



MICRO-SIZE MARS AIRPLANE FOR THE STEPWISE MARS LANDING EXPLORATION PROGRAM

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Abstract

Mars flight exploration mission using a micro-size Mars airplane for the Mars cube service that will be provided by the first mission of the stepwise Mars landing exploration program is proposed and the feasibility study of the airplane is presented. We assume the airplane, the deployable aeroshell and deorbiter are stored in a volume of 3 units (30 cm x 10 cm x 10 cm) and the weight of the airplane is 1 kg. Because of the severe size and weight limitation, we design a glider-type micro-size Mars airplane without any propulsion system, that adopts rigid wing. The present feasibility study shows that the design of micro-size Mars airplane that flies more than 20 km is possible.

Keywords: Mars Airplane, Micro Air Vehicle, Unmanned Airplane, Aircraft Design

1. Introduction

Airplane that flies in the Martian atmosphere (hereafter referred to as “Mars airplane”) is being considered as a new platform for Mars exploration. The Mars airplane will enable wide-area and high-resolution observation of the residual magnetic field, observation of dust distribution in the atmosphere, investigation of cliffs and underground cavities that a rover cannot reach, and so on. Therefore, various types of Mars airplane (for example, [1, 2]) have been studied by NASA, JAXA, and others. However, none of them has been realized due to technical difficulties.

Because Mars' atmospheric density is only about 1/100 of that of Earth's, the lift produced by a wing also becomes about 1/100. Although the gravitational acceleration on Mars is smaller than on Earth (3.7 m/s^2), it is necessary to make the airplane very light. In addition, because the Reynolds number also becomes approximately 1/100 of that on Earth, revolutionary aerodynamic design of the Mars airplane is required with good performance at a low Reynolds number flight condition. Furthermore, because no Global Navigation Satellite System is serviced on Mars and Mars does not have a strong magnetic field, identification of the position and attitude of an airplane is also a challenging technology problem. However, it is meaningful to improve the technology of airplanes designed for flight on Mars, because it is possible to obtain data on Mars over a wide range by conducting Mars

exploration by airplanes. Therefore, it is necessary to conduct flight experiments on Mars to demonstrate the technology of the Mars airplane.

Recently, stepwise Mars landing exploration program is discussed by Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency [3]. The first mission of the program is scheduled to be launched around 2030. In the first mission, multiple small landers will be deployed from the orbiter using deployable aeroshell technology [4]. In addition to that, Mars cube service will be provided where multiple CubeSats will be released to Mars orbit.

In this study, a Mars flight exploration mission using a micro-size Mars airplane is proposed and a conceptual design of the airplane is presented. Because of the severe size limitation, this micro-size Mars airplane is a glider without any propulsion system. This mission assumes to use the Mars cube service of the first mission of the stepwise Mars landing exploration program.

2. Mission plan

The objective of this mission is technological demonstration of Mars airplane. Although the purpose of scientific observation using the micro-size Mars airplane has not yet been determined, here we assume dust observation. We mention dust observation as an example of scientific observation because dust, which is always present in the Martian atmosphere, greatly affects the structure of atmospheric circulation, it is very important to understand the properties of dust in order to understand the Martian meteorology. The Mars airplane is expected to provide information on the vertical distribution of dust concentration in the lower atmosphere, for which direct observation data have not been available to date. In addition, because the Mars airplane fly fast relative to the dust advection velocity, it is expected to measure the dust particle size from the advection momentum when the dust impacts the instrument as the size of the instrument is reduced in the future [5]. Therefore, a particle sensor for dust observation is assumed as the science payload.

Here, 3U-size (300mm x 100mm x 100mm) Mars airplane mission system is considered (Fig. 1). This system is based on the 3U-size nanosatellite BEAK (Breakthrough by Egg-derived Aerocapture Kilt vehicle) [6], which was released from the International Space Station on December 18, 2023 to demonstrate breakthrough technologies using deployable aeroshells for future planetary exploration. The size of the deorbiter system is assumed to be 1U and a deployable aeroshell using shape memory alloy (hereafter referred to as “SMA aeroshell”) is adopted. Here, the deployable SMA aeroshell is octagonal shaped and using a fiber called ZYLON. As a result, the micro-size Mars airplane needs to be folded to fit into a volume of 70mm x 70mm x 180mm.

After being released from the Mars orbiter, this system will be transferred to a Mars landing trajectory using the deorbiter. It will then be slowed down to a subsonic speed by the deployable SMA aeroshell. The micro-size Mars airplane is separated from the aeroshell to start its flight in the air. At the end of the flight, the airplane deploys a parachute to makes a soft landing on the ground for flight data and science data transmission to the satellite.

