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Design Study of High Mach Integrated Control Experimental Aircraft (HIMICO)

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Abstract

The design of High Mach Integrated Control Experimental aircraft (HIMICO) for the 1st flight experiment has been progressed. The experiment aims to establish the design method of separation device, telecommunication devices, heat shield structure, and aerodynamic control devices. Length and weight of the aircraft are 1.2 m and 30 kg, respectively. The preliminary studies have been conducted on the aerodynamics, trajectory, and heat shield structure. The reference trajectory is defined with 24 second of the hypersonic flight duration. Aerodynamic force coefficients have been obtained at a hypersonic wind tunnel and CFD analyses. A separation mechanism and a heat shield structure has been studied.

Keywords: hypersonic, propulsion, aerodynamics, control

1. Introduction

A hypersonic pre-cooled turbojet engine has been tested at a propulsion wind tunnel [1] with the aim of realizing a Mach 5 class hypersonic transport aircraft [2]. In addition, a small hypersonic engine simulating the same intake and nozzle shape as the hypersonic pre-cooled turbojet engine has been developed for thre future flight experiment. Figure 1 shows a wind tunel test model of High Mach Integrated Control experimental aircraft (HIMICO) . The aircraft will be installed at the top of a sounding rocket, and a hypersonic flight will be realized by the combination of parabolic trajectory and pull-up maneuver [3]. In order to solve the technical problems of flight experiments step by step, the experimental aircraft was divided into the first aircraft that does not carry fuel and the second aircraft that carries fuel. As for the first aircraft, the specific feasibility to the S520 sounding rocket has been studied. In this paper, the outline of the design status of the HIMICO-#1 aircraft shape, trajectory, aerodynamic coefficients and heat shield structure are described.

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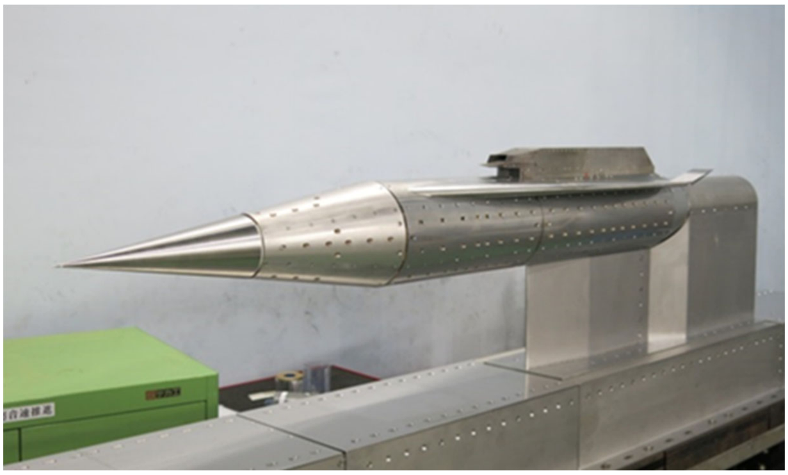


Fig. 1. Wind tunnel test model of High Mach Integrated Control experimental aircraft

2. Overview of HIMICO-#1

Figure 2 shows the experimental outline of the HIMICO-#1 flight experiment. It is assumed that the experimental aircraft will be installed inside the nose cone at the top of the S520 sounding rocket and launched from Uchinoura Space Station in Japan. When the dynamic pressure of the rocket becomes low at the ascending phase, the nose cone will be separated. In the region of altitudes between 100km and 200km, space science observation experiments will be conducted as the other science mission. When the altitude is less than 100km due to descending flight, the spin rate of the rocket will be reduced by a de-spinner, and the aircraft will be separated from the rocket. Communications of radar transponder and telemeter will be performed between the separated aircraft and the ground station. The flight trajectory will be controlled by aerodynamic manoeuvre below the altitude of about 30 km. The target flight dynamic pressure is about 50 kPa at Mach 5, that is the flight condition of future hypersonic transport aircraft. The aircraft will be dumped in the sea after the flight experiment.

