Flight Demonstration for Reentry Capsule with Thin Aeroshell Using Rubber Balloon

By Hideto TAKASAWA,1) Yoichi SUENAGA,2) Takashi MIYASHITA,1) Koshiro HIRATA,3) Kaito WAKABAYASHI,1) Yusuke TAKAHASHI,1) Yasunori NAGATA,4) and Kazuhiko YAMADA4)

1) Division of Mechanical and Space Engineering, Hokkaido University, Sapporo, Japan
2) Department of Advanced Energy, The University of Tokyo, Kawasaki, Japan
3) Department of Industrial Technology and Innovation, Tokyo University of Agriculture and Technology, Fuchu, Japan
4) Institute of Space and Astronautical Science, JAXA, Sagamihara, Japan

(Received March 1st, 2023)

A sample return mission to deep space has been proposed in which the orbital velocity in the atmospheric entry reaches 15 km/s, resulting in extremely severe aerodynamic heating to the sample return capsule (SRC). To mitigate this heating, a new concept of SRC with a lightweight and large-area aeroshell was proposed. This SRC must be aerodynamically stable in attitude at all speeds. To evaluate the dynamic stability of the capsule, the free flight experiment called Rubber balloon Experiment for Reentry capsule with thin Aeroshell (RERA) was conducted on July 1st, 2022. The capsule, with a mass of 1.56 kg and a diameter of 0.8 m, was dropped from a rubber balloon at an altitude of 25 km. The data collected by onboard sensors were successfully transmitted to the ground station. The capsule kept low oscillation in attitude motion without dynamic instability such as vertical rotation. The flow field around the capsule during the experiment had a maximum Mach number of 0.15 and a Reynolds number of 10^5, which reproduced the flow field around the actual deep space SRC (DS-SRC) at low speeds in descent phase. This experiment suggested that the capsule is dynamically stable in the low-speed region.

Key Words: Dynamic Stability, SRC, Balloon Experiment

Nomenclature

- \( C_B \) : ballistic coefficient
- \( C_d \) : drag coefficient
- \( C_{\text{p}} \) : pitching moment slope
- \( D \) : length, m
- \( f \) : frequency, s\(^{-1}\)
- \( I \) : moment of inertia, kg m\(^2\)
- \( M \) : Mach number
- \( m \) : mass, kg
- \( S \) : projected area, m\(^2\)
- \( u \) : velocity, m/s
- \( \rho \) : density, kg/m\(^3\)
- \( \omega \) : angular velocity, rad/s

1. Introduction

A sample return mission for deep space exploration has been proposed, which aims to travel to farther planets or asteroids than the previous Hayabusa missions. However, there are significant challenges such as aerodynamic heating during the atmospheric reentry phase because the capsule's orbital velocity reaches 15 km/s, assuming a sample return from the Saturn gravitational sphere, which is a higher velocity than the Hayabusa mission of 12 km/s. To address this problem, a novel concept of a capsule\(^1\) has been proposed. The capsule, as shown in Fig. 1, has a lightweight and large surface area to achieve efficient aero-deceleration at high altitudes and reduce heating. Additionally, understanding the aerodynamic characteristics such as attitude instability of the thin-aeroshell capsule is essential for improving the safety and probability of success in the atmospheric entry mission. In the worst case, aerodynamic instability in attitude can cause issues such as insufficient aero-deceleration and deviation from the predicted landing site. This type of aerodynamic instability has been observed in the Hayabusa capsule\(^2\) at transonic speeds (\(M = 1.1\)).

Fig. 1. Images of thin-shell type capsule.