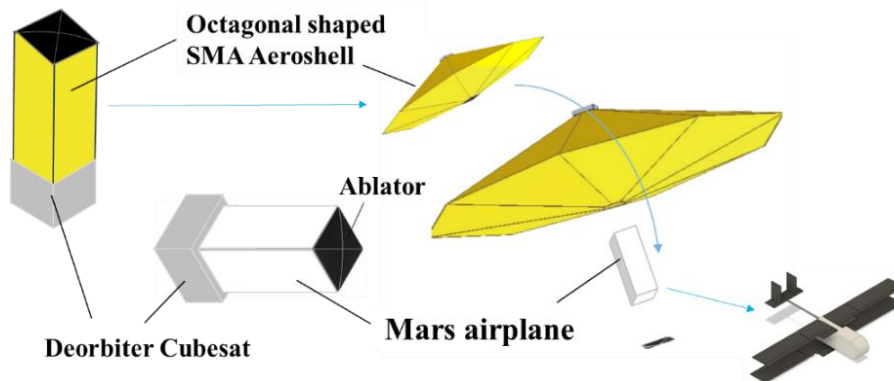


Figure 1 – 3U-size Mars airplane mission system.

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Here, the Hellas Planitia is selected as the flight area because of its low altitude and higher atmospheric density, that makes the flight easier. Because the minimum surface altitude in the Hellas Planitia is approximately -7 km, the airplane continues its flight down to -6 km, then the parachute is deployed for the landing.

3. Orbit calculation for the deployable SMA aeroshell

In considering the design of the micro-size Mars airplane, the deployable SMA aeroshell's orbit calculation is conducted. The aeroshell is responsible for withstanding aerodynamic loads and aerodynamic heating during entry into the Martian atmosphere from Mars orbit. Table 1 shows the specifications of the entry system.

Table 1 – Specifications of the deployable SMA aeroshell

Total weight m [kg]	2.0 (Aeroshell's weight is 1.0)
Diameter [m]	1.2
Front projection area [m ²]	1.13
Drag coefficient	1.0 (when the aeroshell is open)

The low ballistic coefficient of the deployable SMA aeroshell allows for efficient aerodynamic deceleration, resulting in the descent near the Mars surface under the conditions shown in Fig. 2 and Table 2. Figure 2 shows the result of the aeroshell's flight path near the Mars surface. When the Mars airplane detaches at the altitude of 5 to 10 km, the speed is estimated to be 40 to 50 m/s. Based on this result, the initial velocity to be used in the Mars airplane flight simulation is set to the values shown in Table 2.

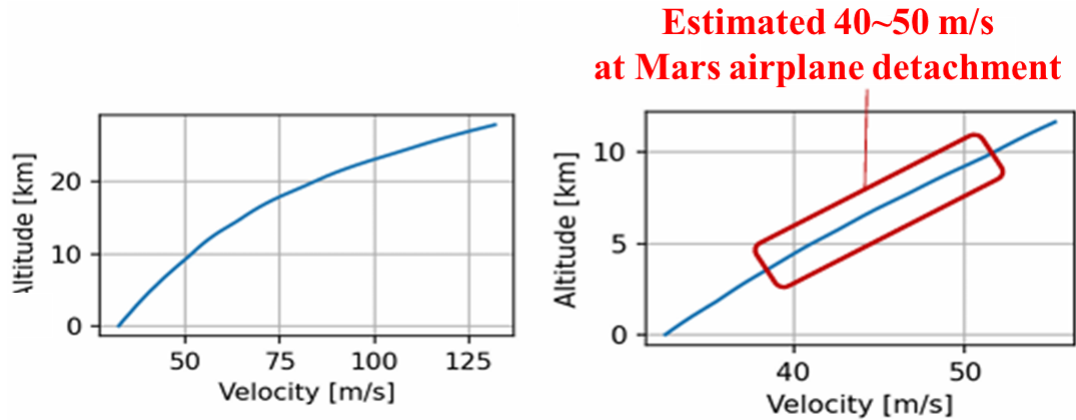


Figure 2 – The flight path of the deployable SMA aeroshell

Table 2 – Initial altitude and velocity of the Mars airplane.

Initial altitude [km]	Initial velocity [m/s]
5	39
10	52
15	64
20	82

4. Conceptual design of the micro-size Mars airplane

The conceptual design of the micro-size Mars airplane considered here is based on the following design principles.

