Study on Mini Re-Entry System Using Deployable Membrane Aeroshell

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An aeroshell made from membrane material have an advantage of reduction in the aerodynamic heating, because its small mass and large area enable us to make the low-ballistic-coefficient flight, in which the vehicle decelerates at very high altitude with low atmospheric density. In this paper, we propose a new concept of mini re-entry system for small satellites. This vehicle is called "FEATHER" (Flexible Expanded Aeroshell with Tiny payload Harness for Entry and Recovery). "FEATHER" is a novel re-entry and recovery system, featuring the autonomous aeroshell deployment, the low-ballistic-coefficient re-entry with less severe aerodynamic heating and so on. FEATHER is composed of the membrane aeroshell made from the high-temperature cloth called ZYLON®, an outer frame made of Shape Memory Alloy (SMA) and a payload. When the aeroshell receives the aerodynamic heating, the temperature of SMA frame rises and restores the circular shape as memorized beforehand. Then the membrane aeroshell is automatically deployed. Therefore the vehicle can achieve the low-ballistic-coefficient flight with a drastic reduction in the aerodynamic heating without any additional sensors, controllers and actuators. The preliminary studies made on FEATHER system so far including the hypersonic wind tunnel experiments are presented in this paper.

Keywords: Re-Entry, Membrane Aeroshell, Deployable Structure, Shape Memory Alloy, Small Satellite

Nomenclature

\begin{itemize}
  \item \(A\): frontal area of fully deployed aeroshell
  \item \(B_d\): ballistic coefficient (=\(m/(C_D\cdot A)\))
  \item \(C_D\): drag coefficient (=\(\text{Drag force}/(p\cdot A)\))
  \item \(E\): Young's modulus
  \item \(I_F\): geometric moment of inertia
  \item \(H_{wall}\): enthalpy at wall
  \item \(H_{total}\): total enthalpy
  \item \(m\): total mass of aeroshell
  \item \(p\): dynamic pressure
  \item \(q\): stagnation heating rate
  \item \(R\): radius of aeroshell
  \item \(R_s\): radius of curvature
  \item \(S_F\): cross-section area of frame
  \item \(T_{eq}\): radiation equilibrium temperature
  \item \(V_e\): velocity
  \item \(\varepsilon\): emissivity (=0.85)
  \item \(\varepsilon_{cr}\): critical strain
  \item \(\sigma\): Stefan-Boltzmann constant
  \item \(\rho_{\infty}\): atmospheric density
\end{itemize}

1. Introduction

In recent years, remarkable advance has been made in our space activities. Especially, the development of small satellite, such as CUBE-SAT\textsuperscript{1)}, has been accelerated. On the other hand, the development of recovery system for a small satellite has not been studied yet. An observational data can be retrieved by using communication method such as radio waves. But small material or biological samples must be recovered physically from the orbit to the ground. If the recovery of payload from a small satellite becomes possible, it is quite helpful for small satellite missions to become more multifaceted.

However existing space transportation system has been always facing a serious problem of the aerodynamic heating during re-entry flight. The aerodynamic heating is in inverse proportion to the size of a re-entry vehicle. For example, the stagnation-point heating depends on the radius of the blunt nose. Therefore when the size of the recovery vehicle becomes small, it is difficult to survive under the severe aerodynamics heating. So a new concept to solve the aerodynamic heating problem is strongly demanded. An atmospheric-entry system using a flexible aeroshell has been proposed by the authors’ research group\textsuperscript{1,2,5). The strategy of its thermal protection is not “Develop high performance material” but “Fly along the trajectory with less severe aerodynamic heating”. The aeroshell made from a flexible membrane is expected to achieve a drastic reduction in the aerodynamic heating, because its large area and small mass decrease the ballistic coefficient and enables the vehicle to decelerate at high altitude, where the atmospheric density is very low\textsuperscript{5,6). In the present paper, as one of variations on the concept, we propose a mini re-entry system using deployable membrane aeroshell for small satellite missions. The objective of the study is to demonstrate that this system is promising by conducting the hypersonic wind tunnel experiments as well as the re-entry trajectory analyses.