A mitigation method for aerodynamic instability is necessary as the current capsule design is intended to descend without a parachute. This means that the capsule needs to be stable in attitude at all speeds, including low speeds without parachute. There are several methods used to evaluate dynamic stability, such as wind tunnel testing\(^3\), Computational Fluid Dynamics (CFD)\(^4\), and flight tests\(^5\). In wind tunnel testing, a model with 1 degree of freedom (DOF) in the pitch direction is often adopted to obtain the amplitude of motion and the flow field, and to understand the phenomena. However, there is no
guarantee that the phenomena in the wind tunnel are the same as those that occur in flight due to the limitations of motion. CFD analysis can be adopted to perform coupled analysis with fluid and motion under conditions similar to those in free flight. While this method can qualitatively reproduce the motions observed in wind tunnel tests, it is difficult to reproduce the motions in flight over a continuous speed range, and the computational load for a long analysis time is significant. Flight tests provide the most accurate representation of actual flight conditions, but there are limited test opportunities. Therefore, by conducting flight tests, it is possible to evaluate the relationship between the wind tunnel test and actual flight using the flight data as a reference and to understand wind tunnel testing. In addition, the flight data can be used as verification data to improve the reliability of numerical analysis. The updated wind tunnel test and numerical analysis are used to predict the behavior of the capsule in flight. The flight results are then fed back to the wind tunnel tests and numerical analysis, and the process is repeated to deepen understanding of the phenomena.

The objective of this study is to evaluate the dynamic stability of a thin-aeroshell capsule at low speeds in free flight by balloon drop. To achieve the study, we conducted a free flight mission called rubber balloon experiment for reentry capsule with thin aeroshell (RERA).

2. Overview of RERA

2.1. RERA capsule

To evaluate the dynamic instability of this capsule at low speeds, it is desirable to reproduce the same flight environment of the deep space SRC (DS-SRC) in flight. The DS-SRC is expected to have a thin heat shield with a diameter of 0.8 m, a total mass of 10 kg. The free flight experiment uses a full-scale and low-weight capsule, called the RERA capsule. The RERA capsule had a diameter of 0.8 m, a total mass of 1.56 kg, the moment of inertia around its body axis of 0.033 kg m² and around the vertical axis of 0.020 kg m². This capsule had an order of magnitude lower moment of inertia than the DS-SRC because the mass was an order of magnitude lower and the shape was the same. Fig. 2 and Table 1 show the appearance of the RERA capsule and the measured conditions of this capsule, respectively. The altitude of 25 km which the rubber balloon is expected not to break was set as the separation altitude. The RERA capsule can be tested in the same order of magnitude in Reynolds number and under 0.2 in Mach number compared to the DS-SRC.

The drawing of the RERA capsule is shown in Fig. 3. The origin was at the front end of the flare. The center of gravity was located 128 mm in the positive z-direction from the origin. The RERA capsule consisted of a front flare (Styrofoam), a back cylinder (Styrofoam), and equipment. Only adhesive KE-60 (Konishi Co., Ltd.) was used to bond the styrene foam to the various components. The equipment was stored inside the back cylinder, and the camera was exposed outside the rear cylinder. The sides were covered with Kapton tape to prevent air from flowing in through the camera section and cooling the equipment. To secure the transmitter antenna, it was placed in a groove in the front flare and a thin sheet of Styrofoam was bonded. Because of its axisymmetric shape, we assume the moments of inertia around the x-axis and y-axis were same, and the moment of inertia of the internal equipment was measured and external Styrofoam were calculated from CAD.

![Photo of the RERA capsule.](image)

**Fig. 2. Photo of the RERA capsule.**

### Table 1. Configuration of the RERA capsule.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass, kg</td>
<td>1.56</td>
</tr>
<tr>
<td>Size, m</td>
<td>(40.8 \times 0.235)</td>
</tr>
<tr>
<td>Material</td>
<td>Styrofoam</td>
</tr>
<tr>
<td>(An expansion ratio of 40)</td>
<td></td>
</tr>
<tr>
<td>Moment of inertia in x direction, kg (\cdot) m²</td>
<td>(2.0 \times 10^{-2})</td>
</tr>
<tr>
<td>Moment of inertia in y direction, kg (\cdot) m²</td>
<td>(2.0 \times 10^{-2})</td>
</tr>
<tr>
<td>Moment of inertia in z direction, kg (\cdot) m²</td>
<td>(3.3 \times 10^{-2})</td>
</tr>
</tbody>
</table>