- The Mars airplane needs to be folded to fit into a volume of 70mm x 70mm x 180mm.
- The Mars airplane weight is limited to 1 kg.
- The Mars airplane is a glider without a propulsion system due to the severe size limitation.
- The fuselage volume should be large enough to accommodate all equipment.
- To increase static stability, the vertical and horizontal tail wings are adopted.

The Mars airplane designed here is shown in Fig.3. This airplane is a biplane to increase wing area. To eliminate uncertainties in the aerodynamic characteristics of the airplane, the airplane adopts a rigid airframe without flexible membrane wings. Its fuselage size is 40 mm x 60 mm x 175 mm so that the required equipment such as processors, transmitter, science payload, sensors and battery can be stored.

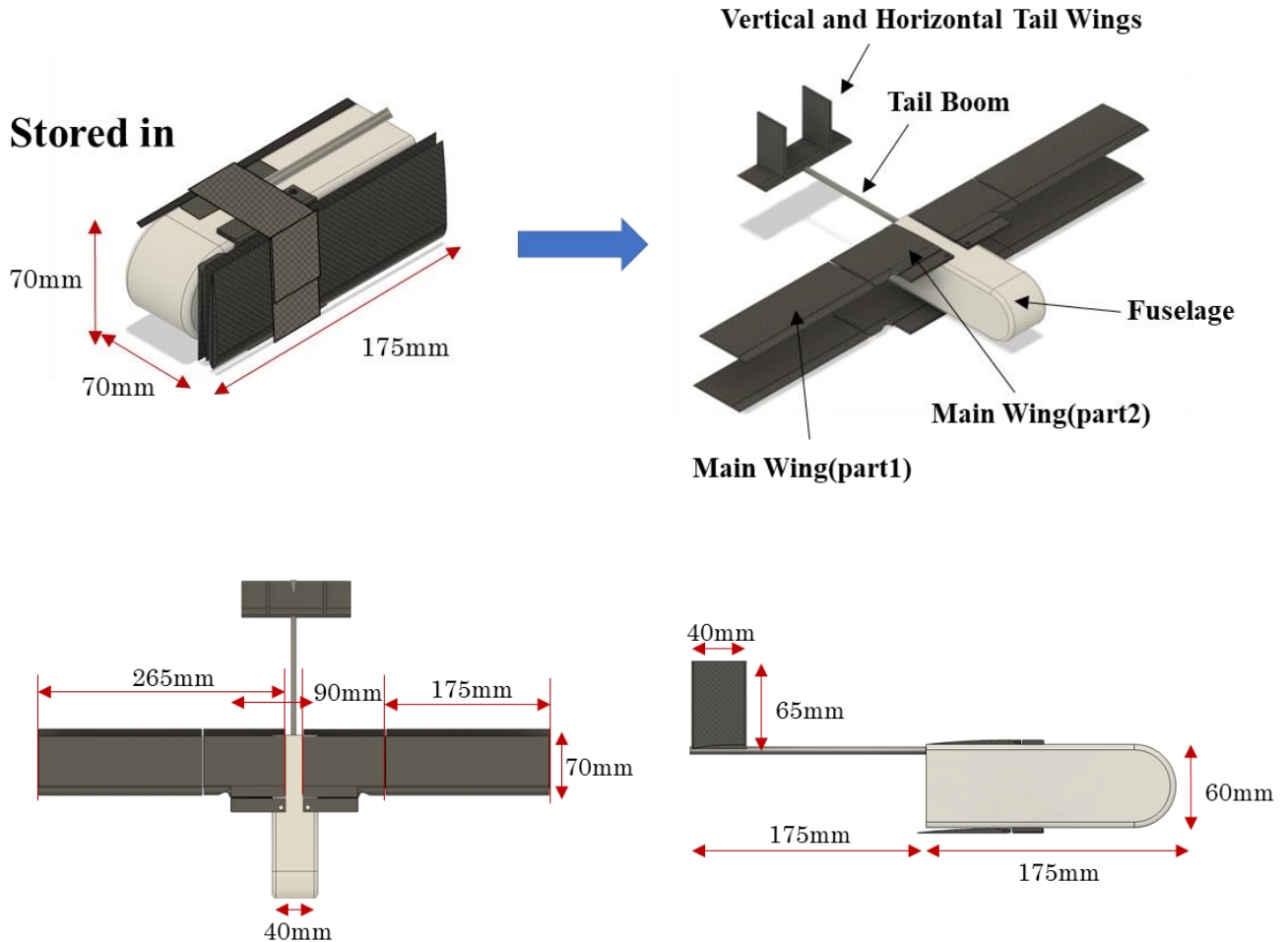


Figure 3 – The 3U-size Mars airplane designed here.

