The day when space becomes a part of our everyday lives

What is the optimum shape of a reusable launch vehicle?

In space at an altitude of 400 km, far above the earth where we live, there is the "International Space Station" (ISS)-a house constructed in space with the cooperation of 15 countries from around the world, including Japan. Usually, six astronauts live on the ISS and go about their everyday lives. The Russian Soyuz spacecraft is used to shuttle astronauts to and from the ISS. Supplies necessary for survival are sent to the ISS by supply ships developed by various countries, including Japan' s "Kounotori (HTV)" . Although these supply ships are launched into space by rockets, a single launch carries a huge cost of billions of yen. Considering that rockets and supply ships are all single-use equipment, realizing a reusable launch vehicle that can travel between the earth and space multiple times should be able to reduce the cost of a single trip into space. Therefore, various countries are continuing research for a reusable launch vehicle.

When developing new aircraft, it is necessary to first decide "what (payloads of passengers or cargo, etc.) will be transported to where." With that, a rough concept of, for example, the aircraft size as well as the required performance, such as the speed, should become clear. Therefore, we have concluded that we will try to design a reusable launch vehicle that can transport passengers into the low Earth orbit of the ISS. What type of aircraft would you make? Should the aircraft fly into space in a single stage, or should it be a multi-stage type like conventional launch vehicles? Should it take off and land vertically, or should it be equipped with wings so that it can take off and land horizontally? In fact, the optimum shape of a reusable launch vehicle is not really known. That is why all over the world and, of course, within JAXA, various airframe configurations are being considered and feasibility studies conducted.

Here, we will introduce the component technologies necessary for realizing a reusable launch vehicle, with a two-stage winged type (fig. 1) as an example of one airframe configuration being examined..

From 1981 to 2011, the world' s only reusable launch vehicle, the "Space Shuttle" , was operated by the U.S. National Aeronautics and Space Administration (NASA) to actively participate in the construction of the ISS. However, due to the significant cost of aircraft maintenance as well as safety issues, they were forced into retirement. If this decision could be reversed and the problems that beset the Space Shuttle could be resolved, it would mean a big step toward the realization of a new reusable launch vehicle. The Space Shuttle is one example of reusable launch vehicles that were studied throughout the world in the 90s and had a blunter shape. In recent years, a sharp, slender configuration has also been considered. With a more clean-cut aircraft that allows air to flow smoothly, the drag applied to the aircraft can be reduced, and the ratio (lift-to-drag ratio) of lift (force that causes the aircraft to float) can be increased. By increasing the lift-to-drag ratio, the direction of travel when returning to the earth from orbit can be curved, allowing large lateral movement. These lateral movement capabilities are called cross-range capabilities; when increased, these improve safety as well as raise the degree of freedom for bases where landing is possible if an on-orbit problem occurs that requires an emergency return. "Computational fluid dynamics" (CFD), where a computer uses numerical analyses to determine the flow around an aircraft, is being utilized for designing the airframe configuration. Since CFD can be used to quickly predict performance with regards to airflow of

The aircraft separates along the way, and the second stage uses the mounted rocket engines to fly into space. The first stage uses the lift generated by the wings and changes direction to return to the base from where it was launched in order to be prepared for the next flight.

Fig. 1: Two-stage winged reusable launch vehicle

varying conditions in the virtual space of a computer, an airframe configuration that meets the design requirements can be efficiently designed.

Issues of “heat” that must be resolved

An aircraft that you are riding has entered an attitude to return to the earth from space. Now, it will re-enter the atmosphere. Since the aircraft is flying at an ultra-high speed of Mach 25 (25 times the speed of sound), the air in front of the aircraft is greatly compressed and reaches high temperatures, causing the aircraft to be strongly heated. This phenomenon is called aerodynamic heating.

