RESEARCH INTRODUCTION

Flying freely

Aircraft that do not require a runway

A runway is generally required for aircraft to take off or land. In contrast, vertical take-off and landing (VTOL) aircraft can take off and land vertically like helicopters, making runways unnecessary and increasing takeoff and landing flexibility.

Various configurations have been considered for VTOL aircraft. There are aircraft that utilize "vectoring nozzles", which simply direct jet-engine exhaust downward during takeoff and landing, in addition to "tiltrotor" aircraft, which have rotors that are directed upward, like a helicopter, during takeoff and landing and forward while cruising, "tiltwing" aircraft, where the orientation of the wings along with the propellers is changed, and "tail-sitter" aircraft, which take off and land with the airframe in a vertical position, like a rocket. Furthermore, aircraft that use different propulsion systems for takeoff and landing and for cruising are under consideration.

There are major advantages to vertical takeoff and landing. However, there are also issues such as the complexity of the propulsion system compared with that of conventional aircraft in addition to the heavier weight of the engine since the lift generated by wings cannot be used during takeoff and landing, resulting in reduced efficiency.

Unconventionally shaped VTOL flying robots

Wouldn't an unmanned VTOL aircraft configured as a compact flying robot be an extremely useful "tool"? From that perspective, the VTOL aircraft does not necessarily require the shape of conventional aircraft. This can be realized by providing a "propulsion system" for floating and a "control system" for changing course. Therefore, research and development is continuing on a "ducted-fan flying robot" that combines an electric fan (rotor) and a simple control system. (Fig. 1) This aircraft can float by vigorously exhausting toward the back of the fan the air taken in from the front to gain downward thrust. Since the fan is covered by a duct, the aircraft can efficiently achieve thrust without airflow escaping from the side. The airfoil-shaped cross-section of the duct plays a role in the lift that works on the leading edge, enhancing the thrust. Moreover, there is the essential advantage of a high degree of safety of a flying robot since the fan is not exposed.

Control operations such as floating, advancing and stopping are performed by four control vanes arranged after the fan. "Position", "attitude" and "speed", which are information necessary for control, are measured using built-in devices such as "GPS" (refer to page 6), "accelerometer" and "gyroscope", in the same way as with conventional aircraft. Based on this information, the on-board computer moves the control vanes to control the aircraft.

Relationship between fans / compressors and engine weight

Throughout the world, there are not many examples of research on aircraft of this type. For that reason, we first embarked on research with the goal of achieving flight. Figure 2 shows the conditions of the indoor flight test. We were able to verify that flight stabilized through automatic control is possible if there are no disturbances such as wind.

In June 2010, outdoor flight testing (Fig. 3) was conducted at the JAXA Taiki Aerospace Research Field

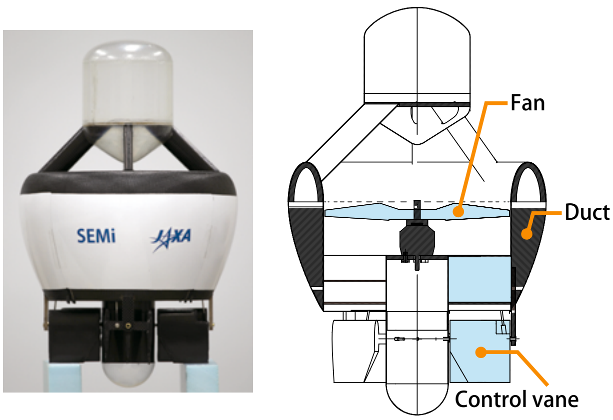
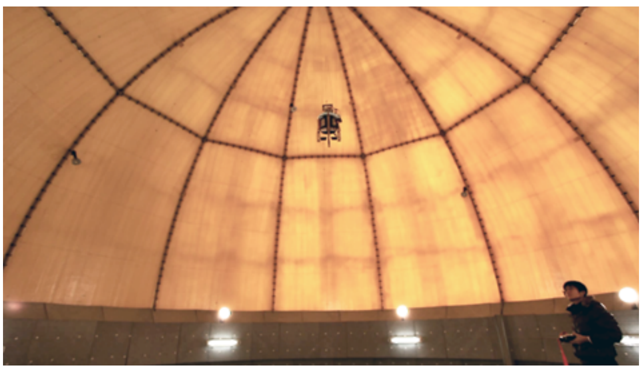


Fig.1 Ducted-fan flying robot



The initial flight test was conducted inside a dome allowing the transmission of GPS signals for control.