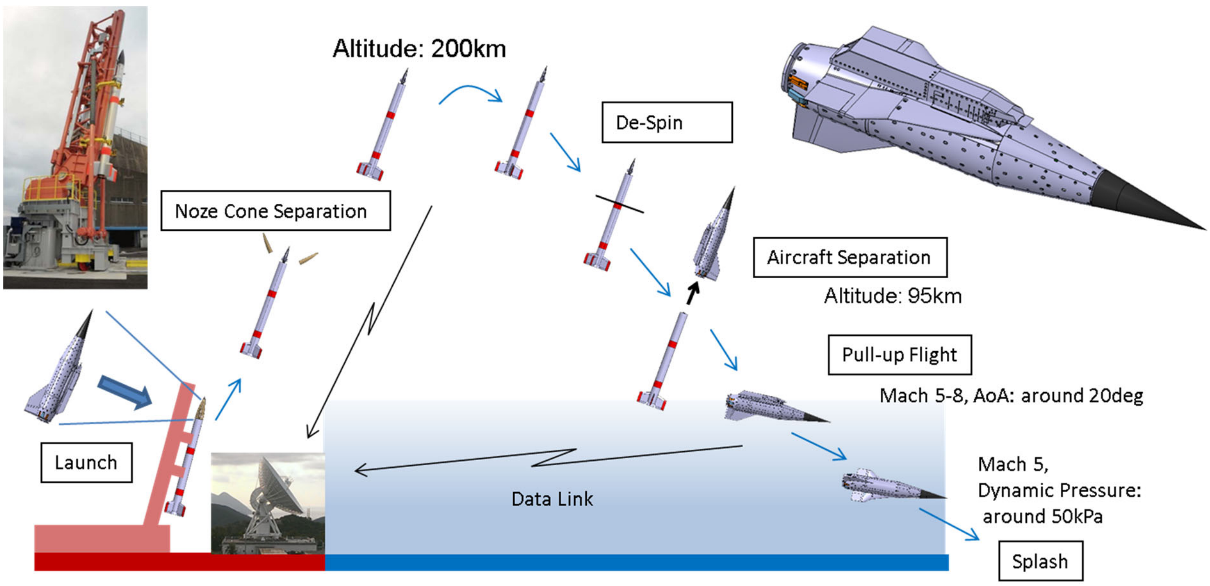


Fig. 2. Overview of HIMICO-#1 flight experiment

Figure 3 shows the overview of the shape and size of HIMICO-#1 aircraft. The fuselage of the aircraft is a combination of a cone and a cylinder. The total length of the fuselage is 1.2 m, and the width of the main wing is smaller than the inner diameter of the nose cone of the sounding rocket. A ramjet engine is installed on the bottom side of the fuselage, but the fuel supply system is not mounted and combustion is not performed at the 1st flight experiment. The objetives of the 1st flight experiment is to confirm the functions of separation of experimental aircraft, data communication, and flight control method. The mass of the experimental aircraft is about 30kg.

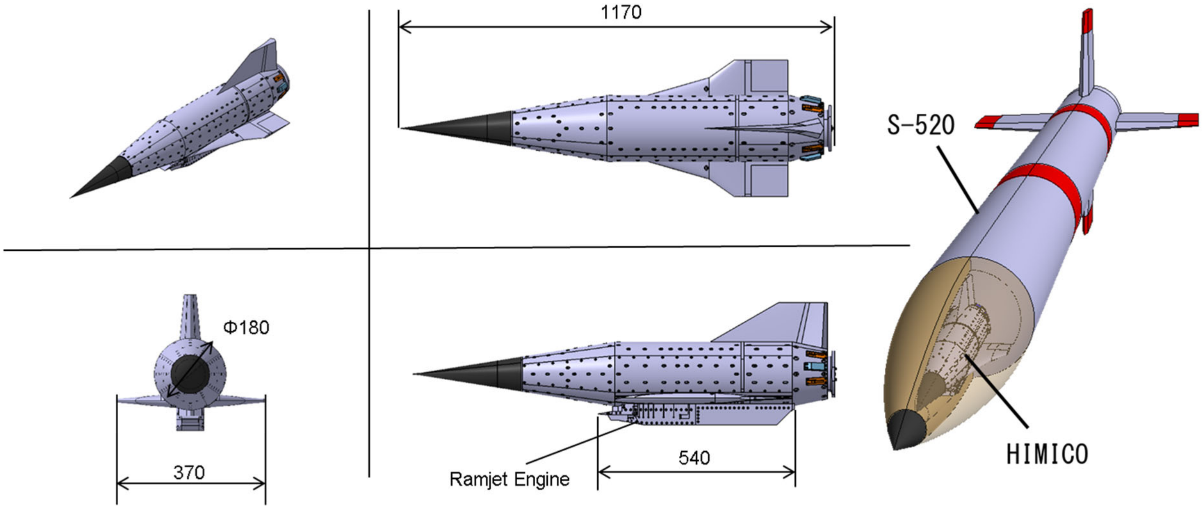


Fig. 3. Dimensions of HIMICO-#1 aircraft (Unit: mm)

Figure 4 shows the leading-edge parts of the S520 sounding rocket equipped with the HIMICO-#1 aircraft. The antennas of radar transponder and telemeter are attached at around the aircraft and the rocket, so that radio waves are transmitted from the rocket side before the separation and from the aircraft after the separation.