The nose tip of a Space Shuttle re-entering the atmosphere was exposed to temperatures exceeding 1400 ℃. Therefore, carbon/carbon composite materials (C/C composite materials), which can withstand temperatures as high as 1600 ℃, were used in places, such as the nose tip, that are exposed to a harsh thermal environment. Insulation that is lightweight and can withstand high temperatures, such as ceramic tiles, was applied to the entire surface of the aircraft in order to protect people from aerodynamic heating. If performance was enhanced and the airframe configuration was sharpened, pointed sections, such as the nose tip and wing leading edges, would reach high temperatures near 2000 ℃, but materials that can withstand such high temperatures have yet to be put into practical use. Therefore, new materials must be developed. The key to that is a type of material called “ultra-high-temperature ceramics” (UHTC). Since the heat-resistance temperature can be altered through the manufacturing method or combination of raw materials, we are researching a construction that can withstand a temperature of 2000 ℃ by coating the C/C composite material with a newly developed UHTC. As the result of making test pieces with various coatings applied to the C/C composite material and subjecting them to wind tunnel tests in the arc-heated wind tunnel, where a high-temperature airflow can be generated, we have developed a UHTC coating that can withstand a high temperature of 1700 ℃ for a short time. (Fig. 2) In addition, we are conducting tests with models simulating the wing leading edge of a reusable launch vehicle (leading edge models) and confirming that they can withstand up to 1450 ℃. At present, we are planning heating tests at 1900 ℃ using the arc-heated wind tunnel with the hope of finally developing a material that can withstand an extremely high temperature of 2000 ℃.

For heat-resistance on the Space Shuttle, a broad area of the airframe was covered with ultra-lightweight ceramic tiles. However, they were beset by various problems, such as their brittleness, which resulted in them cracking easily, or the effort required to inspect and replace them by affixing them to the airframe with adhesive. Weather-resistance, especially light rain, was also a problem. Therefore, we are attempting to develop a heat-resistant construction that can resolve these problems. More specifically, we are considering a construction where surface panels of sturdy heat-resistant metal or ceramic composite materials (CMCs)- ceramic reinforced with carbon fibers or ceramic fibers-are attached with fasteners for easy removal. Since the internal insulation, under the surface panels, is essential, we are researching insulating structures as well as insulation utilizing new materials, such as foam metal and nanomaterials, in order to achieve a weight comparable to ceramic tiles. (Fig. 3)

As the construction material for the entire airframe structure, an aluminum alloy was used on the Space Shuttle. However, for weight reduction, we are conducting research on the applications of carbon fiber reinforced plastics (CFRP) or a CFRP where the carbon fibers are hardened with a more heat-resistant polyimide resin instead of a common epoxy resin.

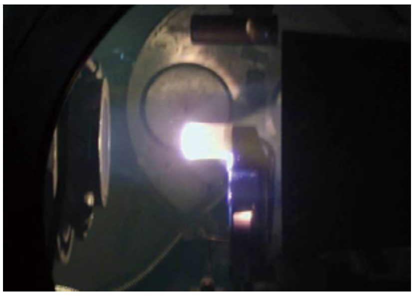

Fig. 2: Arc-heated wind tunnel testing of UHTC-coated C/C composite material

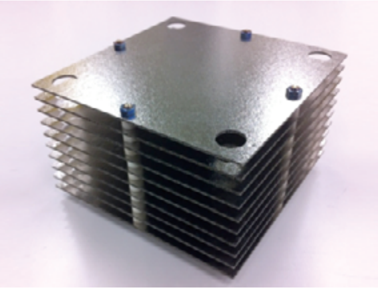

Fig. 3: Prototype of heat-resistant construction to replace ceramic tiles (foam metal/multi-layered radiation shielding construction)

You cannot go into space without a propulsion system.