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Figure 4 shows the deployment sequence of the airplane. The main wings are deployed by using single-axis spring hinges at its folding part. When the main wings are deployed, the hinges' location on the upper wing is in the positive direction of lift generation, so it is required to deploy under low dynamic pressure conditions.

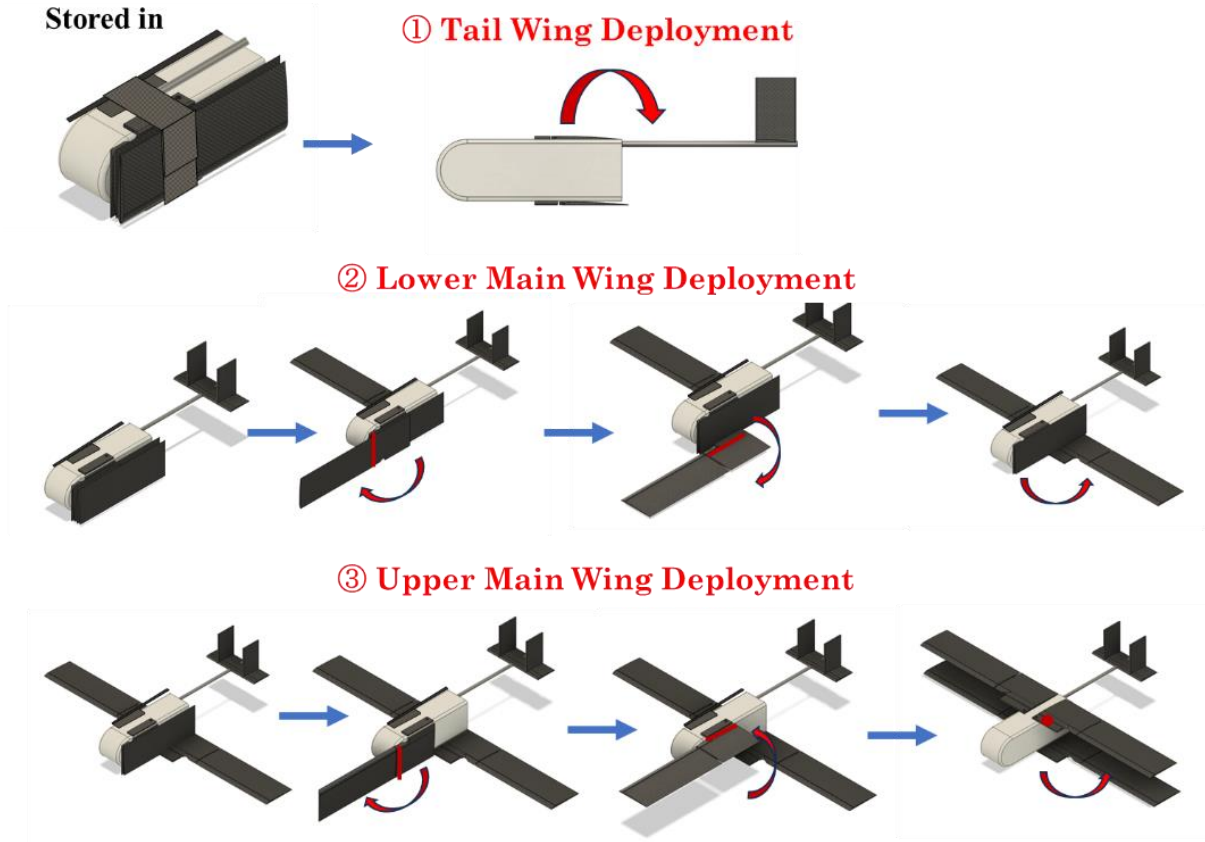


Figure 4 – The airplane deployment sequence.

5. Aerodynamic evaluation of the current design by using flight simulation

Now, a flight simulation is conducted to estimate the aerodynamic performance to satisfy the design constraints shown in Table 3. The input parameters are the wing lift coefficient C_{L_w} , the wing drag coefficient C_{D_w} , initial flight Mach number $M_{initial}$ and position of the center of gravity X_{cg} . The center of gravity position is on a coordinate system which has the origin at the top of the nose and the axis in the chord direction. The design constraint on the glide distance is set to a value sufficient for the horizontal scale of convection cell in the boundary layer of the Martian atmosphere.

