Chap. 1.

[34]Liu, G., and Marshall, J. S., "Particle transport by standing waves on an electric curtain," *J. Electrostat.*, Vol. 68, Issue 4, 2010, pp. 289-298.

[35]Kanamori, H., Udagawa, S., Yoshida, T., Matsumoto, S., and Takagi, K., "Properties of lunar soil simulant manufactured in Japan," *Proc. of the 6th Int. Conf. on Engineering, Construction and Operations in Space*, ASCE, Albuquerque, NM, 1998, pp. 462-468.

[36]Kawamoto, H. and Shibata, T., "Electrostatic Cleaning System for Removing Sand on Solar Panels," *39th IEEE Photovoltaic Specialist Conference (39th PVSC)*, Tampa, FL, 2013.

[37]Kawamoto, H., Seki, K. and Kuromiya, N., "Mechanism on Traveling-Wave Transport of Particles," *J. Phys. D: Appl. Phys.*, Vol. 39, 2006, pp. 1249-1256.