Feasibility Assessment of Low-Ballistic-Coefficient Aerocapture for Jupiter Exploration

By

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Abstract

The aerocapture is known to be an orbit insertion technique around planetary body at a fraction of the propellant of the traditional chemical propulsive technique. Severe aerocapture conditions such as the very narrow entry corridor and the aerodynamic heating environment have prevented us from putting it into practical use in a planetary exploration mission. However, the low-ballistic-coefficient aerocapture where an orbiter is connected to the light and wide membrane decelerator has the potential to reduce the risk of the aerocapture. In the Solar Sail mission which is planed as one of the future missions of JAXA, the orbit insertion around Jupiter of the small orbiter which is separated from the mother spacecraft is included. In this paper, we investigated the feasibility of the aerocapture at Jupiter assuming that a fraction of the Solar Sail membrane of the mother spacecraft was reused in order to insert the separated orbiter into the orbit around Jupiter.

Key words: Aerocapture, Low-Ballistic-Coefficient, Reusing Solar-Sail

1 Introduction

The exploration of the outer space by means of the Solar Sail is considered as one of future missions of JAXA. In the mission, an orbit insertion of a small spacecraft around Jupiter, which is separated from a mother spacecraft, is planed [1]. The orbit insertion sequence for the orbiter is shown in Fig. 1. That is, while the mother spacecraft with the Solar Sail flybys at Jupiter, the small orbiter separated from the mother spacecraft is inserted into an orbit around Jupiter. In the nominal mission profile, the delta-V required for slowing down the spacecraft form the interplanetary orbit, as shown in Fig. 2 where the relation between propellant weight ratio and an apoapsis altitude of a target orbit is shown. As shown, the propellant weight ratio increases with reducing the apoapsis altitude, because a large delta-V is required for a low apoapsis altitude in a target orbit. In the nominal mission profile, the large elliptical orbit, where the apoapsis altitude is rather high (apoapsis altitude: 300Rj, periapsis altitude: 1.5Rj), is considered as the target orbit around Jupiter. This is because it is required to avoid decreasing the payload of the orbiter. However, the insertion into a circular orbit with a low apoapsis altitude is desirable for...
the mission purpose, because a short orbital period around Jupiter produces many opportunities for an exploration. The technology which has a potential to solve both the problems is the aerocapture technique since it may realize a necessary delta-V by using the aerodynamic braking during the shallow atmospheric flight. To realize the effective aerocapture, it is necessary to augment its aerodynamic performance by increasing the aerodynamic area. In the present mission which employs a Solar Sail, one possibility to increase its aerodynamic area is to utilize the Solar Sail of the mother spacecraft for this purpose. To clarify this possibility, we made the feasibility assessment. The objective of the present assessment is to clarify the possibility for inserting the orbiter into an orbit with a low apoapsis altitude with reduced propellant consumption.

2 Aerocapture at Jupiter reusing Solar Sail

2.1 Aerocapture Concept

The aerocapture technique is an orbit insertion technique that uses aerodynamic drag to attain a necessary delta-V while a spacecraft make high-speed flight through the atmosphere of the target planet directly from an interplanetary orbit. Hence the aerocapture technique has a potential to reduce the propellant consumption for an orbit insertion. However, the aerocapture maneuver requires very high level technologies and has not been realized yet.

There are two types of aerocapture methods. One traditional type of aerocapture methods is to slow down a spacecraft at a rather low altitude where the spacecraft is expected to be exposed to the aerodynamic heating during the flight. Hence the spacecraft must be equipped with the heat resistant aeroshell. Furthermore, the aerocapture of this type requires very high level orbital maneuvering system because the difficulty in controlling delta-V in the low altitude leads to very narrow allowable range of a flight-pass-angle. However, another type of aerocapture method is also possible. In the aerocapture of this type, we consider a low ballistic coefficient spacecraft which may be realized by using a light and large membrane deployed around the spacecraft. This becomes possible since a high heat-resistant membrane has been available. This type of spacecraft has a potential to attain a necessary deceleration during flight in a high altitude avoiding aerodynamic heating. Feasibility assessment of the aerocapture in Earth, Venus, Saturn, etc shows its feasibility clarifying many merits such as large allowable range of flight-pass-angle and light thermal protection system ([2], [3], [4]).