Table 3 - Design constraints

	Range
Airplane total weight m [kg]	≤ 1
Mass margin [%]	≥ 10

First, the glide distance is estimated using Equations (1) and (2).

$$m \frac{dV}{dt} = -\frac{1}{2} \rho V^2 (C_{Dw} S_w + C_{Df} S_f) + mg \sin \gamma \quad (1)$$

$$m \frac{d\gamma}{dt} = -\frac{1}{2} \rho V C_{Lw} + \frac{mg \cos \gamma}{V} \quad (2)$$

where S_w is the main wing area and tail wing area [m^2], C_{Df} is the drag coefficient of the fuselage and S_f is the reference area of the fuselage. The airfoil type is 6% triangular airfoil (Fig. 5), which is known to have good aerodynamic performance when Reynolds number is less than 10,000.

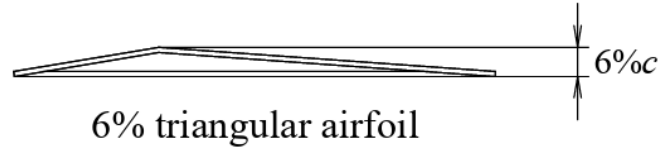


Figure 5 – 6%c Triangular Airfoil Shape [9]

The aerodynamic characteristics of the wing is estimated from equation (3), (4) and (5).

$$C_{Lw} = \frac{a_0}{1 + \left(\frac{a_0}{\pi AR}\right)(1 + \tau)} (\alpha - \alpha_0) = \frac{2\pi}{1 + \left(\frac{2\pi}{\pi AR}\right)(1 + \tau)} (\alpha - \alpha_0) \quad (3)$$

$$C_{Dw} = C_{D0} + \frac{CL^2}{e\pi} \left(\frac{S}{2b^2}\right) (1 + \sigma) \quad (4)$$

$$C_{Df} = C_{fb} + C_{bp} \quad (5)$$

where C_{Lw} and C_{Dw} are the lift and drag coefficient of the biplane wing. a_0 is lift inclination of the triangular airfoil in two dimensions, and AR is aspect ratio. α_0 [rad] is angle of attack at the airfoil lift coefficient is 0. Also, angle of attack α [rad] and the lift coefficient CL are the value at the maximum lift-to-drag ratio of the airfoil. C_{D0} is the parasite drag coefficient in the laminar flow area. C_{Df} is set to 1.1 based on the experimental value by Nagaguchi et al. [10]. The atmospheric density ρ depends on the altitude H [m] and is estimated from equation (6) [11].

$$\begin{cases} T[K] = -31 - 9.98 \times 10^{-4} \times H \\ p[Pa] = 0.699e^{-9 \times 10^{-5} \times H} \\ \rho[kg/m^3] = \frac{p}{0.1921 \times (T + 273.1)} \end{cases} \quad (6)$$

The results of the micro-size Mars airplane flight simulation are shown in Fig. 6 and Fig. 7. The aerodynamic characteristics of the Mars airplane were set to the condition for the maximum lift-to-drag ratio, and the trajectory was calculated with $\alpha = 5.5$ [deg], $CL = 0.465$, $CD = 0.0434$. Table 5 shows the flight distance and flight time for each detachment condition. Advantage of selecting the low altitude Hellas Planitia is clear with much larger flight distance and flight time. This table also shows that the higher the Mars airplane detachment altitude, the longer the flight distance and time it can achieve. Since this simulation assumes a mass point, the airplane has a flight trajectory in which it flies while exchanging potential and kinetic energy, as shown in Fig. 7. When the airplane actually flies, a navigation control is performed to achieve smooth flight.

