Study of Waverider-based Point-to-Point Suborbital Rocketplane

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As a high-speed manned transportation system in the future, point-to-point (P2P) suborbital rocketplane is currently studied in Japan Aerospace Exploration Agency (JAXA) space transportation mission directorate. The vehicle was designed on the basis of the concept of waverider allowing high L/D in hypersonic regime, which is required for longer flight range and smaller load factor. Compared with an ideal waverider, the designed P2P suborbital rocketplane has outer wings for the improvement of the low-speed aerodynamic performance, finite thickness in the leading edge for the reduction of the aerodynamic heating, and twin vertical tails for directional stability. The aerodynamic performance of the P2P vehicle was investigated through numerical simulation of both subsonic and hypersonic flows, and the baseline aerodynamic shape of the P2P vehicle was discussed. The L/D in the trim condition at hypersonic speed was 2.6.

Key Words: Waverider, Suborbital, Aerodynamic Design, Computational Fluid Dynamics

Nomenclature

\( C_D \) : drag coefficient
\( C_L \) : lift coefficient
\( C_m \) : pitching moment coefficient
\( C_p \) : pressure coefficient
\( L/D \) : lift-to-drag ratio
\( M \) : Mach number
\( Re \) : Reynolds number
\( \alpha \) : Angle of attack (AOA), deg

1. Introduction

Interest in the suborbital flights is increasing today. The demand for the suborbital flights is considered to be increased in the future, and at the same time the ticket price will be decreased, which will accelerate the development of the suborbital flight business\(^1\). For example, in the case of SpaceShipTwo, already 300 people have made the reservation for the suborbital flight even at the price of $200,000, and there are more than 50,000 possible passengers waiting for the suborbital flight in the next 10 years.

In the current suborbital flight technology, the vehicle flies in a very narrow area, and only a few minutes of zero-gravity experience is available during the flight. The next step of the current suborbital technology is to widen the flight domain and generate new opportunities. One of the ideas is a long-range, point-to-point (P2P) fast transportation system. According to the report by International Space University\(^2\), 20-50 passengers per day among New York, London, and Tokyo at the price of $50,000 are expected as the possible demands for the fast manned transportation.

Recently, JAXA space transportation mission directorate started to study a P2P suborbital rocketplane for the next-generation high-speed transportation. The P2P suborbital rocketplane is accelerated to hypersonic speed by the rocket engine, and goes into space. Then, it returns to the earth without going into orbit, and reaches a final destination. It will make cargo or manned transportation much faster, and widen the market such as short-term international travel, suborbital tourism, super-high-speed cargo transportation, and so on.

Frequent and reusable operation of the suborbital transportation system can drastically reduce the transportation cost. Therefore, research and development of the suborbital vehicle can be a significant step toward a space plane in the future. For example, an extension of the P2P suborbital rocketplane can be the first stage in TSTO (two-stage-to-orbit) configuration.

The objective of this paper is to discuss the concept and design of the P2P suborbital rocketplane, and to show the baseline shape. The aerodynamic design and the aerodynamic performance were mainly described in this paper, but the vehicle shape was discussed in view of aerodynamic heating, volume, and surface area, too.

2. Vehicle Configuration

The mission considered in this paper is transportation of people within one hour from one city to the other more than 10,000 km away, such as from Tokyo to New York. Take-off gross weight was set as 300 ton in this study. The weight is in the order of that of the current jumbo jet aircraft such as Boeing 747.

As the propulsion system, an ethanol/liquid oxygen rocket engine was selected. Its specific impulse is smaller than that of liquid hydrogen/liquid oxygen rocket engine. However, considering the repetitive reuse of the vehicle, price and operability of the fuel are more important. Ethanol is cheaper than liquid hydrogen. Ethanol is liquid at room temperature, and has good operability. Moreover, bio-ethanol is considered to be in widespread use hereafter, and the use of bio-ethanol...
enables an environmentally-friendly operation. The mixture ratio was set as 1.8 in this study, and the specific impulse of the ethanol/liquid oxygen engine was set as 346 s.

Assuming the necessary ideal velocity increment is 8 km/s, dry mass was calculated as 28.4 ton. The necessary volumes of ethanol and liquid oxygen were calculated from the dry weight, the mixture ratio and the density (ethanol: 789 kg/m³, liquid oxygen: 1142 kg/m³). The tank volumes were calculated taking into account 5% of the ullage for both.

The propellant sizing of the P2P suborbital rocketplane is tabulated in Table 1. The dimension of the vehicle was later determined so that the propellant tanks, the landing gears, and the cabin could be included inside the vehicle.