![Drawing of the RERA capsule.](image)

**Fig. 3. Drawing of the RERA capsule.**

2.2. Equipment system

A block diagram of the equipment is shown in Fig. 4. In this experiment, a 9-axis sensor (MTI-620, Xsens) was used to measure acceleration, angular velocity, and magnetic field in order to evaluate the capsule's attitude. The specifications of the attitude sensor are shown in Table 2. The measurement results shown in Section 3 confirm that the values are within the measurement range. In addition, because the frequencies of pitch and yaw oscillatory motion are expected to about 1 Hz, it is possible to capture motion two orders of magnitude smaller than the response frequency.

An IC-type temperature sensor (model number AD590, Analog Devices) was mounted on the board (U-TeCS, size 60...
mm x 90 mm) developed for this flight test. This sensor measured the surface temperature at the back cylinder near the front flare, transmitter, and battery. In addition, the temperatures at the 9-axis sensor and the U-TeCS board were measured. GPS (receiver: MIKROE-3922, MIKROE, antenna: TW1421, Tallysman) was used to obtain position information in 10 Hz. The camera (OpenMV Cam H7, OpenMV) was mounted on the rear cylinder to acquire images in the rear direction of capsule. If the sun is visible, it can be used for attitude identification. The transmitter and data transmission antenna were provided by JAXA Balloon Group. The battery (model number 3B75, Greatbatch) actually used in the past balloon experiments was selected. Two batteries were connected in series. The battery capacity and operation of the equipment are not a problem in the range of -20 to 60 degrees Celsius. Table 3 shows the measurement frequency of each value.

Figure 5 shows an overall view of the equipment. The maximum diameter was 0.150 m, the height was 0.116 m, and the mass was 1.0 kg. The aluminum plate directly below the GPS antenna and the battery box were bonded to the outer wall of Styrofoam.

![Figure 4](image)

**Fig. 4. A block diagram of the equipment.**

**Table 2. The specifications of the attitude sensor.**

<table>
<thead>
<tr>
<th>Accelerometers</th>
<th>Gyrosopes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard full range</td>
<td>± 10 g, ± 2000 deg/s</td>
</tr>
<tr>
<td>In-run bias stability</td>
<td>10 µg (x, y), 8 deg/h</td>
</tr>
<tr>
<td>Bandwidth (-3 dB)</td>
<td>500 Hz, 520 Hz</td>
</tr>
<tr>
<td>Noise density</td>
<td>60 µg/√Hz, 0.007 deg/s/√Hz</td>
</tr>
<tr>
<td>Non-orthogonality</td>
<td>0.05 deg, 0.05 deg</td>
</tr>
<tr>
<td>Non-linearity</td>
<td>0.1 %FS, 0.1 %FS</td>
</tr>
</tbody>
</table>

**Table 3. The measurement frequency.**

<table>
<thead>
<tr>
<th>Acceleration</th>
<th>Angular velocity</th>
<th>Magnetic field</th>
<th>Quaternion</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 Hz</td>
<td>10 Hz</td>
<td>100 Hz</td>
<td>10 Hz</td>
</tr>
<tr>
<td>HK data (Temperature, Pressure, Voltage, Current)</td>
<td>10 Hz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GPS data</td>
<td>10 Hz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Picture</td>
<td>0.1 Hz</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Figure 5](image)

**Fig. 5. Photo of the equipment.**

### 2.3. RERA's Sequence

The sequence of the experiment is described below.