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2. Mini Re-entry System

2.1. Membrane aeroshell with frame made from Shape Memory Alloy

It is advantageous that the aeroshell made from membrane can be compactly stored in a canister in the launch and orbital flight phases before re-entry. Once the membrane aeroshell is deployed, its drag-producing area becomes very large. On the other hand, the mass per unit area is small. Therefore a very small ballistic coefficient can be obtained. Moreover the effective nose radius becomes large by deploying the membrane aeroshell, resulting in further reduction in the stagnation-point heating rate.

Shape Memory Alloy (SMA) is used as supporting frame. Before atmospheric entry, the frame is compactly stored in a canister, because SMA can be easy to be folded at normal temperature. After the atmospheric entry, the spacecraft receives the aerodynamic heating and the temperature of the SMA frame rises. When the temperature reaches the critical value (typically 310-340K), the SMA frame restores the circular shape as memorized in the oven before the flight. Then the SMA frame is automatically deployed. Thanks to the use of SMA, we do not need any complicated mechanism for the deployment of the aeroshell. In other words, SMA also plays roles of the structural member, actuator, controller and sensor. Thus the present aeroshell system is very simple, reliable and suitable especially for a small spacecraft, which does not have any mass budget to bring additional sensor/controller/actuator system to the orbit.

2.2 The concept of vehicle

The re-entry vehicle is composed of the outer frame, membrane and the payload as shown in Fig. 1. The shape of aeroshell is almost flat and similar to the shape of the contact lens. The outer frame is made of a SMA tube for the purpose of saving the frame mass. The membrane is made from the high-temperature cloth called ZYLON®. The maximum service temperature of ZYLON® is about 920K. Because of reduction in weight, the payload container cannot be a heavy rigid body. In our concept, the payload container will be also made from the multilayer of the same material as the aeroshell. It is like a bag wrapping up the payload for recovery. Considering that the peak heating occurs at the stagnation point, it is necessary to put additional thermal protection over the payload container. The diameter of the fully deployed outer frame is set as to 60cm. The total weight is 350g and the payload weight including the on-board devices is 200g. The membrane weight is 60g. In this system, the mass for the on-board instruments is tightly limited. For the on-board devices, only the GPS receiver, its antenna, the data transmitter and power supply are considered. This is the minimum set of instruments to transmit the data of the vehicle location to the ground station, where the recovery team is standing by. From its characters, we give this system a nickname as "FEATHER" (Flexible Expanded Aeroshell with Tiny payload Harness for Entry and Recovery).

The mission scenario is shown in Fig. 2. First, the aeroshell is compactly stored in a small satellite. The FEATHER vehicle is separated from its mother satellite by a small thruster without using de-orbit motor, because the weight margin for the de-orbiting motor cannot be expected in the case of a small satellite. Consequently, entry angle is almost zero degree. The low ballistic coefficient of the FEATHER vehicle enables one to make a re-entry flight at almost zero entry angle. The surface temperature of the vehicle rises by aerodynamic heating and the circular shape of the outer frame is automatically restored when the frame temperature increases beyond the critical temperature for the SMA material. Then the membrane aeroshell is deployed. After that, the aeroshell receives the aerodynamic drag force and the vehicle decelerates during the descent flight. Eventually the terminal velocity is estimated at about 4 m/s, which is small enough for soft touchdown onto the ground. Because the vehicle decelerates significantly at high altitudes and it will ramble in the sky at low speed before landing, there is a lot of time to transmit the position data taken from the GPS system to the ground station. The recovery team will have enough time to predict precisely the point of landing and to be prepared for recovery of the vehicle.
3. Trajectory Calculation

We numerically simulated the re-entry trajectory under the following conditions. The diameter of the outer frame is 60cm and the total weight is 350g, the radius of curvature at the stagnation point is assumed to be 3m. The drag coefficient is 1.8, based on estimation before the hypersonic experiments explained later. The stagnation heating rate is obtained by Tauber’s relation \(^7\) (Eq. (1)). The radiation equilibrium temperature is calculated by Eq. (2). Here the radiation from one surface was assumed because the one surface radiation became more severe thermally than both surfaces radiation.