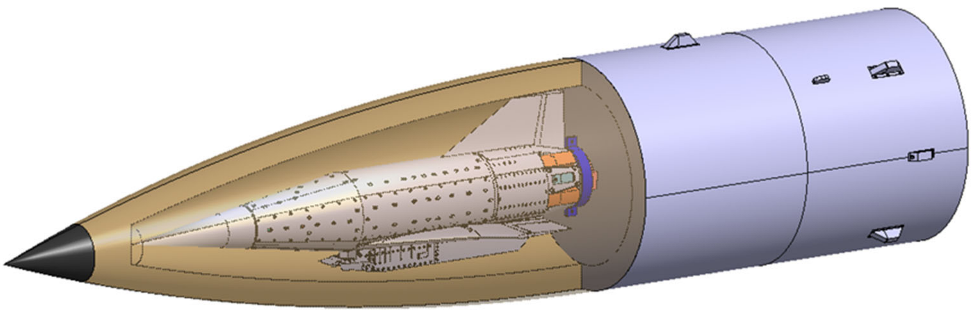


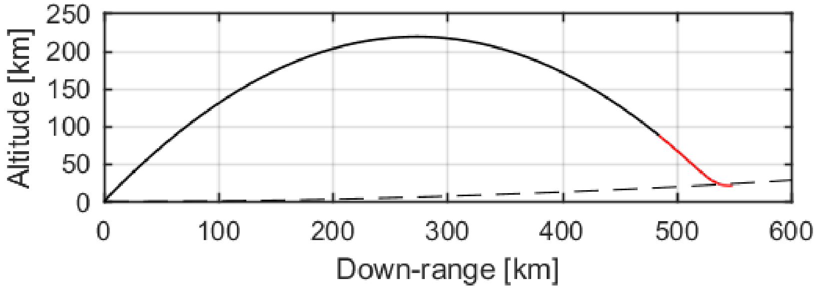
Fig. 4. Configuartion at the top of S520 sound ing rocket with HIMICO-#1

3. Trajectory Simulation

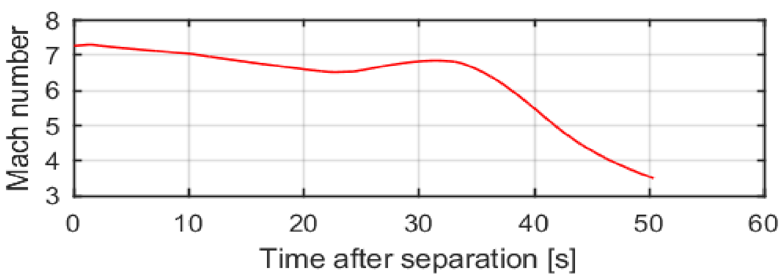
Figure 5 shows the flight trajectory of HIMICO-#1 aircraft. The motion is analysed using a 3-degree-of-freedom motion equation in the vertical plane, and the vertical motion trim is considered. The trajectory analysis parameters of the S520 rocket were corrected using past flight data. The trajectory was analysed by changing the launch angle and the initial mass of the rocket to select the trajectories that can achieve the experimental objectives. As a result, a launch angle of 70 deg. and an initial mass of 2275 kg were selected as a reference trajectory.

For the flight trajectory analysis, an aerodynamic model between Mach 4 and 8 with aerodynamic control surfaces was created by analyses using Local Surface Inclination (LSI) method. The flight trajectory after separation of the experimental aircraft was analysed using the airframe shape / trajectory simultaneous optimization method[4]. The airframe shape and flight trajectory were generated so that a flight of about Mach 5 and dynamic pressure of about 50 kPa could be realized for more than 5 s.

Figure 5 a) shows the relationship between altitude and down range. Due to the demands of space science observation mission, the horizontal distance should be more than 400 km at altitude of more than 100 km. The highest altitude is about 220km. HIMICO-#1 is separated from the rocket at the altitude of less than 100 km. The altitude of the aircraft decreases by a free flight without propulsion. When the altitude is below 30 km, the dynamic pressure of the air increases and pull-up maneuver initiates. Figure 5 b) shows the time history of Mach number after separation. Flight Mach number is about 7 just after the separation. From 30s after separation, Mach number decreases as the dynamic pressure increases, and reaches about Mach 5 at 40s.



a) Altitude and down range



b) Mach number

Fig. 5. HIMICO-#1 reference trajectory

4. Hypersonic Wind Tunnel Test

A hypersonic wind tunnel test was conducted to obtain the aerodynamic characteristics of the airframe shape of HIMICO-#1. The tests were conducted in the hypersonic wind tunnel at JAXA Chofu Aerospace Center. Airflow conditions were Mach 5, total pressure of 1 MPa, and total temperature of 700K.

