Ballistic Range Experiment of Spherical Body in Particle-laden Environment

By Chihiro MASAKI,1) Yasumasa WATANABE,2) and Kojiro SUZUKI1)

1)Department of Advanced Energy, The University of Tokyo, Kashiwa, Japan
2)Department of Aeronautics and Astronautics, The University of Tokyo, Tokyo, Japan

(Received June 30th, 2017)

Considering a spacecraft that encounters particle-laden environment, such as dust particles flying up over the regolith by the jet of the landing thruster, high-speed flight of a projectile in particle-laden environment was experimentally simulated by using the ballistic range. In case of high-speed motion, cracking of particles occurs as well as the damage on the projectile surface. To establish the experimental simulation technology and to obtain the fundamental characteristics of such complicated phenomena, a projectile was launched by the ballistic range at the velocity up to 500 m/s and the collective behavior of particles around the body was observed by the high-speed camera. To eliminate the effect of the gas-particle interaction and to focus on the effect of the interaction between the particles and the projectile’s surface, the test chamber pressure was evacuated down to 30 Pa. The particles about 100 – 400 μm diameter were scattered in the test chamber uniformly. The projectile was launched into a particle sheet in the tangential direction. The high-speed camera captured both the projectile and particle motion. From the movie, the interaction between the projectile and particle sheet was clarified. The damage on the surface of the projectile recovered after the shot was also observed.

Key Words: Particle-laden Environment, Ballistic Range, High-speed Collision, Impact

1. Introduction

Particle-laden environment is not unusual in space. In deep space missions, a space probe may encounter a particle-laden environment during an interplanetary flight, atmospheric flight or travel on/under the ground. Such encounter may cause serious damage on the spacecraft body. Generally speaking, the particle-laden environment can be categorized into three situations: the dusty atmosphere, the regolith as packed particles and the cloud of sparsely scattered particles in vacuum.

A typical example of the dusty atmosphere will be found on Mars. When an atmospheric probe enters the Martian atmosphere in a dust storm, the flow around the body is significantly influenced by the gas-particle two-phase flow effect.1) In such case, the aerodynamic heating may be augmented and the damage on the surface may become more severe due to the augmented aerodynamic heating as well as the impact of the dust particles. On those problems, the experimental studies and the numerical studies have been made in the past.1-3) A typical example of the packed particles will be found in the regolith on planets, satellites and asteroids. For investigation on the interior structure under the ground, impact probe missions have been considered in the past.4) The behavior of the regolith at the impact will be well described by the soil dynamics and some numerical analysis methods have been developed.5)

The most well-known example of the cloud of sparsely scattered particles will be the Saturn's ring. However, such environment also appears by an artificial effect. When a spacecraft is approaching to the ground of an asteroid, lots of dust particles must fly upward at high speeds, receiving the jet of the thruster on the spacecraft.6,7) If the same or another spacecraft is flying in the dust cloud, it may encounter the particle cloud at high relative velocity. The behavior of the particle cloud is expected to be described by the dynamics of the granular flow. The granular flow has been extensively studied so far.8) However, most of them consider relatively low speed regimes. The phenomena in high-speed regimes, which may be encountered by a spacecraft, have not been clearly understood. The granular flow dynamics in high-speed regimes must become much complicated because of the crash and abrasion of particles due to high-speed impact among the particles and/or between particles and the spacecraft surface.

Therefore, it is necessary to experimentally clarify the fundamental characteristics of the high-speed granular flow. Specifically, the case that a projectile flies at high-speed in the particle-laden environment must be studied for consideration on possible hazardous situation of a spacecraft.

In the present study, the ballistic range facility in our laboratory was employed to simulate the flight of a spacecraft flying through a particle-laden environment. It can launch a 10-gram projectile up to a speed of about 500 m/s depending on the charged pressure. The effect of the gas-particle two-phase flow can be eliminated by evaluating the test chamber beforehand.

The objectives of the present study are as follows:
1) To establish the experimental technique to simulate the high-speed flight of an object in the cloud of sparsely scattered particles by using the ballistic range,
2) To observe the phenomena, which occur on the projectile and the particle cloud around the body, by using a
high-speed camera,
3) To find the characteristic features of the phenomena including the destruction of particles due to collisions and to clarify the effect of the experimental conditions including the materials of the particles and the projectile and so on.