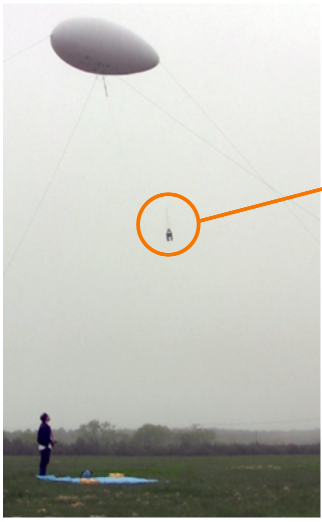
Fig.2 Indoor flight testing

(Hokkaido). With this test, fundamental data was obtained in order to design a control system for ascent. At the same time, verification of the outdoor flight testing method was also performed. In addition, wind tunnel tests continue in order to design the aircraft shape (Fig. 4).

If stabilized flight is shown to be possible in these tests, the next aspect that we must consider is "safety". Since this is an unmanned aircraft, uses in applications incompatible with manned aircraft may also be considered. However, if adequate safety cannot be guaranteed, distant flight out of view of the operator or fully automatic unmanned missions will not be possible. For that reason, the aircraft must be able to fly along a designated course as well as avoid collisions with other aircraft.(*) Furthermore, if it crashes, for example, due to a malfunction, there must be measures to minimize damages. For instance, we believe that we could reduce damage in a crash with an airframe built to be more lightweight while maintaining sufficient strength. In this regard, the study of materials will also be important.

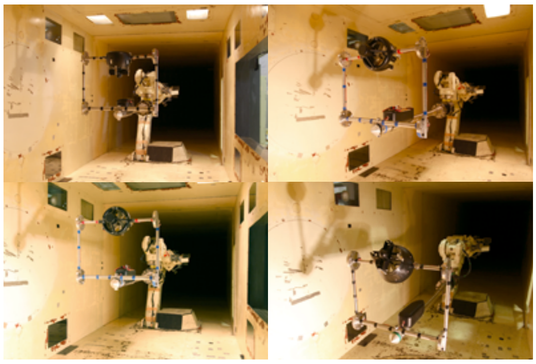
If compact VTOL flying robots were put into practical use, they could play an active role in a variety of situations and applications, for example, to take simple and inexpensive aerial photographs in industrial applications such as agriculture, scientific research and quick surveying of damage at the scene of a disaster. Based on the various testing data that we have obtained, we intend to conduct more precise flight simulations and continue research and development with the aim of establishing airframe design technology and improving flight performance. .

(*) As a method for avoiding collisions with other flying objects, a system of recognizing surrounding features using sensors and automatically evading them is being considered for installation on the aircraft. However, since this would increase the weight of the unit, it would not be suitable for this aircraft, where compact and lightweight features are desired. Meanwhile, JAXA is continuing research and development of the Disaster Relief Aircraft Information Sharing Network (D-NET), a rporating unmanned aircraft into this type of system, where they can operate together organically while avoiding collisions with other aircraft.



The aircraft was hung by a cord from a tethered balloon to prevent it from falling, and tests were conducted with the aircraft hovering and with it ascending to about 7m.

Fig.3 Outdoor flight testing in Taiki, Hokkaido



In order for a ducted-fan flying robot to ascend/descend, move forward/backward and left/right as well as fly freely in all directions at a low speed, it must be able to withstand airflow from various angles. Therefore, measurements were taken in a wide range of attack angles, from -90° to +90° .

Fig.4 Testing of actual models in a wind tunnel (wind speed of 1.5 to 15 m/s)

[Flight Research Center]

Daisuke Kubo

RESEARCH INTRODUCTION

Aircraft flying the Martian sky

Mars exploration methods

In July 1998, Japan launched its first Mars probe, "Nozomi" (Fig. 1). Nozomi's objective was to observe Mars' atmosphere from its orbit. However, the spacecraft experienced various problems during its struggle to reach Mars, and was unfortunately unable to enter Mars' orbit. The Mars exploration methods have consisted in either entering the planet's orbit and observing a wide area from the sky, as with Nozomi, or landing a vehicle such as a rover (Fig. 2) on the planet and directly examining the composition of the ground, for example.