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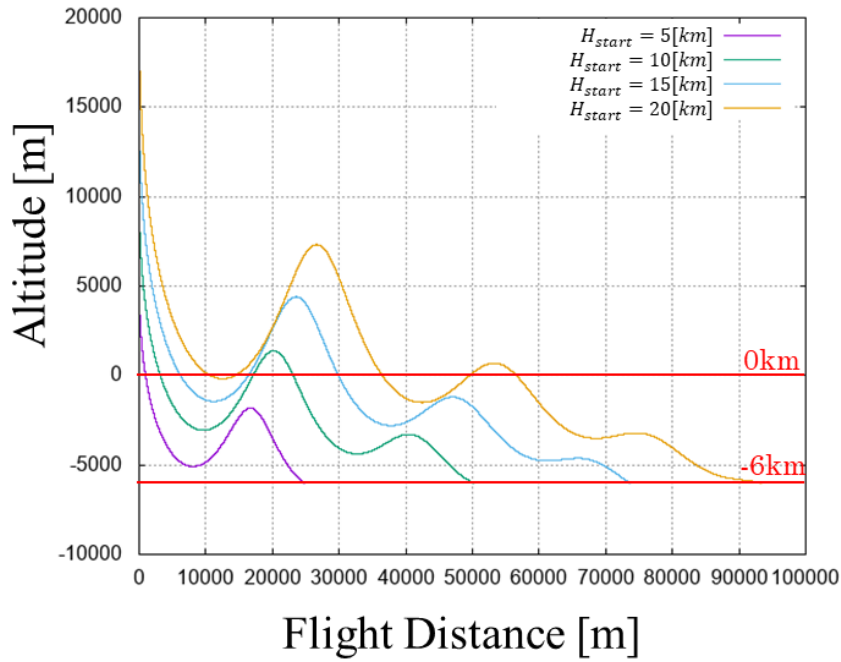


Figure 6 – The flight path of the micro-size Mars Airplane

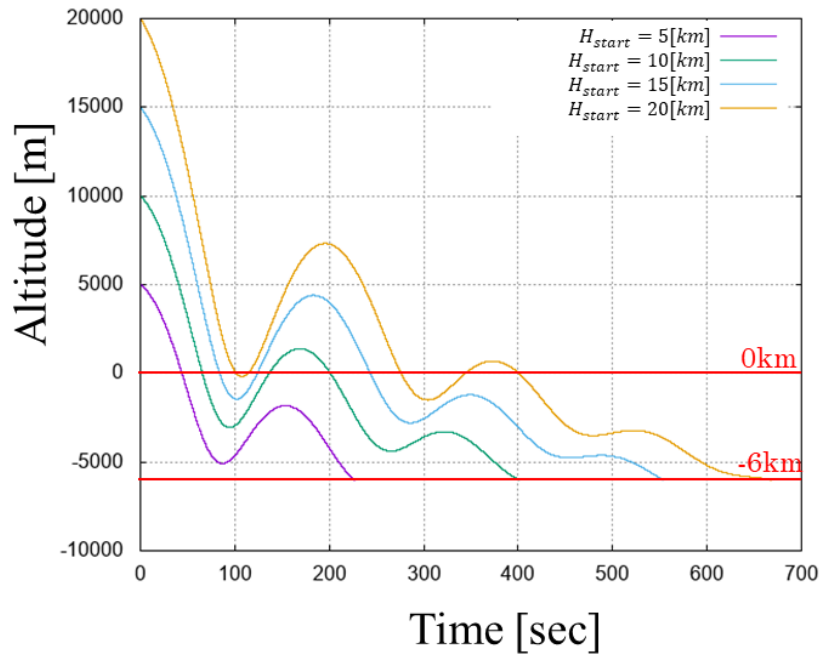


Figure 7 –Time history of the flight altitude of the micro-size Mars Airplane

Table 5 - Flight Distance and Flight Time for each condition

Terminal altitude [km]	0		-6	
Detachment altitude [km]	Distance [km]	Time	Distance [km]	Time
5	9.5	0'44"	24.8	3'47"
10	23.1	3'21"	50.2	6'41"
15	29.9	4'03"	73.6	9'13"
20	56.6	6'40"	93.4	11'08"

Figures 8 and 9 show the Reynolds number and Mach number histories of the micro-size Mars airplane, respectively. Figure 8 shows that the Reynolds number is less than 10,000 no matter what detachment altitude. Therefore, the triangular airfoil type is suitable for the micro-size Mars airplane.

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Figure 9 shows that the Mach number becomes supersonic speed immediately after detachment at a detachment altitude of 10km or higher. Therefore, there is a tradeoff between maximization of flight distance and minimization of the maximum Mach number. At transonic and supersonic speeds, the aerodynamic coefficients are expected to deviate from the model assumed in this study, and the shock wave may increase drag and reduce the flight distance.