1. Turning on the power of the equipment
2. Checking the system operation
3. Launch of the balloon
4. Ascent to an altitude of 25 km
5. Cutting the rope between the balloon and capsule
6. Free flight of the capsule
7. Landing (splashing down) on the sea

### 2.4. Trajectory analysis

Trajectory analysis was performed to evaluate the free flight conditions of the RERA capsule. In addition, the flight conditions during reentry (DS-SRC) were also evaluated to assess the similarity of the flight environment. The conditions of the present trajectory analysis are listed in Table 4. In the balloon experiment, there was a possibility that the capsule rotates vertically. Therefore, a wide range of ballistic coefficients were used for analysis. The ballistic coefficient is defined by Eq. (1) using the mass m, projected area S, and drag coefficient C_d. The drag coefficient is assumed to be constant and independent of velocity.

Based on the experimental conditions, the capsule mass was set to 1.0—2.0 kg, and C_d was basically set to 1.0, or 0.6 considering the capsule rotation. Therefore, the ballistic coefficient C_B was set to 6.7 for the highest case and 2.0 for the lowest case.

\[
C_B = \frac{m}{C_d S}
\]  

**Table 4. Trajectory analysis conditions.**

<table>
<thead>
<tr>
<th>Capsule</th>
<th>Reentry</th>
<th>Balloon experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Software</td>
<td>Tacode v1.12</td>
<td>(DS-SRC)</td>
</tr>
<tr>
<td>Atmosphere model</td>
<td>NRLMSISE-00 Atmosphere Model</td>
<td>(RERA)</td>
</tr>
<tr>
<td>Initial velocity, km/s</td>
<td>15</td>
<td>0</td>
</tr>
<tr>
<td>Initial altitude, km</td>
<td>200</td>
<td>25</td>
</tr>
<tr>
<td>Initial latitude, longitude, deg</td>
<td>0, 0</td>
<td>42.34, 144.08</td>
</tr>
<tr>
<td>Flight pass angle, deg</td>
<td>-11</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Diameter, m</td>
<td>Mass, kg</td>
</tr>
<tr>
<td>-----------</td>
<td>-------------</td>
<td>----------</td>
</tr>
<tr>
<td></td>
<td>0.8</td>
<td>10.0</td>
</tr>
<tr>
<td></td>
<td>0.8</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Figures 6 and 7 show the profile of altitude versus velocity, and Mach number versus Reynolds number, obtained by the trajectory analysis. In the range of ballistic coefficients in this analysis, the velocity at landing was 5 to 10 m/s. The Mach number was less than 0.3 in this balloon experiment. This means that the compressibility effect is low, and the flow field mainly depends on the Reynolds number.

The Reynolds number of the balloon experiment was on the same order of magnitude in that for DS-SRC case. This experiment could be performed in the same flight environment as the low-speed region at reentry. However, since the moment of inertia was different from that of the DS-SRC, the attitude and motion were not similar.

2.5. Development test

The flight model of RERA was developed through various tests before the launch, including a temperature test, a vacuum test, a strength test, an evaluation test of electromagnetic wave and a strength of adhesive test. Figure 8 shows the photo of the Environmental test. These tests were successfully completed.

Fig. 6. Profile of altitude versus airspeed.

Fig. 7. Profile of Mach number versus Reynolds number.

Fig. 8. Environmental test at room temperature.

3. Flight Results

3.1. Flight history

The RERA capsule was launched from the Taiki Aerospace Research Field in Hokkaido Japan on 1st July 2022 at 3:32 a.m. (JST). The capsule reached an altitude of 25 km 72 minutes after launch, separated from the balloon, and began its free flight. After 29 minutes of free flight, flight data could no longer be received, and it was judged that the capsule had landed at sea. The time history of altitude is shown in Fig. 9. The time of separation is set as time 0. It can be confirmed that an altitude at the time of separation was higher than 25 km. The flight environment at the time of separation is shown in Table 5. The angular velocities were not zero and, the roll direction had a high angular velocity. Acceleration and angular velocity are values in the object coordinate system shown in Fig. 3, and ground speed and airspeed are values in the latitude, longitude, and altitude directions. North is positive in the latitude direction, east is positive in the longitude direction, and upward is positive in the altitude direction. The ground speed was calculated by differentiating the GPS data over time. The airspeed was calculated using the speed of air at each altitude at 5:00 a.m. on the same day from the NCEP® meteorological data.