Because entry velocity to the atmosphere at Jupiter from an interplanetary orbit is about 59.5 km/sec, the flight condition for the aerocapture is more severe than for other planets. However, Aerocapture of a ultra low ballistic
coefficient spacecraft with the Solar Sail membrane may have feasibility.

The Orbit insertion sequence in the Jupiter aerocapture reusing the Solar Sail is shown in Fig.3. When the small spacecraft is separated from the mother spacecraft, a fraction of the Solar Sail membrane, which are used as a propulsive system in the interplanetary flight, is separated, too. The membrane connected to the small spacecraft is reused as the decelerator for the aerocapture. The full potential of the membrane could be appreciated by using it as both propulsive system (Solar Sail) and decelerative system (Aerocapture). In this assumption of the aerocapture mission at Jupiter, feasibility assessment was made.

2.2 Flowchart of the feasibility assessment

In this paper, the procedure of the feasibility assessment is divided into two parts. First, Aerocapture trajectory analysis was conducted to determine the optimum membrane size for the aerocapture at Jupiter. Next, we considered an adequate method for supporting the optimum size of the membrane during the aerocapture flight. For this purpose, an analysis in which a fluid dynamics and a structure dynamics are coupled is made to investigate the shape of the membrane in the atmosphere flight condition.

3 Sizing membrane by Trajectory Analysis

3.1 Methodology of Sizing

A flowchart of the present sizing procedure is shown in Fig.4. At beginning of sizing, we assumed the total spacecraft mass before an orbit insertion as 140kg, and the entry velocity as 59.5km/sec at an altitude 1029km, which is calculated from \( V_{\text{inf}} \approx 6.4396 \text{km/s} \) [1].

Trajectory analyses are made to determine the optimal size of the membrane by checking the following point.

- Mass merit,
- Membrane temperature limit,
- Apoapsis altitude in target orbit.

The schematic of an aerocapture orbit is shown in Fig.5. The spacecraft is slowed down by aerodynamic drag during an atmosphere flight and is inserted into an orbit around Jupiter. Since, the periapsis in this orbit remains in a low altitude where an atmospheric influence is large, a certain acceleration of the spacecraft at the apoapsis is required for raising the periapsis altitude. Hence, a small propulsive system is necessary even for the present aerocapture. In this trajectory analysis, we estimated delta-V and a propellant mass for the periapsis raise (Target \( h_p=1.5R_j \)). Because an aerocapture orbit depends on ballistic coefficient \( C_B \) which depends on the multiplication of an area \( S \) and the drag coefficient \( C_D \) of the spacecraft, an estimation of \( C_D S \) during an atmosphere flight is necessary. However, we assume, as a first step, that both \( C_D \) and \( S \) are constant and is 2.0 and an area of initial membrane, respectively even in various flow
conditions. The atmospheric model used for the trajectory analysis is based on the observational data from the Galileo probe at Jupiter[5]. The apoapsis altitude in the target orbit, which is obtained from the calculation depends on an initial membrane area \( S \) (Maximum area: 1963m², Circular membrane of 50m diameter) and an entry flight path angle \( \beta \).

3.2 Mass Merit Estimation
A total mass required for an orbit insertion using the aerocapture (Fig.4 left) was compared with that required for the case of the only-propulsive system (Fig.4 right), in order to estimate the mass merit expected for the aerocapture. The relation between the apoapsis altitude in a target orbit and total mass (TPS mass was omitted) for an orbit insertion is shown in Fig.6. Each lines show only propulsive system and the aerocapture using three membrane sizes (100%, 50%, 0% of the maximum membrane). When a required mass for the aerocapture is smaller than that for the case of only-propulsive system, a mass merit of the aerocapture is expected. And, the difference of the required mass between the aerocapture and the only-propulsive system corresponds to the propellant mass saved by the aerocapture.