Mars is a planet with many mountains and valleys, including 27-km-high Olympus Mons, which is the highest mountain in the Solar System, as well as Valles Marineris, the largest canyon in the Solar System. There are many cliffs that are difficult to approach with a rover; however, Mars could be studied in more detail if there was a tool that could freely examine such locations. Exploratory aircraft are candidates for this application. Aircraft can observe a wide area at an altitude near the ground surface. They could also land in order to directly examine the ground. (Table 1)

Fig. 1: Mars probe "Nozomi"

Fig. 2: Rover for lunar exploration, developed by JAXA Space Exploration Center

Differences between Earth and Mars

Currently, JAXA is continuing its Mars exploration program aimed at a launch around 2020. With this program, we would first like to demonstrate a verification flight of an exploratory aircraft through Mars' sky.

What must we consider in order to fly aircraft on Mars? Table 2 shows the differences between Earth and Mars. "Lift", the force that lifts up aircraft in the atmosphere, is determined by factors such as the "atmospheric density", "wing area" and "square of velocity".[*] Since Mars' gravity is 1/3 that of Earth, the necessary lift is also 1/3; however, since the atmospheric density is as thin as 1/100th, adequate lift must be achieved by increasing wing area

Table 1: Exploration capabilities

	Orbiter	Rover	Aircraft
Area	Global	10s to 100s of meters	100s of meters to 10s of kilometers
Method	Remote sensing from orbit using a variety of Eelectromagnetic waves	Observation and chemical examination using electromagnetic waves while exploring on the surface	Remote sensing from a low altitude using electromagnetic waves
Observation time for the same location	Depends on the orbit	Long-term observation possible	Depends on the flight conditions

and velocity.

Could a Mars aircraft fly at a high speed to obtain adequate lift? Lift results from the pressure difference above and below the wings, generated by the flow around the aircraft wings. When an aircraft flies in Earth's sky, the flow around the wings is a "laminar flow" upstream, in which the air flows smoothly; however, this transitions midway into a "turbulent flow", in which the flow looks rough and disturbed. Generally, this transition occurs at the front of the wing as the velocity of the aircraft increases. However, in a thin atmosphere, like that of Mars, the flow around the wing tends to remain laminar, even when the aircraft flies at a velocity exceeding the speed of sound. It is fairly difficult for a laminar flow to follow the shape of an object such as a convex surface, due to the balance between its pressure and momentum. Therefore, a situation called "separation" occurs, where the flow separates away from the wing surface. This separation is not favorable since it may suddenly decrease lift, eventually causing a stall (Fig. 3). Any other critical problems that cannot be imagined on Earth could happen on Mars. For that reason, we must gain an understanding of the various phenomena that an aircraft may go through when flying around Mars.

We often utilize a "wind tunnel" to study the aerodynamic characteristics of aircraft. The wind tunnel is a device that simulates actual flight conditions by generating airflow around models, for example, of aircraft. In fact, however, it is difficult to simulate flight conditions on Mars in a wind tunnel built on Earth.(*2)

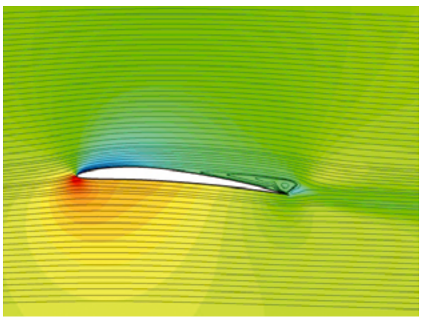
What may happen to Mars aircraft

Our Fluid Dynamics Group employs "computational fluid dynamics" (CFD), an analytical approach for determining airflow conditions and sound expansion, to unravel the aerodynamic phenomena. Figure 4 shows the numerical results of pressure fluctuations occurring around the wing of an aircraft flying at Mach 0.2 (M=0.2; 0.2 times the speed of sound) through the Mars atmosphere with an angle of attack of 4.5° . The red areas indicate a high pressure, while the blue areas indicate a low pressure. At this time, sound is generated from the airfoil edge at a certain frequency; however, this sound wave is fed back into the generation process of vortex fluctuations on the upper surface of the wing, and a resonance called an "acoustic feedback loop" is formed, which leads to a significant increase of both pressure and vortex fluctuations. Therefore, the wing may severely vibrate up and down as its lift greatly oscillates in time. Figure 5 illustrates the resonance states when the Mach number or angle of attack is changed. We can see that the resonance occurs and disappears with slight changes to the Mach number or angle of attack, as the vortex and pressure variations are altered greatly behind the trailing edge of the wing.