Fig. 9. Time history of altitude
The time history of temperature measured by the RERA capsule is shown in Fig. 10. The temperature at the flight altitude obtained from the meteorological data NCEP is also shown. The minimum outside temperature obtained from NCEP was about -60 degrees Celsius. However, because of the low density and the fact that the capsule was sufficiently sealed with Styrofoam, the temperature around the onboard equipment was at least 20 degrees Celsius. The maximum temperature in the flight test was less than 60 degrees Celsius, which is the maximum operating temperature of the equipment, confirming that the temperature around equipment was always within the normal operating temperature range.

![Fig. 10. Time history of temperature.](image)

### Table 5. Flight environment at the time of separation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceleration (x, y, z), m/s²</td>
<td>(-0.04, -0.06, -0.9)</td>
</tr>
<tr>
<td>Angular velocity (x, y, z), deg/s</td>
<td>(14.4, -1.7, 61.3)</td>
</tr>
<tr>
<td>Ground speed (lati, long, alt), m/s</td>
<td>(-0.76, -14.9, 5.0)</td>
</tr>
<tr>
<td>Airspeed (lati, long, alt), m/s</td>
<td>(3.0, -2.4, 5.0)</td>
</tr>
<tr>
<td>Altitude, km</td>
<td>25.6</td>
</tr>
<tr>
<td>Latitude and longitude, deg</td>
<td>(42.30, 144.07)</td>
</tr>
</tbody>
</table>

### 3.2. Flight environment

The profile of velocity versus altitude and profile of Mach number versus Reynolds number obtained by the balloon experiment, and trajectory analysis are shown in Figs. 11 and 12. Figure 11 shows that the results of the trajectory analysis and the experimental results are in good agreement, although discrepancies are observed at altitudes below 10 km. A drag coefficient of 1.0 for the free flight was used for the case of ballistic coefficient of 3.12 kg/m², while from a comparison of the speeds at landing, the speed of the RERA corresponded to a ballistic coefficient of about 4 kg/m². The wind tunnel test results suggested that the drag coefficient is independent of velocity at low speeds below 50 m/s. This also meant that at altitudes below 10 km, the effective drag coefficient of RERA capsule has decreased due to oscillations in the attitude.

![Fig. 11. Profile of altitude versus airspeed.](image)

Airspeed in the direction of altitude was the primary component of the capsule’s airspeed in the experiment. This is because the capsule has lightweight and is basically carried by the wind. The velocity at landing was less than 10 m/s. From the results, it was confirmed that the experimental and analytical results are in good agreement, and that the capsule was tested in a flow field similar to that of the reentry trajectory. Therefore, the following chapters will allow the evaluation of the motion at low velocities during reentry.

![Fig. 12. Profile of Mach number versus Reynolds number.](image)

### 3.3. Attitude

The time histories of acceleration and angular velocity of the RERA capsule are shown in Figs. 11 and 12, respectively. The time origin is the time of separation. The time history of acceleration indicated that the acceleration in the z-direction is almost constant during free flight. This suggests that the capsule is oscillating in attitude, however, is not undergoing the motion such as longitudinal rotation. The angular velocity history indicated that the roll motion is suppressed as soon as it begins free flight.

Based on the previous study, the frequency of motion in pitching direction can be estimated by Eq. (2):

\[
f = \frac{\omega}{2\pi} = \frac{1}{2\pi} \sqrt{-\frac{C_{mae} \rho_{\infty} w^2 SD}{2I}}
\]

where \(\rho_{\infty}\) is the density of uniform flow, \(u_{\infty}\) is the velocity of uniform flow, \(S\) is the projected cross-sectional area, \(D\) is the representative length, and \(I\) is the moment of inertia around
the vertical axis. A capsule diameter of 0.8 m was used as the representative length $D$. $C_{m0}$ is the static pitching moment slope with respect to the angle of attack, and -0.173 from the previous study was used.