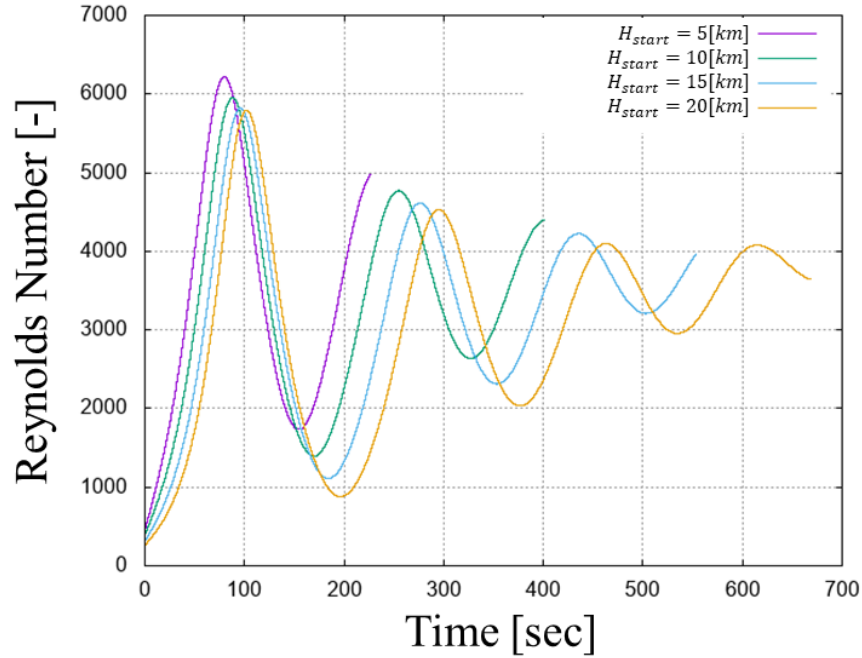


Figure 8 –Reynolds Number history of the micro-size Mars Airplane

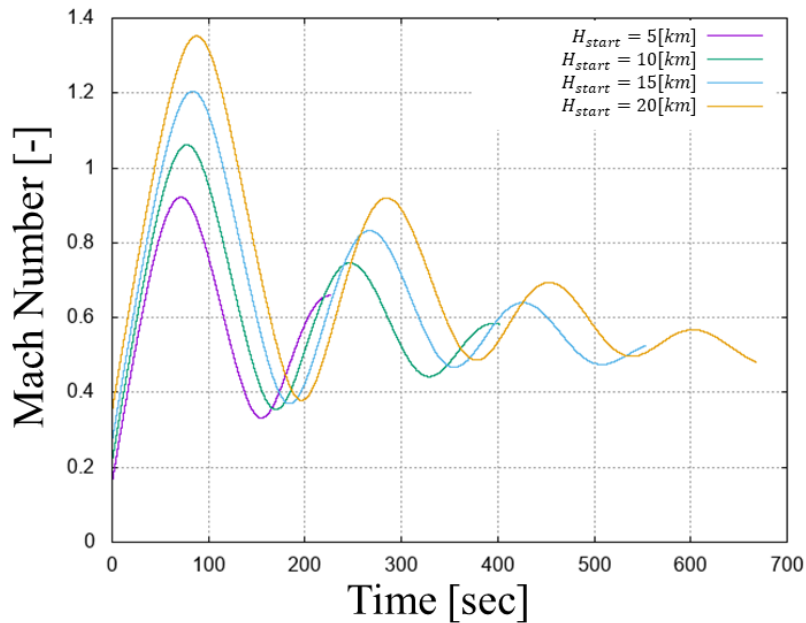


Figure 9 –Mach Number history of the micro-size Mars Airplane

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Figure 10 shows the lift of the Mars airplane. Lift changes during the flight depending on the flight altitude (air density) and flight speed (dynamic pressure) of the Mars airplane. Because gravity on Mars is 3.71 m/s^2 , the maximum lift can be 3G or more. Therefore, structural design with sufficient strength and rigidity is also important.