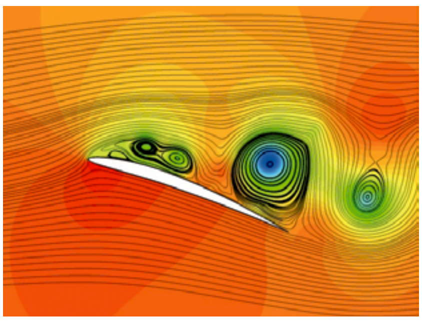
In the design of aircraft for Mars flights, we must eliminate this resonance phenomenon. We are conducting numerical analysis to understand what conditions may bring

Table 2: Differences between Earth and Mars

	Radius (km)	Gravity (m/s^2)	Surfece temperature (K) *1K=273℃	Atmospheric pressure near ground surface (hPa)	Atmospheric density near ground surface (kg/m^3)	Atmospheric composition (%)
Earth	6378	9.8	288.2	1.01×10^3	1.23	N_2 78 O_2 21
Mars	3396	3.7	213	6.1	1.55×10^{-2}	CO_2 95 N_2 2.7



Even with a small angle of attack, separation is observed near the trailing edge of the wing.



When the angle of attack is increased, the airflow separates from the leading edge of the wing, which leads to a stall.

Fig. 3: Separation in laminar flow

the feedback process of a sound wave to a critical level of the resonance state. By doing so, we can contribute to the development of a system with which the aircraft can autonomously prevent this situation in case lift oscillation actually arises from an acoustic feedback loop.

(*1) Lift can be determined by the following equation.

$L=1/2 \cdot C_L \cdot \rho \cdot V^2 \cdot S$

A larger lift can be achieved with a larger lift coefficient (C_L), density (ρ), velocity (V) or wing surface (S). If the wing shape is the same, C_L depends on the angle of attack. If the angle of attack is increased, C_L also increases; however, once the angle of attack exceeds a certain value, C_L begins to decrease sharply.

(*2) **In conventional wind tunnel testing, a scaled-down model of the actual device is used, and the test is conducted according to either the "Reynolds number" (Re) or the "Mach number" (M) in order to simulate actual flight conditions. The Reynolds number is the ratio of inertial forces to viscous forces involved when air flows around an object. By matching the Reynolds number, the flow phenomena governed by viscous forces, such as separation and turbulent flow transition, are supposed to be identical to the actual device. On the other hand, the Mach number, the ratio of the flow speed to the speed of sound, represents the magnitude of pressure fluctuations around the airframe or the effects of gas compressibility. Since the Reynolds number becomes lower in the thin atmosphere of Mars than on Earth, to meet the Reynolds number requirement, the size of the model must be reduced a great deal in addition to decreasing the airflow speed. In contrast, if a high-speed flight is assumed to obtain a sufficient lift, we must match the Mach number, which results in an even larger Reynolds number. For this reason, in order to accurately simulate flight conditions on Mars, the pressure in the wind tunnel must be lowered to actually accomplish the low-density flow, as is done in the "planetary wind tunnel" at JAXA's Institute of Space and Astronautical Science or in the "Mars wind tunnel" being developed at Tohoku University.

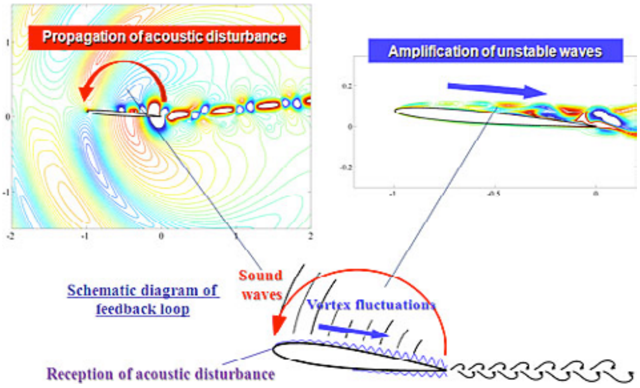


Fig. 4: Pressure field in a low-density flow around the wing ($M=0.2$, $\alpha=4.5$, $Re=10,000$)