Figure 6 shows the HIMICO-#1 test model used for the hypersonic wind tunnel test. The size of the model is 25% scale of the assumed experimental aircraft to be mounted on the S520 sounding rocket. The total length is 300mm. The fuselage has a shape that combines a cone and a cylinder. A double delta-shaped main wing was placed on the lower fuselage, and a trapezoidal vertical stabilizer was placed on the upper fuselage. In addition, an engine part that simulates a hypersonic engine is placed under the main wing. The engine part was not provided with a flow path. The model simulates a non-starting condition in which a shock wave is formed at the engine inlet. A flow channel was provided in the previous research[4], the internal flow changed depending on the angle of attack between the start state in which it passes at supersonic speed and the non-start state in which it passes at subsonic speed. The change of intake flow affected the aerodynamic characteristics of the airframe. Then, the flow path was not provided in this experiment. Six component forces with angle of attack from -35deg to 35deg were acquired corresponding to the high angle of attack flight during the flight experiment.

Fig. 6. HIMICO-#1 wing tunnel test model

Figure 7 shows a Schlieren image (Mach 5, angle of attack 15deg) obtained in the wind tunnel test. A strong shock wave is formed under the conical front body. Also, a second shock wave and expansion wave are formed near the fuselage slightly upstream of the engine. A detachment shock wave is formed at the engine inlet. This is because there are no flow paths in the engine part.

A weak shock wave is formed on the upper side of the front body. Also, a relatively strong shock wave is formed in the conical downstream portion of the front body.

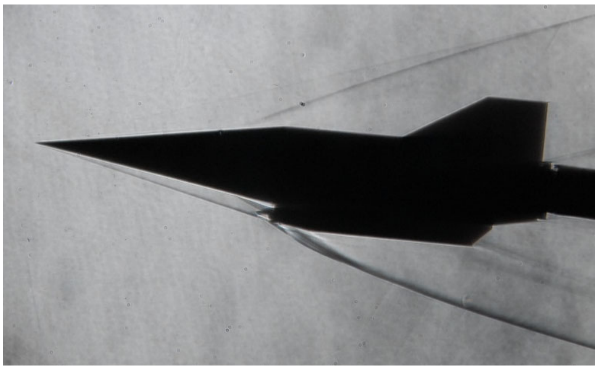


Fig. 7. Schlieren image (Mach 5, angle of attack 15deg)

In the hypersonic wind tunnel test, the airframe surface flow was visualized by the oil flow method. Figure 8 shows the visualization results of the surface flow on the underside of the fuselage due to the oil flow (Mach 5, angle of attack -20deg). In order to obtain directional stability characteristics, HIMICO-#1 is assumed to fly at a negative angle of attack with the vertical stabilizer on the lower side and with a large angle of attack. There is a separation in the wide area of the front fuselage, main wing, and underside of the engine. At the leading edge of the main wing, an oblique flow field is formed from the leading edge toward the fuselage. This flow may be caused by a high negative angle of attack that increases the pressure on the upper surface of the wing and causes flow within the boundary layer. In this test, the angle of elevon was set at 30 deg downward of the wing. This angle is selected to simulate the flight with high negative angle of attack. On the underside of the elevon, the airflow hits strongly on the elevon and forms an axial surface flow.

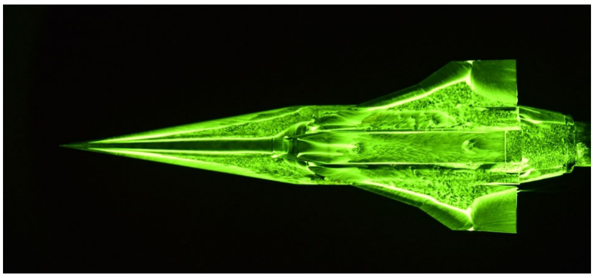


Fig. 8. Visualization of surface flow by oil flow method (Mach 5, angle of attack -20deg)

5. Aerodynamic performance analysis

Numerical analyses were performed to estimate the aerodynamic characteristics of HIMICO-#1 and to apply it to a flight control analysis. Numerical analysis was performed using FaSTAR[5] developed by JAXA Numerical Analysis Technology Research Unit. In order to confirm the validity of the numerical analysis results, the analysis was performed under the same conditions as the hypersonic wind tunnel test.