Even if the airframe can be constructed with materials that can withstand the heat, a reusable launch vehicle cannot be realized if it does not have an engine that can adequately accelerate the aircraft and be used many times. Various designs are being considered at JAXA, but there is still no definitive engine where, like with the airframe, we can say “this is the answer” . A rocket engine is essential in space and in the upper atmosphere where there is not enough oxygen. Use of air-breathing engines at altitudes with enough air is being considered. Air-breathing engines have the advantages that there is no need to take along an oxidizing agent to burn fuel and that fuel efficiency is improved if you were to speak of a car. However, they have the disadvantages that the engine itself is heavy in proportion to its thrust and that aerodynamic heating becomes a problem during ascent since the aircraft is flying where air is dense. We are at the stage where various possibilities, such as hydrogen, methane and alcohol, are being considered for the fuel. Rather than focusing only on engine performance, we must carefully consider performance of the entire system, fuel costs as well as ease of pre-flight preparations and post-flight maintenance when determining the engine specifications. Currently, this should be considered the stage where information is still being gathered in order to decide on an engine.

In order to go into space, the aircraft must be loaded with a large amount of fuel and oxidizing agent. Cryogenic liquid oxygen should be selected as the rocket engine oxidizer, and the fuel would also be a cryogenic liquid if liquid hydrogen or methane were selected. For weight reduction, we are investigating making the tanks with CFRP as well. However, since the pipe supplying the engine with liquid from the tank is metal, it would be necessary to adhere the pipe outlet to the CFRP tank at the point where the liquid is taken in. If this type of cryogenic liquid enters a composite material tank, there is a fear of debonding at the connection of the tank and pipe due to a difference in the thermal expansion coefficients of CFRP and metal. Therefore, considering the difference in the thermal expansion coefficients, we have devised an outlet shape where debonding will not occur even at very low temperatures. In fact, it was confirmed that debonding did not occur at the location of this problem when a tank model at a scale of 1 m in diameter was cooled by submerging it in liquid nitrogen at -196 ° C. (Fig. 4) In the future, we plan to continue cooling tests as well as confirm through testing that connections do not debond, even when pressure is applied inside the tank.

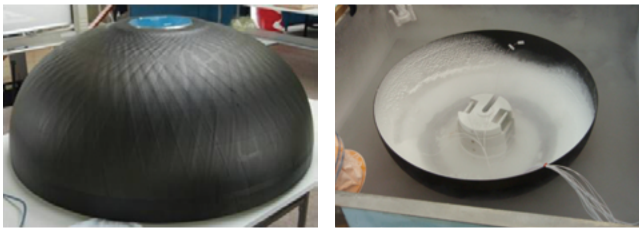
Fig. 4: Cryogenic CFRP tank model (left) and cooling test (right)

There is one more fuel-tank-related problem that must be resolved. As a prospect for fuel tanks, we are considering CFRP where the carbon fibers are hardened with an epoxy resin; however, cracks easily occur in epoxy resin when the temperature is lowered. Furthermore, there is also the drawback that the resin itself becomes hard as the temperature decreases and chains of cracks easily occur. CFRP is constructed by layering many thin sheets. In fact, by making each of these single layers thin, we know that adjacent layers prevent the crack opening should it occur in one layer, making it difficult for cracking to occur. For example, when creating CFRP with a 2 mm thickness, normal CFRP is made by layering about 16 sheets; however, it is difficult for cracking to occur if the layers are made very thin and 32 sheets are layered. The result of leak tests conducted using helium gas has confirmed that cracks and gas leakage are prevented.

Becoming flying robots

After takeoff, a launch vehicle can steadily accelerate to fly into space at a speed of Mach 25. In addition, when returning to the earth, it can break away from an orbit circling Earth, re-enter the atmosphere at an ultra-high speed of Mach 25, and then gradually reduce its altitude and speed to land on the ground. Although both altitude and speed change significantly while aircraft go back and forth between the earth and space, in order to fly safely, the capabilities to operate flaps and the gas jet according to the situation at the time and to fly along the optimum route with the optimum attitude (aircraft angle) are essential. These functions are called guidance and control. With conventional guidance and control, first, models indicating how aircraft should operate at each speed, for example, low speeds or supersonic speeds, were used by a computer on the ground to calculate, in advance, instructions (control parameters called gains) on how aircraft should respond to changes in flight conditions. Then, these gains were imported into the control computer on the aircraft. For that reason, it was extremely time-consuming to develop guidance/control programs to respond to a wide-ranging flight environment, and it was not possible to adequately respond when a problem occurred and an emergency landing at an unscheduled base became necessary. However, with computer developments in recent years, operating models consisting of complex formulas and large amounts of data can be imported into aircraft computers. In addition to computer developments, advances in control theory have made it possible to recalculate emergency flight paths in real time as well as back-calculate flap operations from a desired aircraft response.