<table>
<thead>
<tr>
<th>Table 1. Propellant sizing of P2P suborbital rocketplane.</th>
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<tbody>
<tr>
<td>take-off gross weight</td>
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<tr>
<td>dry weight</td>
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<tr>
<td>necessary ideal velocity increment</td>
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<tr>
<td>specific impulse</td>
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<tr>
<td>mixture ratio</td>
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<tr>
<td>liquid oxygen tank volume</td>
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<td>ethanol tank volume</td>
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3. Aerodynamic study

3.1. Waverider concept

High L/D is necessary to obtain longer flight range using a limited amount of propellants and smaller load factor for the future manned transportation. Waverider is one of the promising concepts of such transportation systems, which was adopted in the present study. Several hypersonic or reentry vehicle concepts using the idea of waverider were proposed and studied by other researchers, too.

The upper surface of the waverider is designed parallel to the freestream. The lower surface is designed along the inviscid streamlines for the shock wave surface given by a designer. As a result, the shock wave surface is completely attached to the leading edge, and no flows spill from the lower to the upper surface. Thus, high-pressure region of the lower surface generates compression lift, which leads to high L/D. However, waverider has several practical issues, such as aerodynamic heating, off-design characteristics, longitudinal and directional stability, low-speed aerodynamic characteristics.

3.2. Aerodynamic design of P2P suborbital vehicle

In this study, an ideal waverider was first designed, and the aerodynamic shape of the P2P suborbital rocketplane was designed by adding several changes to overcome the above practical issues of the ideal waverider. Generally, waveriders have cruise Mach number, and P2P vehicles not. However, aerodynamic performance in hypersonic regime is insensitive to the change in Mach number because of Mach number independence principle. Therefore, the concept of waverider can be applied to the design of the P2P suborbital rocketplane. Rocket engine is installed on the base plane of the vehicle, but the shape without the engine is discussed in this aerodynamic study.

The ideal waverider used in this work was cone-derived.

The semi-vertex angle of the basic cone was 13 degrees, and the design Mach number was 7. In order to obtain large volume inside, the cone angle was large, and the resulting waverider was thick. The height of the basic cone was set as 30 m. The lower surface of the waverider was determined by the inviscid streamlines obtained by numerically solving Taylor-Maccoll equation. This ideal waverider is denoted as type 1.

Several changes were conducted to type 1, and type 2, 3, 4, and 5 were designed. A brief explanation on the design of these 5 types is given in Table 2, and the overview of them is shown in Fig. 1. Type 5 is the baseline aerodynamic shape of the P2P suborbital rocketplane. Type 2, 3, and 4 are the interim shapes on the way from type 1 to type 5.

Type 2 was designed by attaching outer wings to type 1 for the improvement of the low-speed aerodynamic performance. The previous numerical study showed that the outer wings significantly increased L/D in subsonic regime, and hardly affected L/D in hypersonic regime. The overview near the outer wing is shown in Fig. 2. The expansion surface was set downstream in the upper surface of the outer wings, expecting the increase in the lift and pitching-down moment, and the decrease in the base drag. The expansion surface was also set downstream in the lower surface to reduce the base drag.

Type 3 and 4 were designed by adding leading edge bluntness to type 2 for the reduction of aerodynamic heating. The leading edge radius of type 3 and type 4 is 0.5 % and 1 % of the total length, respectively.

Type 5 was designed by attaching twin vertical tails to type 3 for the directional stability. The trihedral figures of type 1 and 5 are shown in Fig. 3. The body axis necessary to define the angle of attack is parallel to the upper surface line on the symmetrical plane.

<table>
<thead>
<tr>
<th>Table 2. Waverider-based aerodynamic shapes.</th>
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<tbody>
<tr>
<td>type 1</td>
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<tr>
<td>type 2</td>
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<tr>
<td>type 3</td>
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<tr>
<td>type 4</td>
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<tr>
<td>type 5</td>
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Fig. 1. Overview of 5 types of aerodynamic shapes.
3.3. Numerical simulation method

Numerical simulation based on computational fluid dynamics (CFD) was conducted for both subsonic and hypersonic flows. For subsonic CFD, $M = 0.3$, and $\alpha = 0, 5,$ and $10$. For hypersonic CFD, $M = 7$, and $\alpha = 0, 2.5, 5,$ and $10$. For both, $Re$ was set as $10^6$. This is because $Re$ effect was not so important in the present conceptual design phase, and because large $Re$ requires too fine grids and too long computational time.

For the grid generation, a commercial software HexaGrid\textsuperscript{9,10} was used in this work. It was jointly developed by JAXA and Research Center of Computational Mechanics, Inc. (RCCM). It is an automatic and fast grid generator. It generates hexahedra grid around solid surface discretized in triangles, in STL format. In HexaGrid, the Cartesian grid from the external boundary and the prismatic grid layers near the body surface are smoothly connected. A detailed explanation on the grid generation method is described in Refs. 9 and 10.