Figure 9 shows Mach number distribution around HIMICO-#1 aircraft, which is obtained by a CFD analysis. The analysis conditions are Mach 5 and angle of attack of 5 deg. The aerodynamic model with various angles of control surfaces are generated by CFD analyses for use in flight control analyses.

Like the schlieren image of the wind tunnel test results, a shock wave is formed on the underside of the forebody. In addition, a low Mach number region is formed near the fuselage slightly upstream of the engine. As a cause of this flow, there is a possibility that the influence of the boundary layer around the engine is transferred upstream. In the upper part of the fuselage, a boundary layer with a low Mach number develops from the middle of the cylindrical part, and a shock wave is formed due to its influence. In the Schlieren image of Fig. 7, similar shock waves are formed at the upstream cone. Therefore, it can be said that the results of experiments and numerical analysis are slightly different regarding the boundary layer on the fuselage surface and the formation position of the shock wave affected by it.

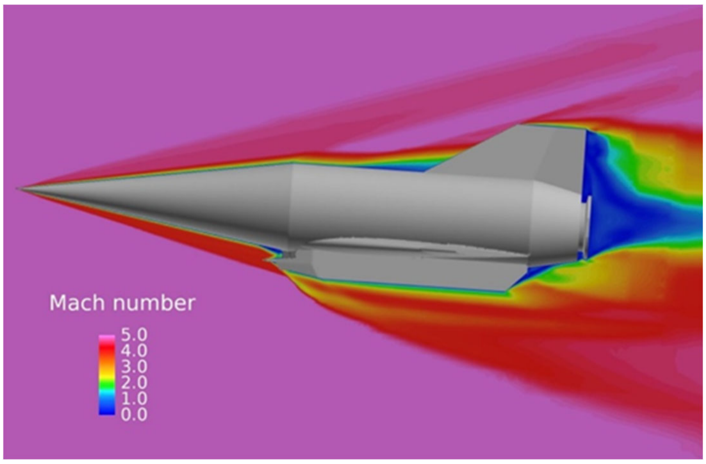


Fig. 9. Mach number distribution around HIMICO-#1 aircraft

Figure 10 shows a comparison of the lift coefficient (CL) obtained from wind tunnel tests and numerical analysis at Mach 5. The rudder angle and the elevon angles was set to 0 deg. From this figure, the difference in lift coefficient is small within the range of angle of attack of -25deg to +25deg assumed in flight experiments.

Figure 11 shows a comparison of the drag coefficient (CD) obtained from wind tunnel tests and numerical analysis at Mach 5. As for the drag coefficient, the value of the numerical analysis was larger than that of the wind tunnel test at the negative angle of attack.

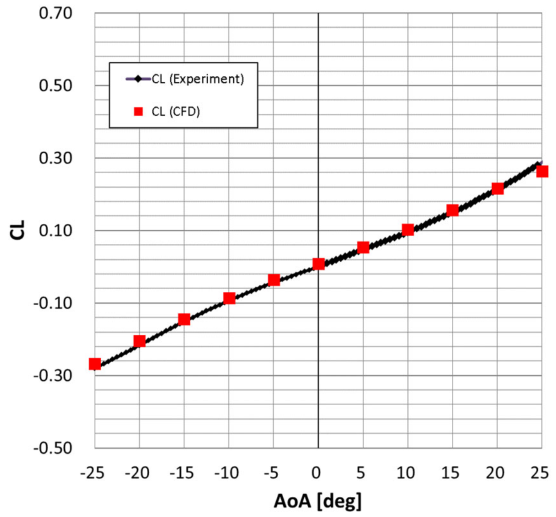


Fig. 10. Lift coefficient (Mach 5, Rudder angle: 0deg)

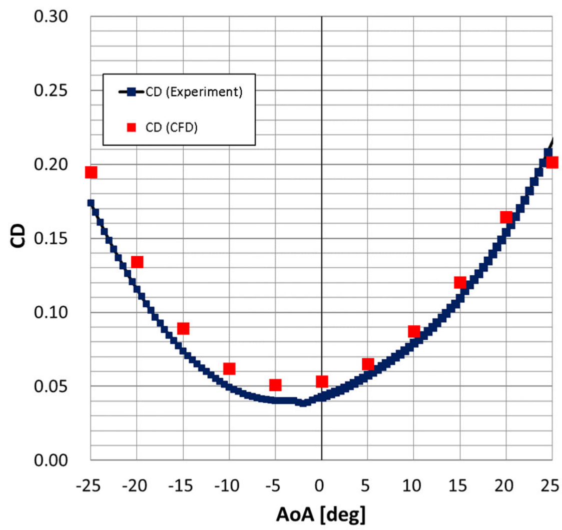


Fig. 11. Drag coefficient (Mach 5, Rudder angle: 0deg)