2. Method of Experiment

2.1. Ballistic range and measurement system

The schematic view of ballistic range is shown in Fig. 1, and the illustration around the test chamber (schematic of the present experimental setup) is shown in Fig. 2. To simulate the cloud of particles, a particle sheet falling freely by the gravitational force is formed in the test chamber. The thickness of sheet is 2 mm. Such thin particles seem convenient for observation of the phenomena in the direction normal to the sheet. In the case of thick cloud, a recorded image will become integrated one in the normal direction and the analysis of the image will become difficult to obtain the cross section of the phenomena. A projectile is launched in the tangential direction to the sheet as shown in Fig. 2. A high-speed camera Phantom Miro 310 (Nobby Tech. Ltd.) was used to capture the image in the test chamber through the glass window. The specifications and the operation parameters are listed in Table 1. For image capturing at high frame rate, the high-intensity metal halide lamp MID-25FC (Lighterrace Inc.) with the power 250 W was used. Particles and projectiles were illuminated in the backlight direction. In the preliminary tests, both the forward light and backlight directions were compared. The clearer images were obtained with the backlighting.

To launch a projectile in high speed, the ballistic range facility in the laboratory was used. It can launch a projectile with about 10 g mass up to a speed of 500 m/s, depending on the charged pressure. This facility was used for high-speed impact experiment of the penetrator into ice.9 As shown in Fig. 1, the facility consists of the high-pressure chamber, the barrel tube, the accelerate tube, the adapter, and the test chamber. A projectile is set in front of the diaphragm section before the shot. The injection velocity is controlled by appropriately charging the compressed air in the high-pressure chamber. The maximum available pressure is 1 MPa relative to the atmospheric pressure.

Fig. 1. Schematic view of ballistic range facility.

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Brightness resolution</th>
<th>Monochrome (12bit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity (ISO / ASA)</td>
<td>16,000</td>
<td></td>
</tr>
<tr>
<td>Minimum exposure time</td>
<td>1.0 μs</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2. Illustration of test chamber.

Table 1. Specifications and filming parameters of high speed camera.

<table>
<thead>
<tr>
<th>Imaging parameters</th>
<th>Image acquisition rate</th>
<th>20,000 fps</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Exposure time</td>
<td>1.0 μs</td>
</tr>
<tr>
<td></td>
<td>Image resolution</td>
<td>512 x 256 pixels</td>
</tr>
</tbody>
</table>

2.2. Projectiles

The projectiles used in the experiment were designed by considering the visibility of the projectile shape, the appropriate size for observation, and the strength to withstand the strong acceleration in the tube. The projectile consists of a hemispherical nose and a cylindrical rear part because of its good visibility and stability. Its outer diameter is equal to the inner diameter of the acceleration tube so that the projectile comfortably fits into the ballistic range inlets. In the ballistic range experiment, a sabot is usually attached behind a projectile to receive the acceleration force by the high pressure air behind the sabot in the tube. However, the sabot, which is separated after injection from the exit of the tube and flies behind the projectile, is expected to disturb the motion of the particles. The sabot-less launch method used in the present experiment is suitable for the observation of the phenomena. To reduce the projectile mass and to obtain high launch velocity, the thickness of the body is reduced to about 2 mm, which allows the body to have sufficient strength for the acceleration.

Two kinds of materials, polycarbonate and aluminum, are selected for projectiles as a typical resin material and a typical metal material, respectively. The weights are 3.9g and 8.6g, respectively. A photograph of both types of projectiles is shown in Fig. 3. The image of the polycarbonate projectile was captured more clearly than the aluminum one. The image of the aluminum projectile in each frame is slightly blurred due to the reflection of the light at the surface. The oil clay in the box of the size 15 × 20 × 20 cm was set behind the particle sheet to stop the motion of the projectile. The damage at the impact in the stopper was less severe for the aluminum model than for the polycarbonate model.
Fig. 3. Image of projectiles, left: aluminum projectile, right: polycarbonate projectile (Nose diameter: $\phi25.75$ mm, rear cylinder diameter: $\phi25.75$ mm, total height: 40.75 mm, wall thickness: 2 mm).

### 2.3. Particle sheet

#### 2.3.1. Particles

Considering that the objective of this study is to clarify the fundamental properties of the particle behavior around the projectile, the material and the particle size were selected from a viewpoint of the visibility for the present camera system. Two types of materials are selected for the particles, the brittle one and the hard one.

As the brittle type, the glass beads (particle diameter = 400 $\mu$m) was used. Better visibility was obtained for the glass beads with the optical system in this work. As the hard type, the emery, which is used for polishing powder, (particle diameter = 100 $\mu$m) was selected. The 180 times magnified images of both particles are shown in Fig. 4. The emery has an elongated rugged shape.

Fig. 4. Magnified image of particles. (Left : glass beads, right : emery).