\[
q [MW/m^2] = 1.35 \times 10^{-10} \frac{\rho_c}{R_N} V_{\infty}^{3.01} \times \left( 1 - \frac{H_{wall}}{H_{total}} \right) \quad (1)
\]

\[
T_{eq}[K] = \left( \frac{q}{\rho_c} \right)^{0.25} \quad (2)
\]

After the FEATHER vehicle is separated from its mother satellite, it deaccelerates due to the aerodynamic drag and its altitude decreases. In the present analysis, we calculate the re-entry trajectory below 150km altitude, because the primary objective of the trajectory analysis is to demonstrate that the vehicle with the proper size can survive under the aerodynamic heating environment. At altitude 150km, the radiation equilibrium temperature of FEATHER already reaches 470K due to the aerodynamic heating. The aeroshell is assumed to be fully deployed before the time at altitude 150 km, since the temperature is high enough to initiate the phase transition of SMA at altitudes higher than 150km. Therefore we assume that the aeroshell has been already deployed before the calculation starts. An angle of attack is assumed to be zero degree and the initial velocity is set as to 8km/s. The initial condition is summarized in Table 1.

The diameter of the fully deployed aeroshell is assumed to be 50cm. We determine the maximum total weight for the stagnation-point radiation equilibrium temperature not to exceed 920K. The mass allotted for the SMA frame is calculated from the vehicle total mass, payload mass including the on-board devices (200g) and the membrane mass (60g). On the other hand, when the flight trajectory is determined, the maximum aerodynamic force acting on the aeroshell is calculated. For the outer frame to be able to sustain the aerodynamic force as the compressive load, the cross-sectional area (Eq. (3)) and the geometric moment of inertia (Eq. (4)) are determined from the limit of compression failure and the buckling limit, respectively:

\[
S_F \geq \frac{\pi C_0}{E_{cr}} \frac{P}{R^2} \quad (3)
\]

\[
I_F \geq \frac{\pi^4 C_0}{4} \frac{P}{E} R^4 \quad (4)
\]

We obtain the external and internal diameter of the outer frame and calculate the weight for the SMA frame from \(S_F\) and \(I_F\). When the mass of the SMA frame determined by the analysis of the strength exceeds the maximum available SMA mass from the trajectory analysis, the vehicle total mass is modified. Finally the total mass and the SMA frame mass are determined in an iterative manner. The external and internal diameters of the outer frame are 6mm and 5mm, respectively. The ballistic coefficient \(B_A\) is about 0.7kg/m\(^2\). The specification of the vehicle finally determined is summarized in Table 2.

\[
\begin{array}{|c|c|}
\hline
\text{Initial altitude} & 150km \\
\hline
\text{Initial velocity} & 8km/s \\
\hline
\text{Entry angle} & 0 \degree \\
\hline
\end{array}
\]

\[
\begin{array}{|c|c|}
\hline
\text{Max diameter} & 60cm \\
\hline
\text{Total mass} & 350g \\
\text{(Payload mass)} & (200g) \\
\text{(Membrane mass)} & (60g) \\
\text{(SMA frame mass)} & (90g) \\
\hline
\text{Radius of curvature at the stagnation point} & 3m \\
\text{External diameter of the outer frame} & 6mm \\
\text{Internal diameter of the outer frame} & 5mm \\
\text{Drag coefficient} & 1.8 \\
\text{Ballistic coefficient} & 0.7kg/m^2 \\
\hline
\end{array}
\]

The calculation results are shown in Figs. 3, 4 and 5. Figure 3 is a velocity-altitude plot of the re-entry trajectory. Figure 4 is a time-history of the flight altitude and velocity. Figure 5 is a time-history of the stagnation-point heating rate and the radiation equilibrium temperature. From these results, it is obvious that the velocity of the FEATHER vehicle is significantly reduced at high altitudes and the aerodynamic heating becomes moderate. It is confirmed that the surface temperature is smaller than the maximum service temperature of ZYLON even at the stagnation point and that the vehicle can survive under the aerodynamic heating during the re-entry flight. The terminal velocity becomes about 4m/s. Thus the FEATHER vehicle can make a soft landing.
4. Wind Tunnel Experiment