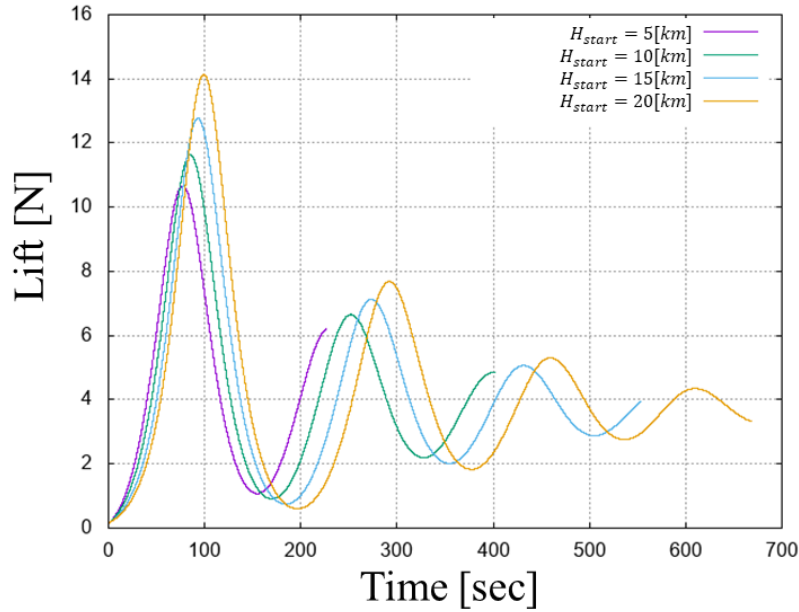


Figure 10 –Lift history of the micro-size Mars Airplane

6. Conclusion

A micro-size Mars airplane flight exploration mission using the Mars cube service that will be provided by the first mission of the stepwise Mars landing exploration program of Japan was proposed and the feasibility study of the airplane was presented. We assumed the airplane, the deployable SMA aeroshell, and deorbiter are stored in a volume of 3 units (30 cm x 10 cm x 10 cm) and the weight of the airplane is 1 kg. Because of the severe size and weight limitation and eliminating uncertainties in the aerodynamic characteristics of the airplane, we designed a glider-type micro-size Mars airplane without any propulsion system, that adopts a rigid airframe without flexible membrane wings. The present feasibility study showed that the design of micro-size Mars airplane that flies more than 20 km is possible.

7. Acknowledgments

We thank Tatsuki Horii of Aeroflex for the idea of the deployment mechanism of the Mars airplane.

References

- [1] Braun R D, Wright H S, Croom M A, Levine J S and Spencer D A. Design of the ARES Mars airplane and mission architecture. *Journal of Spacecraft and Rockets*, Vol. 43, No. 5, pp 1026-1034, 2006.
- [2] Nagai H and Oyama A. Development of Japanese Mars Airplane. *Proc 67th International Astronautical Congress*, Guadalajara, Mexico, 2016.
- [3] Yamada K and Nagata Y. Conceptual study of EDL system using inflatable aeroshell for stepwise Mars landing exploration program. *Proc 20th International Planetary Probe Workshop*, Marseille, France, 2023.
- [4] Yamada K, Nagata Y, Abe T, Suzuki K, Imamura O, Akita D. Suborbital Reentry Demonstration of Inflatable Flare-Type Thin-Membrane Aeroshell Using a Sounding Rocket. *Journal of Spacecraft and Rocket*, Vol. 52, No. 1, pp 275-284, 2015.
- [5] Kobayashi M, Krüger H, Senshu H, Wada K, Okudaira O, Sasaki S, Kimura H. In situ observations of dust particles in Martian dust belts using a large-sensitive-area dust sensor. *Planetary and Space Science*, Vol. 156, pp 41-46, 2018.
- [6] Nagata Y, Moriyoshi T, Yamada K, Akiyama F, Ota T, Miyamori T, Matsuo K, Ueshima H, Fujiwara, Imamura O, Shoji Y, Akita D, Watanabe Y, Suzuki K. Development and Flight Plan of Nanosatellite BEAK for Breakthrough Technology Demonstration Using Deployable Aeroshell. *2nd International Conference on Flight Vehicles, Aerothermodynamics and Re-entry Missions and Engineering, FAR2022*, Heilbronn, Germany, 2022.
- [7] Cruz J R, Way D W, Shidner J D, and Davis J L, Adams D S and Kipp D M. Reconstruction of the Mars Science Laboratory Parachute Performance. *Journal of Spacecraft and Rockets*, Vol. 51, No. 4, pp 1185-1196, 2014.
- [8] ESA, “https://www.esa.int/Education/CanSat/Design_your_parachute_A_Guide_to_Landing_Your_CanSat_Safely_Teach_with_Space_T10”, Retrieved 15 June 2024.
- [9] Shiozaki Y and Okamoto M. Reynolds number dependence of airfoil shape. *The 48th Annual Meeting of Japan Society for Aeronautical and Space Sciences*, Tokyo, Japan, 2017.
- [10] Nakaguchi H, Hashimoto K and Muto S. An experimental study in aerodynamic drag of rectangular cylinders. *Japan Aeronautical Space Science*, Vol. 16, No. 168, pp 1-5, 1968.
- [11] NASA, “<https://www.grc.nasa.gov/WWW/K-12/airplane/atmosmrm.html>”, Retrieved 15 June 2024.

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