Figure 12 shows the pitching moment coefficient (Cm) obtained by CFD analyses at Mach 5 and elevator angle of 0 deg. When the moment centre is located at 57% of the total length from the tip of the fuselage, the Cm slope is negative and longitudinal stability is obtained.

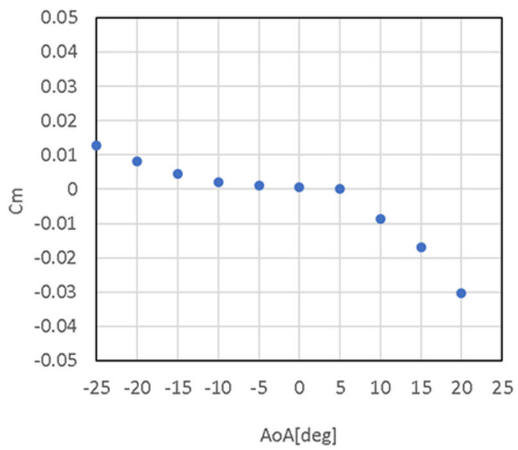


Fig. 12. Pitching moment coefficient (Mach 5, elevator angle: 0deg)

6. Examination of structure and equipment

Figure 13 shows the structure and equipment of HIMICO-#1 aircraft. The structural pattern was obtained by a structural optimization analysis, assuming the acceleration conditions at the launch of the sounding rocket and the aerodynamic loads caused by the pull-up manoeuvre. A radar transponder and a telemeter transmitter that have been used in sounding rocket experiments are installed inside of the fuselage. Multiple antennas are placed at the downstream position of the fuselage to ensure communication with ground stations regardless of the attitude of the aircraft. A flight computer, control wings, and actuators are installed to control the attitude of the aircraft and put it into the target trajectory.

A thermal protection system is installed on the fuselage surface to prevent heat from the aerodynamic heating. The materials are titanium, cork, and aluminium alloy from the outside. Assuming the worst case, in which the aircraft flies at the angle of attack of 90deg, the aerodynamic heating was estimated, and the insulation thickness was determined so that the temperature inside of the aircraft is kept below 50 deg. Celsius until the end of the flight experiment. A solid part made of nickel alloy was placed at the leading edge of the fuselage, and the centre of gravity was adjusted to achieve vertical stability. As control wings, elevons are placed at the trailing edge of the main wing, and a rudder is placed at the trailing edge of the vertical tail.