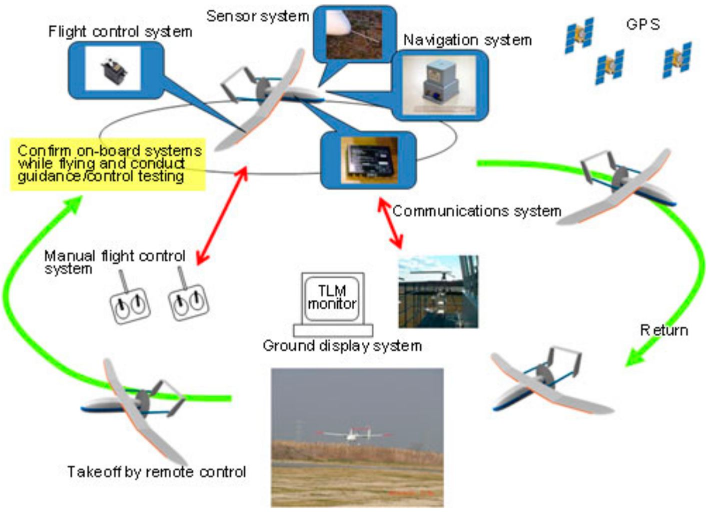

Fig. 5: Overview of guidance/control program verification test at JAXA' s Taiki Aerospace Research Field

Actual operations do not exactly match operations in models. There are uncertainties due to weather conditions, deviations permitted during aircraft manufacturing, errors of sensors measuring speed, for example, as well as prediction errors of aerodynamic characteristics. Controlling aircraft while completely ignoring these errors may lead to the danger of the aircraft becoming uncontrollable. Therefore, we are researching a method of verifying safe flight by assuming various errors and conducting an extremely large number of simulations as well as a method of designing a guidance/control program resistant to errors.

A verification test of the guidance/control program using unmanned vehicles at JAXA' s Taiki Aerospace Research Field is planned for July of this year. (Fig. 5)

Various research and development is continuing on airframe configurations and technologies other than those described here. When space flights become an everyday thing, what technologies and what configuration will be used for the reusable launch vehicle flying throughout the sky?

What aircraft do you see in your future?

How can we go into space? Hypersonic turbojet engines

At the Aerospace Research and Development Directorate, research and development is continuing on a "hypersonic turbojet engine" as the engine for a hypersonic passenger aircraft that flies at Mach 5; however, this engine has possibilities for use in aircraft that will go into space. The features of a hypersonic turbojet engine are its use of liquid hydrogen as fuel, producing a large amount of energy for its light weight, and the use of liquid hydrogen for cooling air that flows in at a high speed and high temperature. With previous research, these technologies have demonstrated engine operation as well as the fuel supply system and operational procedures at Mach 2. However, we must demonstrate that the engine can operate safely with high-temperature air flowing in at even higher speeds of Mach 3 to 5. Therefore, we plan to first conduct combustion tests at Mach 3 to 5 using ground facilities to confirm that the necessary thrust can be safely generated.

Heat is also a problem with the hypersonic turbojet engine. The nozzle where the jet is discharged is a variable mechanism deformed by speed. This variable mechanism is made of metal, and it is covered by a cowling made of a C/C composite material. Similar to the cryogenic CFRP tank, there is a fear that joined parts will be damaged due to different thermal expansion coefficients. Therefore, in the future, we plan to verify the methods of installing variable mechanisms.