The frequency of motion estimated from the results of trajectory analysis is compared with that in the actual flight. Because the dynamic pressure was constant, the frequency was estimated to be 1.6 Hz at a ballistic coefficient of 3.12 kg/m$^2$. During actual flight, the effective drag coefficient changes due to the oscillation of the capsule. Therefore, a Fast Fourier transform (FFT) was performed on the angular velocity at 300 to 1300 seconds after separation to determine the frequency of motion during the flight. The peak frequencies of pitch and yaw were 1.5 Hz and 1.5 Hz, respectively, with peaks in the range of 1.0 to 2.0 Hz. This is in good agreement with the frequency of the estimation shown in the above Eq. (2) and suggests that the method can estimate the frequency of motion even with three-dimensional motion, and that the frequency of motion was on the order of 1 Hz.

\[ C_{m0} \text{ is the static pitching moment slope with respect to the angle of attack, and -0.173 from the previous study was used.} \]

\[ \text{The frequency of motion estimated from the results of trajectory analysis is compared with that in the actual flight.} \]

\[ \text{Because the dynamic pressure was constant, the frequency was estimated to be 1.6 Hz at a ballistic coefficient of 3.12 kg/m}^2. \]

\[ \text{During actual flight, the effective drag coefficient changes due to the oscillation of the capsule. Therefore, a Fast Fourier transform (FFT) was performed on the angular velocity at 300 to 1300 seconds after separation to determine the frequency of motion during the flight.} \]

\[ \text{The peak frequencies of pitch and yaw were 1.5 Hz and 1.5 Hz, respectively, with peaks in the range of 1.0 to 2.0 Hz. This is in good agreement with the frequency of the estimation shown in the above Eq. (2) and suggests that the method can estimate the frequency of motion even with three-dimensional motion, and that the frequency of motion was on the order of 1 Hz.} \]

3.4. Camera

Figure 15 shows the camera images at an altitude at each time point with 0 s as the time of separation. In Fig. 15-(a), the rubber balloon is still seen in the sky just before separation. The direction of the sun is obtained from image (b) and used to identify the attitude. There is a 10-second period between images (c) and (d). However, there was almost no change between the images, indicating that the angular velocity in the roll direction was slow. This result is consistent with the data of angular velocity from a 9-axis sensor.

![Figure 13. Time history of acceleration.](image)

![Figure 14. Time history of angular velocity.](image)

4. Conclusions

To evaluate the dynamic stability of a thin aeroshell capsule, a free-flight experiment called RERA was conducted. In this experiment, the capsule was separated from the rubber balloon at an altitude of 25 km and landed on the sea after free flight. Data on the behavior of RERA capsule during the flight was obtained. This suggests that the capsule is oscillating in attitude, however, is not undergoing the motion such as longitudinal rotation. This suggests that the angular velocity in the pitch and yaw directions did not diverge at low speeds. In this experiment, the flight environment was similar to that of reentry, but the rotational motion was not the same as that of reentry due to differences in the moment of inertia. Although it is indicated from the results of the 1-DOF test using wind tunnel that the moment of inertia affects the rotational motion, it is not clear whether the same tendency is observed in a free flight with 3-DOF. It is necessary to evaluate the effect of moment of inertia on motion in a free-flight for clarifying the mechanism of instability and developing an actual capsule. In the future, we will conduct balloon experiments using capsules with different moments of inertia and evaluate the attitude during free flight.

Acknowledgments
The scientific balloon (DAIKIKYU) flight opportunity was provided by ISAS, Japan Aerospace Exploration Agency (JAXA) (Project ID: BS22-07). This work was supported by JSPS KAKENHI (Grant No.20H02360) and JST SPRING (Grant Number JPMJSP2119).

References


7