3.3 Membrane Temperature Limit
An allowable altitude during the aerocapture flight is limited by the temperature limit for the membrane structure. The temperature limit of the Solar Sail membrane, Polymide Film is about 400 degC, which corresponds to the heating rate of 18.6kW/m² in case of radioactive equilibrium on both sides of the membrane. In the altitude where heating rate is less than the maximum heating rate 18.6kW/m², a large membrane is required for attaining a large delta-V.

Figure 7 shows a relation between a membrane size and a maximum heating rate during an aerocapture flight in various apoapsis orbits. Aerodynamic heating is estimated by using the convective heating rate value determined by the formula \( 0.5 \rho V^3 \). A larger delta-V and a larger membrane size is required for an insertion into a target orbit with a lower apoapsis altitude. Figure 7 shows that a minimum membrane size, in which a membrane temperature limit is satisfied, exists in an orbit insertion with each apoapsis.

3.4 Optimal Membrane Size (the Lowest Apoapsis Altitude)
Taking into account of previous results presented in the section 3.2, 3.3, we estimated the mass merit and the membrane temperature limit. Fig.8 shows a relation between a membrane decelerator size and a saved propellant mass which is obtained Fig.6 result. The red line in Fig.8 corresponds to the red line in Fig.7 and shows the minimum membrane size. Hence, only aerocapture in which the membrane temperature limit is satisfied is acceptable in the range of various membrane size and various target orbit. The acceptable aerocapture appears in right hand side region of the red line. In addition, the aerocapture condition which satisfies both the mass merit and the membrane temperature limit exist in the triangle.
Fig.8 Relation between membrane size and saved propellant mass by Aerocapture

Table.1 Aerocapture condition (at the lowest apoapsis altitude)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Membrane size</td>
<td>0.57</td>
</tr>
<tr>
<td>Membrane area $S$, m$^2$</td>
<td>1119</td>
</tr>
<tr>
<td>Ballistic coefficient $C_b$, kg/m$^2$</td>
<td>0.063</td>
</tr>
<tr>
<td>Apoapsis altitude $h_a$, RJ</td>
<td>54</td>
</tr>
<tr>
<td>Entry Flight-path angle $\phi$, deg</td>
<td>-3.742</td>
</tr>
<tr>
<td>Saved propellant mass, kg</td>
<td>0</td>
</tr>
</tbody>
</table>

Fig9. Aerocapture trajectory reusing the optimum membrane size (Table.1)

A method to support the membrane during the flight

4.1 Flowchart for a method to support the membrane

In the Aerocapture trajectory analysis to determine the optimal membrane in the previous chapter, we assumed that $C_D$ and $S$ was constant ($C_D=2.0$, $S$ : the initial membrane area) even in various flow conditions. However, this is not always the case since the membrane is deformed by the aerodynamic force acting on it. Then, for a more accurate analysis, we must predict drag area $C_D S$ of the spacecraft. On the other hand, if the membrane which isn't supported adequately is deformed too excessively, its $C_D S$ departs from the original one too excessively. This causes the delta-V required for the orbit insertion can not be attained. In other hand, the inadequate delta-V may leads to an unsuccessful aerocapture. Hence, we must consider an adequate method for supporting the membrane and predict the shape of the membrane supported by the method during the atmospheric flight as the feasibility assessment of the aerocapture.