#### 2.3.2. Particle sheet generating device

In order to create the particle-laden environment in the test chamber, a device to generate a particle sheet was developed. The uniformity of the particle number density on the sheet is important. Therefore, a mechanism for dropping particle from a slit was prepared. The particles are falling through the slit by the gravitational force. As shown in the Fig. 5, the length of the slit is 100 mm and the gap is 2 mm. Distance from muzzle to the upstream end of the particle sheet is about 80 mm. Due to the volume of the dust reservoir above the slit, the duration of the particle sheet is about 10 seconds. As shown at the left side of Fig. 5, a shutter at the slit is closed before the experiment, and it is removed by the motor at an arbitrary trigger timing. The falling speed of the free dropping particles was estimated from the moving distance on two continuous frames. It was about 3.0 m/s, which is much smaller than the projectile speed. Consequently, the particles are considered to be floating still in the test chamber in the time scale of the projectile’s passage. Using the above device, almost the uniform two-dimensional planar particle sheet was successfully generated.

The particle-supply rate and the number density are calculated and shown in Table 2. The supply rate is calculated by dividing the amount of particles in the funnel by the discharge time. In addition, the number density is calculated by dividing the supply rate by the swept volume of the particle. These parameters can be changed by adjusting the slit width.

<table>
<thead>
<tr>
<th>Particle</th>
<th>Diameter ($\mu$m)</th>
<th>Supply rate (g/s)</th>
<th>Number density (particles/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass beads</td>
<td>400</td>
<td>12.4</td>
<td>$4.8 \times 10^8$</td>
</tr>
<tr>
<td>Emery</td>
<td>100</td>
<td>15.6</td>
<td>$1.9 \times 10^9$</td>
</tr>
</tbody>
</table>

Fig. 5. Illustration of particle sheet generating devise.

### 2.4. Performance check of facility

#### 2.4.1. Operations and experimental conditions

The experiment was carried out in the following procedure. 1) Set the projectile, 2) Evacuate the test chamber to 30 Pa, 3) Fill air into the high-pressure chamber, 4) Start particle sheet generating device by the remote control switch, 5) Launch the projectile and capture the movie by the high-speed camera. When a projectile is launched without depressurizing the test chamber, particles are pushed away by the air in front of the projectile. In order to avoid such a phenomenon, and to simplify the situation, the pressure reduction before the experiment was necessary. The experimental parameters are summarized in Table 3.

<table>
<thead>
<tr>
<th>Parameter or items</th>
<th>Values or items</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charged pressure (Air)</td>
<td>0.3 MPa, 0.5 MPa, 0.7 MPa</td>
</tr>
<tr>
<td>Test chamber pressure</td>
<td>Nominal 30 Pa</td>
</tr>
<tr>
<td>Projectiles</td>
<td>Polycarbonate (3.9g) / Aluminum (8.6g)</td>
</tr>
<tr>
<td>Dust particles</td>
<td>Glass beads (400 $\mu$m) / Emery (100 $\mu$m)</td>
</tr>
<tr>
<td>Temperature</td>
<td>Room temperature</td>
</tr>
</tbody>
</table>
2.4.2. Preliminary experiment

In the ballistic range experiment, the size and speed of projectiles are restricted by the diameter of the accelerate tube and the acceleration performance of the ballistic range facility, respectively. Therefore, the speed range available in this experiment was investigated beforehand.

A series of preliminary experiment using the polycarbonate projectile in the test chamber pressure 30 Pa was conducted in the absence of the particle sheet. These experiments were conducted with the charged pressures at 0.3 MPa, 0.5 MPa, and 0.7 MPa.

Composite photographs of the snap shots at the frame interval 50 µs are shown in Fig. 6. In this figure, the white dashed line shows the center line of the accelerate tube. From these photographs, the flight speed, path angle (the angle between the center line and the velocity vector) and the angle of attack (the angle between the projectile axis and the velocity vector) are calculated from the images of two continuous frames of the high-speed movie. The variation of the projectile speed with the charged pressure is shown in Fig. 7. The charged pressure and the projectile speed have a linear relationship in the present experimental condition. For comparison, the result of the aluminum projectile at the charged pressure 0.5 MPa was also shown. The speed of aluminum projectiles is lower than polycarbonate ones by 100 m/s because of their heavier mass.

It should be noted that the angle of attack and the path angle were estimated assuming that the motion out of the image plane can be ignored. Figures 8 and 9 show the time histories of the angle of attack and the path angle. The horizontal axis shows the distance from the muzzle to the tip of the projectile. In order to know the variation due to the shot with the same charged pressure, the shot with charged pressure 0.5 MPa were conducted three times. The estimation error in these angles is within 1.2 degree, considering the amount of deviation of selected pixels. In these figures about angles, the variations of the angle of attack and path angle are at most 0.2 degrees in the absence of particles. The flight path is considered to be almost straight within the estimation error. The time history of the projectile speed was calculated as shown in Fig. 10. The variation of the velocity is not so large in comparison with the error bar calculated from the amount of deviation of selected pixels.
3. Result and Discussion

The test conditions are summarized in Table 4. The snapshots of high-speed movie of a projectile flying in a particle sheet are shown in Figs. 11-13. From these snapshots, the influence of the gas in front of the projectile and that used for acceleration in the tube seem negligible.