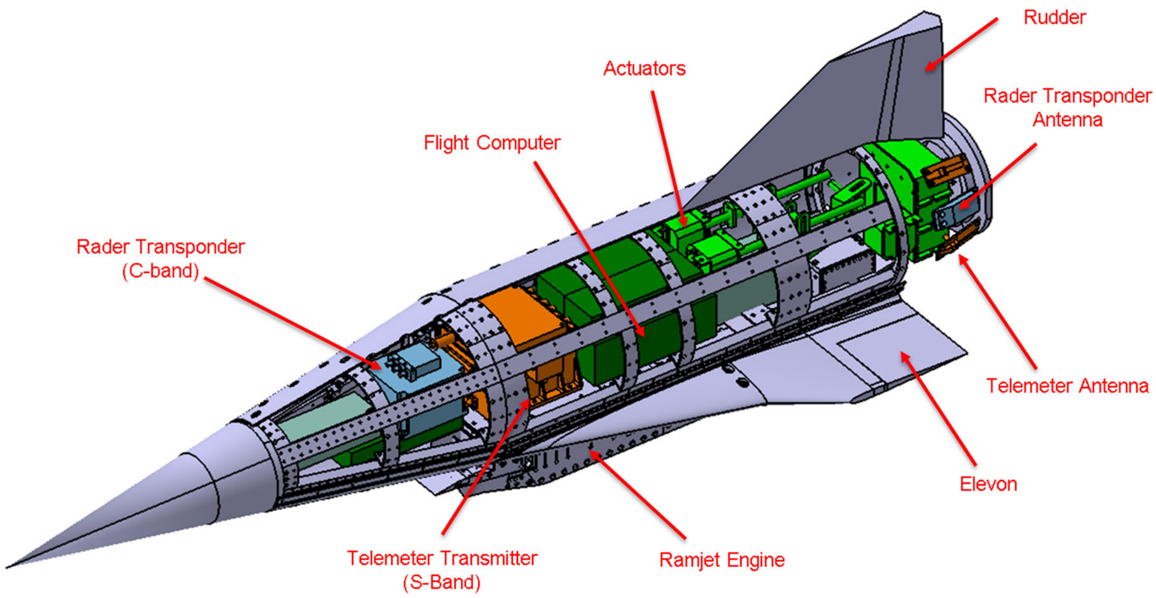


Fig. 13. Structure and equipment of HIMICO-#1 aircraft

Figure 14 shows the concept of the separation mechanism. The rear end of the experimental aircraft is fastened with a Marman clamp and fixed with bolts with separation nuts. By releasing separation nuts, the Marman clamp is opened and the push board pushes out the experimental aircraft with the force of the separation spring.

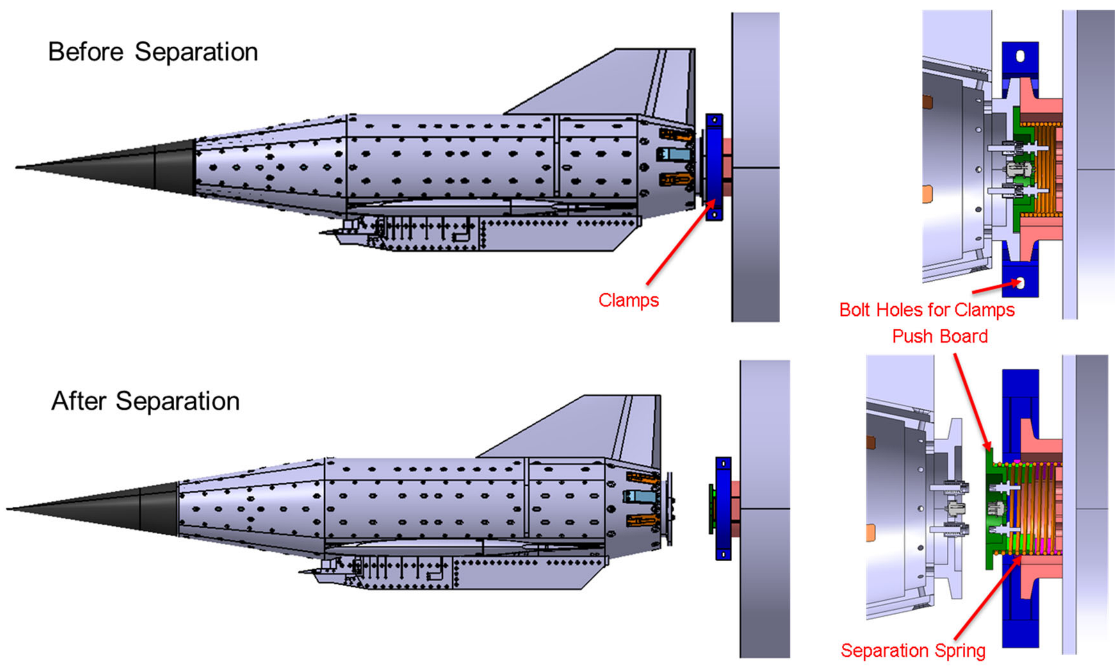


Fig. 14. Separation mechanism

7. Flight control simulation

Figure 15 shows time history of attitudes (roll, pitch, yaw) ,which is obtained by a flight control simulation. The simulation is performed assuming the experimental aircraft is separated from the rocket at the attitude angle of 80 deg. without side jet control. As a result of the simulation, it is confirmed that even if the initial attitude angle is 80 deg., the attitude can be controlled by aerodynamic control wings after the dynamic pressure increases and the target attitude required by the pull-up manoeuvre can be attained. To maintain the directional stability, the aircraft is assumed to fly with the attitude, in which the vertical tail is placed at the bottom side of the fuselage. Then, the aircraft is assumed to change the attitude, in which the engine is placed at the bottom side of the fuselage, after completing the pull-up manoeuvre.