A flowchart of considering the method for supporting the membrane is shown in Fig.10. As a configuration of Solar Sail membrane, we assume the configuration like petals, deployment tests of which have been conducted [6]. First,
the method for supporting the simple triangle membrane is considered. The optimum membrane size (see Table.1) corresponds to four pieces of the equilateral triangle membranes of 25m side length. In this paper, the method for supporting the membrane with cables (like parachute) was selected from various methods such as spinning, inflatable flame etc. This is because this method is lightweight method and existing system which is supported with cable like parachute can be applied to this method. Although Other method may have potential to support membrane adequately, they are not considered because spinning need to be controlled to protect high spin rate from damping aerodynamic force during the atmosphere flight [4], and the technology of inflatable flame still has unknown parts. The schematic of the method for supporting the membrane with cables (parachute type) is shown in Fig.11. When the small spacecraft is separated from the main spacecraft, the membranes required for the aerocapture (four pieces of the equilateral triangle membranes of 25m side length) are also separated and the small spacecraft pulls the membrane with cables like a parachute.

Fig.11 Schematic of the method for supporting the membrane with cables (parachute type)

4.2 Coupled analysis
To predict the shape of the membrane supported with cables in the atmosphere, a coupled analysis for aerodynamic and structural analysis was made. The flowchart of this analysis is shown in Fig.12. The dynamics of both membrane forced by the flow field and the cable which support the membrane are simulated by particle-based model. A schematic of the initial shape of the membrane for simulation is shown in Fig.13.

Fig.12 Flowchart of flow-structure coupled analysis

Fig.13 Schematic of initial shape of the membrane for simulation

First, the coupled analysis was made to predict the shape of a piece of the equilateral triangle membrane of 25m side length. The triangle spring model [7] was used to simulate the deformed triangle membrane. The calculation
was started from the initial shape which shows the equilateral triangle membrane was connected to the main body with axisymmetrical three cables (see Fig.13 above). This shape was described using 100 small triangles by particle-based model (see Fig.13 below). The characteristic of the membrane and the cable correspond to polyimide film [8], ZYLON code [9] in the calculation.

To calculate aerodynamic force in a aerocapture flight, the low-density flow around the membrane was calculated by a Direct Simulation Monte Carlo (DSMC) method [10], which is a particle simulation using random number. Although DSMC requires high computational cost and isn’t suitable for a parametric study, DSMC is necessary for calculating the low-density flow around the membrane which is deformed like concave. We performed three-dimensional calculation using hard sphere model for collision cross section. The 100% diffusive reflection was used in the surface of the membrane and the wall temperature was fixed at 400 degC. As 1000 steps calculation of membrane dynamics runs, flow field around the membrane is calculated by DSMC.

First, this coupled analysis was made at the lowest point (altitude 700km) along the aerocapture trajectory in Fig.9. The flow condition of that point is shown in Case A of Table.2. The coupled analysis was made until the membrane and cables become steady. As a result, the steady shape of the membrane and cables, the flow field around the membrane in the calculation point was obtained.

![Fig.14 Initial and steady shape of the membrane and cables (case A, altitude 700km)](image1)

![Fig.15 Initial and steady shape of the membrane and cables (case B, altitude 380km)](image2)

<table>
<thead>
<tr>
<th>Case</th>
<th>Altitude, km</th>
<th>Velocity, km/sec</th>
<th>Density, kg/m³</th>
<th>Kn</th>
<th>Dynamic Pressure, Pa</th>
</tr>
</thead>
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<tr>
<td>A</td>
<td>700</td>
<td>59.178</td>
<td>$1.92 \times 10^{-10}$</td>
<td>2.19</td>
<td>0.34</td>
</tr>
<tr>
<td>B</td>
<td>380</td>
<td>5.936</td>
<td>$1.93 \times 10^{-8}$</td>
<td>0.0218</td>
<td>0.34</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Case</th>
<th>Altitude, km</th>
<th>Velocity, km/sec</th>
<th>Density, kg/m³</th>
<th>$C_D$</th>
<th>$S, %$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>700</td>
<td>59.178</td>
<td>$1.92 \times 10^{-10}$</td>
<td>2.05</td>
<td>1.0</td>
</tr>
<tr>
<td>B</td>
<td>380</td>
<td>5.936</td>
<td>$1.93 \times 10^{-8}$</td>
<td>1.99</td>
<td>19.5</td>
</tr>
</tbody>
</table>
4.3 Result of the analysis