In Fig. 11, the dark area was seen behind the projectile. This area indicates that the particles hardly went around into the wake region. On the other hand, in Fig. 11(e), a dark area was also seen in front of the projectile. Comparing the cases of the glass beads and the emery, the patterns of the particle motion around the projectile are different. Though the mechanism of the formation of such dark zone has not been clarified yet, these pictures imply that at the impact on the projectile surface, the glass beads were broken into much smaller pieces and deposited on the projectile surface. These particles were seen as a shadow.

In the case of Fig. 12, the light emission was expected to occur at the collision of the emery particles at the aluminum surface. In fact, the bright zone around the projectile spread more widely than in Fig. 11. The comparison among Figs. 11, 12, and 13 indicates that the interaction between the particles and the projectile depends on both the particle and the projectile material.

Figure 14 shows a photograph of aluminum surface after flying through the emery sheet. The scratched line on the nose surface was apparently caused by the collision with a particle sheet.

The temporal variation of the projectile velocity during the flight in the particle sheet was calculated in the same way as explained in subsection 2.4.2 and is shown in Fig. 15. The flight distance in the particle sheet was measured from the upstream end of the particle sheet to the tip of the projectile. Considering the size of the error bar shown in the figure, the decrease in the velocity due to the momentum loss by the collision with the particle sheet was not evident.

Figure 16 indicates the brightness distribution on the center line of the body in Fig. 11(d). The particle compression layer thickness is defined as the thickness of the bright region in front of the projectile. Figure 17 shows the variation of particle compression layer thickness. From this graph, the growth rate of this thickness with respect to the flight distance seems almost the same for the different test conditions. However, the flight distance in the particle sheet is not sufficient in the present experimental setup. To evaluate the drag force due to the collision with the particle sheet, and to reveal the overall tendency of the particle compression layer thickness, larger particle sheet and longer flight path length are necessary in the test chamber.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Condition number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Projectile</td>
<td>Polycarbonate</td>
</tr>
<tr>
<td>Particle</td>
<td>Glass beads</td>
</tr>
<tr>
<td>Charged pressure(Air)</td>
<td>0.3 MPa</td>
</tr>
<tr>
<td>Test chamber</td>
<td>30 Pa</td>
</tr>
<tr>
<td>Average velocity</td>
<td>330.1 m/s</td>
</tr>
</tbody>
</table>

Table 4. Test conditions.

Fig. 11. Snapshots of high-speed movie of a spherical model flying in particle sheet at condition (1) (time from edge of particle sheet: a:0 ms, b:0.05 ms, c:0.1 ms, d:0.15 ms, d:0.2 ms).
Fig. 12. Snapshots of high-speed movie of a spherical model flying in particle sheet at condition (2) (time from edge of particle sheet: a:0 ms, b:0.05 ms, c:0.1 ms, d:0.15 ms, d:0.2 ms).

Fig. 13. Snapshots of high-speed movie of a spherical model flying in particle sheet at condition (3) (time from edge of particle sheet: a:0 ms, b:0.05 ms, c:0.1 ms, d:0.15 ms, d:0.2 ms).
4. Conclusions

In order to simulate the particle-laden environment around a projectile flying at high speed, the experiment was conducted by using the ballistic range facility. The major conclusions are as follows:

1) It was successfully performed a high-speed (about 500 m/s) flight of a projectile in the particle sheet using the ballistic range facility. To generate the cloud of particles in the test chamber, the particle sheet generating device with the slit was developed. In the sheet, the particles are almost uniformly distributed on the two-dimensional vertical plane. The particle velocity was negligible in comparison with the projectile speed.

2) The pattern of the particle behavior around the projectile was successfully captured. Behavior of particles was clearly observed. The scratched line by the particle sheet could be seen in front of the projectile.

3) Particles are reflected and some are destroyed on the projectile surface. The pattern depends on both the projectile and the particle material. From a series of the snapshots of the high-speed movie, the change in velocity and particle compression layer thickness of the projectile was evaluated.

To clarify the characteristics of the particle compression layer and to evaluate the drag force due to collision with the particles, much longer flight path in the particle sheet is necessary. The length of the particle sheet generating device will be extended by two times in the future work.

Acknowledgments

This work is supported by Grant-in-Aid for Scientific Research (B) No. 16H04585 of Japan Society for the Promotion of Science.

References