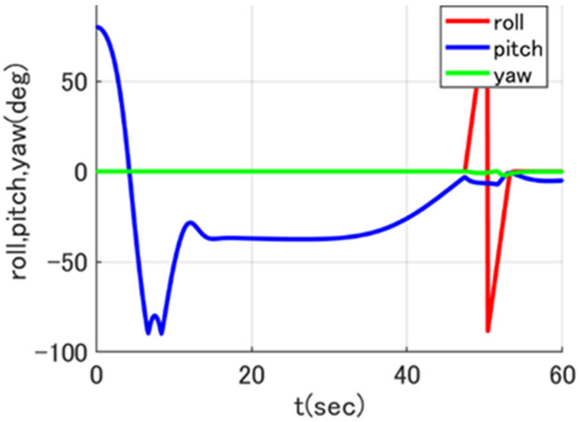
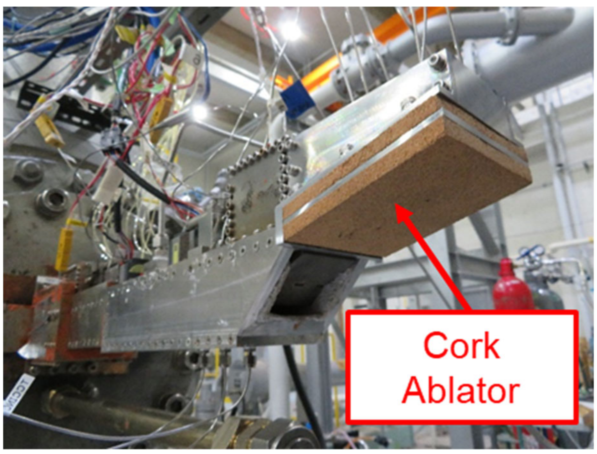


Fig. 15. Time history of attitude

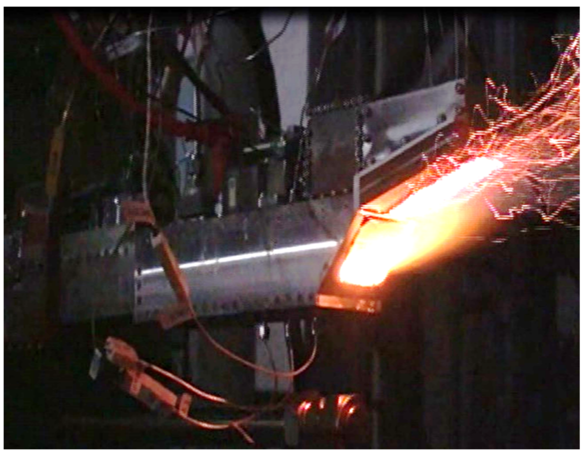
7. Thermal insulation test

HIMICO will be equipped with a hydrogen-fuelled ramjet. When the engine is operated, high-temperature combustion gas flows over the surface of the rear fuselage, so a heat shield structure is required to protect the on-board equipment inside the fuselage. Therefore, a thermal insulation test was conducted.

Figure 16 a) shows a photograph of the test equipment used for the thermal insulation test. The tests were conducted in the hypersonic high-enthalpy wind tunnel at the Kashiwa Campus of the University of Tokyo. To simulate Mach 4 flight conditions, the total pressure of the air supplied to the engine was set to 300kPa and the total temperature to about 900K. To protect the fuselage from the heat of the combustion gas discharged from the engine, a cork ablator with 7mm thickness was placed on the surface of the fuselage. A fuselage simulation part made of nickel alloy was placed on the upper surface of the ablator, and a cork plate for thermal insulation was placed on the upper surface. Figure 16 b) shows a photograph during the engine combustion test. The surface of the cork ablator was burnt in this test.



a) Test setup



b) Thermal insulation test

Fig. 16. Thermal insulation test

8. Conclusion

The design of the High Mach Integrated Control experimental aircraft (HIMICO) using S520 sounding rocket was studied and the following results were obtained.

- A flight trajectory that can realize both space science observation experiments and hypersonic flight experiments was obtained.
- Assuming the launch load of the sounding rocket and the aerodynamic load at pull-up manoeuvre, structural optimization analysis was performed and the structural pattern was designed.
- A flight control simulation was performed, and it was confirmed that even if the attitude after separation from the rocket was 80 deg., it can be controlled by aerodynamic forces and the target dynamic pressure can be attained.
- Hypersonic wind tunnel test and numerical analysis were performed to evaluate the aerodynamic characteristics at Mach 5. As for the drag coefficient, there is a difference between the wind tunnel test and the numerical analysis.
- To prevent the combustion gas from the hydrogen-fuelled ramjet from heating the rear fuselage, a thermal insulation test was conducted using a cork ablator.

Acknowledgements

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