The result of the calculation at the lowest point (altitude 700km, case A of Table.2) along the aerocapture trajectory is shown in Fig.14. The schematics on left hand side of Fig.14 show the initial shape and the schematics on right hand side of Fig.14 show the steady shape. The schematics on upside of Fig.14 are shown from the side view and the schematics on downside of Fig.14 are shown from the leeward view. Fig.14 shows that the steady position of the membrane exists on rather leeward side of the initial position and an angle between each cable becomes very small. Because the frontal projection area $S$ of the steady membrane decreases to only 1.0% of the initial membrane, it is difficult to attain adequate CDS for the insertion into the target orbit.

An effect of an aerocapture flight condition (the atmospheric density, the velocity of the spacecraft) is thought as a reason that the membrane, which is supported with cables, become small concave. To examine an effect of an aerocapture flight condition, two cases which differ in the atmospheric density and the velocity of the spacecraft was compared. One case is case A of Table.2 (low density, high velocity), which corresponds to the lowest point (altitude 700km) along Aerocapture trajectory. Another case is case B of Table.2 (high density, low velocity). Dynamic pressure is equal in both cases.

The result of the calculation in case B is shown in Fig.15. Fig.15 shows that the steady membrane is kept larger concave and an angle between each cable is kept larger than in case A. The frontal projection area $S$ of the steady membrane is kept to be 19.5% of initial membrane. The results of case A and case B are shown in Table.3. These results show that the steady shape, $C_D$ and $S$ of the membrane, which is supported with cables, differs in the atmospheric density, the velocity of the spacecraft much, in the case of the equal dynamic pressure.

The mechanism of this result is shown in Fig.16. It is thought that the aerodynamic force to a concave membrane consists of the axial force and the side force and the concave configuration depends on a balance between the axial force and the side force. Then, this force balance may depend significantly on a balance between the atmospheric density and the velocity of the spacecraft. For example, in case A (low density, high velocity), the side force becomes much smaller than the axial force and an angle between each cable becomes very small. However, in case B (high density, low velocity), the side force becomes larger than in case A and an angle between each cables is kept large. This growth of the side force in case B is confirmed from the growth of density in the concave membrane in case B (see Fig.17). However, the flow condition in case B corresponds to an unsuccessful aerocapture flight condition, in which the spacecraft falls into the atmosphere because of the low velocity. If the aerocapture is done at lower altitude than at the altitude in case A to obtain the proper balance between the density and the velocity, the membrane cannot survive the aerodynamic heating. Hence, unfortunately, feasibility of the aerocapture at Jupiter in which the membrane is supported only with cables may be low, because of the unbalance between the atmospheric density and the velocity of the spacecraft.

These results in this paper may indicate that a successful aerocapture in which the membrane is supported only with cables (parachute type) is limited by velocity of the spacecraft.
5 Summary

For the aerocapture mission at Jupiter reusing the Solar Sail membrane as the membrane deaccelerator, we made two the feasibility assessment.

First, we conducted the sizing of the membrane deaccelerator. The results of the sizing are summarized as follows;

- Aerocapture has potential to insert the spacecraft (total mass: 140kg) into the target orbit with lower apoapsis altitude than the traditional only-propulsive system, although the mass merit is very small. If 57% of the Solar Sail membrane (diameter 50m) is reused, target orbit (apoapsis altitude: 54Rj, periapsis altitude: 1.5Rj) may be determined in the range of the membrane temperature limitation.

Secondly we investigated a method for supporting the membrane. The results are summarized as follows;

- The shape of the membrane deaccelerator, which is supported only with cables (parachute type) in the atmosphere during the aerocapture flight, depend significantly on a balance between the atmospheric density and the velocity of the spacecraft.

- The effect of supporting the membrane only with cables (parachute type) is limited by the velocity of the spacecraft during the aerocapture flight.

Reference