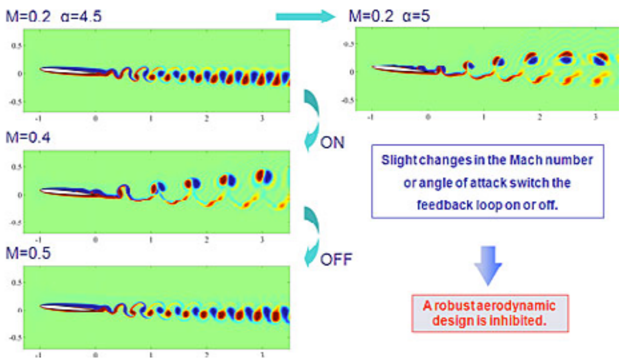
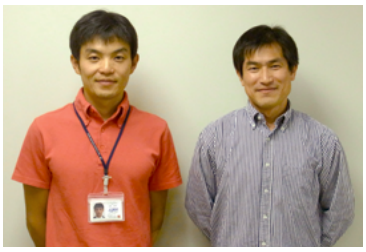


Fig. 5: Onset of the resonance phenomenon through acoustic feedback loop (Re=10,000)



[Fluid Dynamics Group]

(from left) Tomoaki Ikeda, Takashi Atobe

Intermission Break

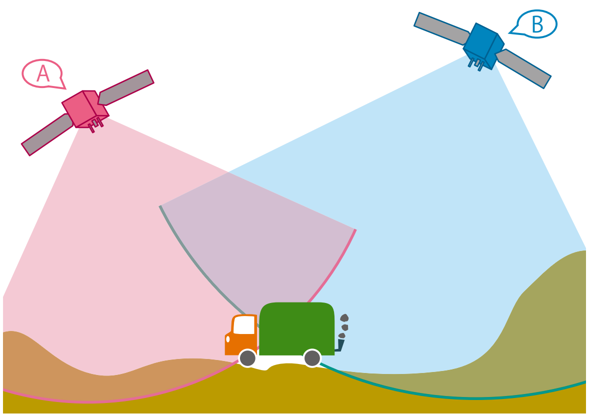
Global Navigation Satellite Systems (GNSS)

■ Systems that know your "position"

With personal navigation systems used in car navigation systems and cell phones, systems that know your position have rapidly spread over the past few years. These use the Global Positioning System (GPS), developed in the United States. GPS is comprised of artificial satellites emitting radio waves, ground control stations controlling those satellites, and receivers, which receive the radio waves. As of January 2009, 31 artificial satellites have been launched, with four or more in each of six orbits at altitudes of about 20,000 km. At all times, four or more satellites can be seen from anywhere on Earth if there are no obstructions, such as high-rise buildings.

■ Principle of GPS positioning

GPS satellites emit radio waves including Coordinated Universal Time (UTC) data, provided by the US Naval Observatory (USNO). The radio waves broadcasted from satellites at a specific time arrive slightly delayed at receivers incorporated into car navigation systems or cell phones equipped with GPS features. Since a distance can be determined as the product of the speed of the radio waves and the length of time that it takes for the radio waves to arrive, the distance between the satellite and receiver can be determined from this time difference. By receiving radio waves emitted from three or more satellites at a specific time, the distance to each satellite can be determined, and we are able to find the receiver's location. (Fig. 1) However, if the clock in the GPS receiver is not accurately synchronized with UTC, radio waves from a fourth satellite are required to adjust for this margin of error..



The radio waves emitted from satellite A at a specific time are received. The distance to satellite A can be determined as the product of the speed of the radio waves and the length of time for the radio waves to arrive after being emitted. By determining the distance to satellite B for the same time in the same way, the point where the distances intersect, in other words, your position, can be determined.

Fig.1 Principle of GPS positioning (two dimensional)

■ Various GNSS and the Quasi-Zenith Satellite System (QZSS)

GPS, which was developed in the United States, is a well-known Global Navigation Satellite System (GNSS); however, there are others, such as Galileo, developed in Europe, and the Russian GLONASS.

JAXA is embarking on construction of a system where one satellite is positioned over Japan at all times by combining multiple "quasi-zenith satellites" with an orbit nearly along the zenith (i.e., directly above) of Japan. By adding the radio waves emitted from quasi-zenith satellites nearly overhead, a location can be accurately determined, even if multiple GPS satellites are not visible, for example, in mountainous regions and around high-rise buildings in inner urban areas.

Fig.2 "Michibiki", first quasi-zenith satellite to be launched this summer