For demonstration of deployment mechanism and structural stability, and measurement of the drag coefficient, we conducted the hypersonic wind tunnel experiment at the hypersonic and high-temperature wind tunnel in Kashiwa campus, the University of Tokyo. The diameter of the uniform flow core is about 120mm and the freestream Mach number is 7.0-7.1. The stagnation pressure $P_0$ and the stagnation temperature $T_0$ are 0.95MPa and about 670-720K, respectively. The flow condition of this wind tunnel is summarized in Table 3. The outer frame is made of the SMA rod with diameter 1.5mm. When it is fully deployed, the diameter of the aeroshell is 45mm and the frontal area of the model is 1590mm$^2$. The aeroshell is made from ZYLON® of the spun yarn fabric type. First, the model is folded compactly and is automatically deployed by aerodynamic heating as shown in Fig. 6. The experimental model is inserted into the flow 10 seconds after the tunnel start, and is in the hypersonic flow for about 15 seconds.

The result of the aerodynamic force measurement is shown in Fig. 7. The aeroshell is slowly deployed and its aerodynamic drag is increasing gradually. Finally the drag coefficient $C_D$ reaches the steady state at 1.78. This result is in good agreement with the theoretical estimation by the Newtonian method$^7$. A series of the Schlieren images around the model are shown in Fig. 8 ((1): during injection, (2): just after the model injection, (3): during deployment, (4): fully deployed). It is clearly seen that the shape of shock wave changes from bow-like one to more flat one. After fully deployed, the shape of the membrane aeroshell becomes slightly concave around the center body (payload section) as seen in the image (4) of Fig. 8. From these results, it is demonstrated that FEATHER can produce large drag force stably in the hypersonic flow.
The flat shape of the aeroshell may cause the significant flow acceleration near the outer edge and the local peak heating there because of the rapid reduction in the boundary layer thickness. On the other hand, the convex shape of the payload and the concave shape of the aeroshell around it are expected to generate the complicated shock wave interactions, resulting in the severe local peak heating. When such local peak heating occurs, the damage on the membrane aeroshell becomes very critical. To confirm experimentally that the vehicle is free from the damage due to such local peak heating, the additional hypersonic wind tunnel experiments that can realize the heating comparable to an actual flight are conducted at the 1.27m hypersonic wind tunnel in JAXA ARD. The detail of the experiment is reported in Ref. 9. The freestream Mach number is 9.45. The stagnation pressure $P_0$ is 1.0MPa and the stagnation temperature $T_0$ is about 920-950K. The distribution of the aerodynamic heating rate over the body, the temporal variation of the surface temperature over the model surface is measured by the IR thermal video$^{10}$.

After the wind tunnel test, we found no local damage on the membrane aeroshell. This fact indicates that such local peak heatings are not critical even though they many exist. As already pointed out in Fig. 8, the shape of the membrane becomes concave due to the aerodynamic force, and a dent may appear just inside the outer frame (Fig. 9 (a)). The pressure of such dent enhances the local peak heating there. In the present case, however, smooth connection between the outer frame and the membrane aeroshell (Fig. 9 (b)) is realized in the presence of the aerodynamic force as seen the silhouette of the experimental model in the hypersonic flow (Fig. 8 (4)). The quantitative evaluation of the heating rate distribution including the outer frame will be made by using the thermal video results as well as the CFD analysis in the future.

![Time-history of drag force coefficient](image1)

![Schlieren images](image2)

5. Conclusion

We propose a mini re-entry system FEATHER with the deployable membrane aeroshell for payload recovery from a small satellite on the earth’s orbit. The aeroshell is composed of the flexible membrane material and the deployable outer frame made of SMA. The ballistic coefficient is reduced by using the membrane aeroshell and the results of the trajectory calculation show that the aerodynamic heating is reduced enough for the vehicle to survive. The hypersonic wind tunnel experiments demonstrate that the aeroshell is automatically deployed, receiving the aerodynamic heating. The deployed aeroshell is kept stable in the hypersonic flow and producing a large drag force, which is necessary for the low-ballistic-coefficient re-entry flight. Consequently, the present system is suitable especially for re-entry mission with a small satellite because it is simple, light and reliable without requiring any complicated mechanism.

References


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