As an unstructured flow solver, JTAS (JAXA Tohoku university Aerodynamic Simulation) code\textsuperscript{11} was used in this study. It is a well-validated code and used in drag prediction of aircraft\textsuperscript{11,12}. In hypersonic regime, the flows around the cone and the caret waverider were calculated for the code validation. The calculated $C_l$ and $C_D$ were less than $3\%$ different from the theoretical ones. In JTAS code, full Navier-Stokes equations were solved on the unstructured grid by a cell-vertex finite volume method. HLLEW (Harten-Lax-van Leer-Einfeldt-Wada) method\textsuperscript{13} was used for the numerical flux computations. LU-SGS (Lower/Upper Symmetric Gauss-Seidel) implicit method\textsuperscript{14} was used for time integration. The second-order spatial accuracy was realized by a linear reconstruction of the primitive variables with Venkatakrishnan’s limiter\textsuperscript{15}. Spalart-Allmaras model\textsuperscript{16} was used as a turbulent model, and the turbulent transition was not taken into account. The equations for the turbulence model were also solved using the second-order scheme.

An example of the computational grid generated by HexaGrid is shown in Fig. 4. This is the computational grid for hypersonic CFD of type 5. The number of cells is 4.98 million. The grid generation time was less than 30 minutes using JAXA Supercomputer System (JSS). As seen in Fig. 4, the connection between the main body and the vertical tail is not properly captured. However, in the conceptual design phase, fast and moderately accurate computation is important. Therefore, the grid improvement was not investigated in this study.

In the calculation of the aerodynamic coefficients, reference area is the projected area of the body and the outer wings seen from the top. Therefore, for example, reference area of type 1 is different from that of type 5 (see Fig. 2). The reference length is the centerline chord.

The center of gravity was set as $65\%$ horizontally from the nose and $65\%$ vertically from the upper line on the symmetrical plane. $C_m$ is positive in the pitching-up direction.

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**Fig. 2.** Expansion surfaces downward in the outer wing.

**Fig. 3.** Trihedral figures of type 1 and type 5.

**Fig. 4.** Computational grid for hypersonic CFD of type 5.
3.4. CFD results

Designing type 5 from type 1, the outer wings, leading edge bluntness, and twin vertical tails were added. Each effect was discussed below.

The effect of the outer wings was observed by comparing type 1 and 2. Figure 5 shows the comparison of the aerodynamic coefficients at $M = 0.3$, and it revealed that $C_L$ and $L/D$ at $M = 0.3$ significantly increased with the outer wing attached. The comparison of the aerodynamic coefficients at $M = 7$ is shown in Figs. 6, 7, 8, and 9. $C_L$ and $C_D$ of type 2 were smaller than those of type 1. This is because the aerodynamic force at the outer wings was smaller because of the expansion surfaces (see Fig. 2), as shown in Fig. 10. Note that the total aerodynamic force, not the aerodynamic coefficient, of type 2 was larger than that of type 1 because of the larger reference area. On the other hand, the aerodynamic force at the outer wings far away from the center of gravity affected $C_m$, and the slope of $C_m-\alpha$ curve of type 2 is smaller than that of type 1. Type 1 does not have longitudinal static stability, however type 2 does. Generally, an ideal waverider tends to have too large pitching-up moment and positive gradient in $C_m-\alpha$ curve, and therefore the attachment of the outer wings is advantageous in view of longitudinal stability, too.

The effect of leading edge bluntness was observed by comparing type 2, 3 and 4. As seen in Figs. 7 and 9, larger leading edge bluntness made $C_D$ larger and therefore made $L/D$ smaller. Figure 10 shows that the high-pressure region near the leading edge became wider in order of type 2, 3, and 4. As the leading edge bluntness became large, the aerodynamic performance rapidly got worse. Leading edge bluntness of the vehicle should be determined by the trade-off between aerodynamic performance and aerodynamic heating. However, the study on thermal protection system was not conducted in detail yet. At the moment, leading edge radius was set as 0.5 % of the total length, the same as that of type 3.

The effect of twin vertical tails was observed by comparing type 3 and 5. The tails affected only the flowfield on the upper surface near them and generated the high-pressure region, as shown in Fig. 10. Therefore, as seen in Fig. 8, $L/D$ at small $\alpha$ was decreased with the tails attached. At large $\alpha$, the tails go into shadow of the main body, the aerodynamic performances were almost the same between type 3 and 5.

The flowfields around type 1 and type 5 at $M=7$, $\alpha=0$deg are shown in Figs. 11 and 12, respectively. Figure 11 shows the flowfield around the ideal waverider, where the high-pressure region is kept on the lower surface. In contrast, as shown in Fig. 12, the flowfield around type 5 exhibited the spill-over of the high-pressure region from the lower to the upper surface because of the non-ideal shape by the attachment of the outer wings and the leading edge bluntness.

4. Baseline Shape of P2P Suborbital Vehicle

The designed aerodynamic shape of the P2P suborbital vehicle in this study is type 5. Maximum $L/D$ at $M = 7$ is about 3 when $\alpha = 2.5$ deg as shown in Fig. 9. According to Fig. 8, the trim angle at $M = 7$ is almost 0 deg, and $L/D$ is about 2.6 in the trim condition. The small value of the maximum $L/D$ in spite of the waverider-based design is thick base plane causing large base drag. To obtain the volume necessary for the installation of all the equipments, the designed vehicle had to be thick.

The dimension of the vehicle was determined so that the propellant tanks, the landing gears, and the cabin could be put inside the volume of the vehicle. The resulting dimension of the vehicle is tabulated in Table 3. The equipment layout is shown in Fig. 13. The multi-lobe tanks\(^7\) were adopted for both of the ethanol and liquid oxygen tanks because of the poor volumetric efficiency caused by the waverider-based design. The vehicle has two cabins, and each cabin has 6 passengers. This cabin design is currently conceptual. By taking into account the weight of other components such as thermal protection system, propellant system, and avionics system, the size and the number of passengers can be changed in the future.

![Fig. 5. Comparison of $C_L$, $C_D$, and $L/D$ between type 1 and 2 at $M=0.3$.](image)

![Fig. 6. Comparison of $C_L$ between 5 types at $M=7$.](image)
Fig. 7. Comparison of $C_D$ between 5 types at $M=7$.

Fig. 8. Comparison of $C_m$ between 5 types at $M=7$.

Fig. 9. Comparison of $L/D$ between 5 types at $M=7$.

Fig. 10. Comparison of $C_p$ distributions between 5 types at $M=7$, $\alpha=0^\circ$.
The surface area is 950.6 m$^2$. Assuming that the structural weight is 35% of the dry weight, it is 9.94 ton from Table 1. Thus, the area density of the structure is 10.5 kg/m$^2$. At the present, the area density of an airplane structure is about 20 kg/m$^2$. To realize the P2P suborbital vehicle designed in this study, reduction in structural weight is necessary.

### Table 3. P2P suborbital rocketplane sizing.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centerline chord length</td>
<td>27.6 m</td>
</tr>
<tr>
<td>Span</td>
<td>16.6 m</td>
</tr>
<tr>
<td>Height</td>
<td>5.7 m</td>
</tr>
<tr>
<td>Reference area (projected area)</td>
<td>375.6 m$^2$</td>
</tr>
<tr>
<td>Surface area</td>
<td>950.6 m$^2$</td>
</tr>
<tr>
<td>Volume</td>
<td>730.7 m$^3$</td>
</tr>
</tbody>
</table>

5. **Trajectory Analysis**

A two-dimensional trajectory analysis was conducted to investigate the downrange ability of the designed P2P suborbital rocketplane. Only the descent phase was calculated. Assuming that aerodynamic and gravity losses in the ascent phase are 20% of the ideal velocity increment in reference to the Space Shuttle data, the initial velocity is set to 6.4 km/s. The initial altitude is 100 km, and the initial flight path angle is 0 deg. The simulation was finished when the velocity was decreased till 1 km/s. For simplicity, the aerodynamic coefficients at $M = 7$ and $\alpha = 0$ deg (trim condition) were constantly used through the simulation. This assumption seems to be valid in the initial estimation of the downrange ability because the hypersonic aerodynamic performance is not much affected according to Mach number independence principle. The aerodynamic heating at the nose was estimated by Detra-Kemp-Riddell formula.

The result of the trajectory analysis is shown in Fig. 14. The vehicle took a skipping trajectory. The downrange was 8600 km, the maximum aerodynamic heating at the nose was 1.87 MW/m$^2$, the maximum load factor was 1.73, and the flight time was 2085 s. The aerodynamic heating was very severe, and the design of the thermal protection system is a challenging issue and should be investigated in the future. Moreover, considering the manned transportation, a non-skipping trajectory is much better, and will be studied in the future, too.

6. **Conclusions**

In this paper, the concept and the aerodynamic study of a P2P suborbital rocketplane were described. Considering the repetitive reuse of the vehicle, the ethanol was selected as the fuel which is cheap and has good operability. To achieve high $L/D$ in hypersonic regime, the concept of waverider was adopted. Starting from the ideal waverider design, the baseline shape of the P2P suborbital rocketplane was designed by attaching the outer wings, leading edge bluntness, and twin
vertical tails. Especially, the outer wings significantly improved the subsonic aerodynamic performance. The designed P2P suborbital rocketplane achieved 8,600 km of downrange, and the maximum \( L/D \) in hypersonic regime was about 3.

References

2) International Space University: Great Expectations: an Assessment of the Potential for Suborbital Transportation, 2008