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学位論文題目	Studies on a Mars Airplane with Aerial Deployment Technique (空中展開技術を利用した火星探査飛行機に関する研究)
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## 論文内容要約

Recently, much attention has been given to exploring Mars for research on the physical and biological origins of the Solar System. JAXA is currently considering the Mars exploration mission MELOS (Mars Exploration with Lander-Orbiter Synergy). This mission involves conducting multiple explorations with several probes. In this way, interest in Mars exploration has been growing steadily every year.

In the past, rovers and satellites have mostly been used to explore Mars. The former can obtain high-resolution data, but the area of exploration is narrow. The latter can explore vast areas but the obtained data are of low resolution. Because of these limitations, the use of airplanes is being seriously considered at NASA as a new method of exploring Mars. They offer the possibility of obtaining high-resolution data on a regional scale of several hundreds to thousands of kilometers, which cannot be achieved with rovers or satellites. When attempting to measure the total effects of the surroundings from all positions, for example measuring magnetic fields or gravitational fields in particular, the altitude has a powerful impact on spatial resolution of the distribution of the objects of the observations. In addition, a Mars airplane would fly in the open sky, unlike past exploration methods. Therefore it will be able to perform three-dimensional direct observations of the atmosphere by measuring wind speed, density, or temperature and by collecting the atmosphere or dust. In this sense too, Mars airplanes would be superior to other types of space probes. Mars airplanes would permit one more new type of observation: monitoring the geological strata exposed on scarps. It is difficult for surface based rovers to land on topography such as scarps. Even when they have landed on a safe flat surface, they lack the capacity to travel to distant scarps. On the other hand, satellite probes observe the surface from a great height, so they cannot observe geological strata exposed on scarps. However, a Mars airplane would be able to investigate the origins of Mars by flying through valleys such as the Valles Marineris (Mariner Valleys) observing the geological strata on the scarps from the side.

One of the biggest problems with using an airplane is the very low atmospheric density on Mars; it is only 0.7% the atmospheric density on Earth. Therefore, the aerodynamic characteristics are quite different from those on Earth because of the flow at low Reynolds numbers. In addition, such a low atmospheric density makes it difficult to obtain the required lift because the required wing area is inversely proportional to the density. The weight needs to be thoroughly reduced to achieve the required lift. A Mars airplane needs a large wing area, which leads to another problem. For transport to Mars, the airplane must be small and compact. To solve

these conflicting problems, the Mars airplane needs a deployment mechanism for the wing. In addition, aerial deployment techniques are suitable for the Mars airplane because they eliminate the need for a takeoff system and take advantage of the initial altitude. Because of these reasons, several design concepts for a Mars airplane plan for deployment in the air. However, the aerial deployment motion is complex and can fail because of the aerodynamic and inertial forces during deployment.

A conceptual design is vital to develop a difficult and special airplane such as a Mars airplane. A conceptual design is necessary to study the feasibility of creating an airplane that satisfies all these varied demands. It is important to perform a conceptual design to make educated guesses to the questions, “What form is suitable?”, “What airplane concept will work?”, and “What are the important variables for its design?” Grasping such vital points of the design early in the development process will permit the designers to easily optimize the detailed design and airplane specifications at the same time as they avoid serious failures. As this shows, the conceptual design is a vital matter that will govern future airplane development.

Another problem with aerial deployment is the great variability of conditions during deployment. One variable factor during deployment that must be considered is surrounding gust wind. If the entry capsule is surrounded by powerful and widely varying winds, there is a danger that aerial deployment of the airplane will fail as its behavior changes abruptly during deployment. The deployment mechanism must of course be strong and light, and must also ensure reliable deployment in midair.

The objective of this research was to propose a Mars exploration airplane using aerodynamic deployment technology while considering the low Reynolds number flow field and aerial deployment mechanisms. Three studies were conducted: (1) the conceptual design of the Mars airplane, (2) simulation of the aerial deployment behavior, and (3) robust optimization of the deployment mechanism. Based on the results of these studies, a design for a Mars airplane is proposed.

First, a conceptual design method was developed for a Mars airplane. This method is based on the conventional design method, and special considerations of the low Reynolds number flow and deployment mechanism were added. A mission scenario, design conditions, and constraints were defined for the design of the specifications. The design method has five stages: aerodynamic and geometric properties, propulsion, power, basic mass, and mass of the deployment mechanism. The specifications of the airplane are calculated through iteration of these five stages. The aerodynamic characteristics of the wing were determined based on an experiment under a low Reynolds number condition. The characteristics at the maximum lift-to-drag ratio were extracted from the experimental results and then formulated as a function of the Reynolds number and aspect ratio. The relationship between the lift to drag ratio, Reynolds number, and aspect ratio for low Reynolds number was clarified to indicate that within the range of the Mars airplane being considered high aspect ratio would provide higher performance both in terms of aerodynamic characteristics and airframe specifications. In terms of the consideration for the deployment mechanism, conceptual design methods for the deployment methods of both the folding type and inflating type deployable wings were formulated and the design results were compared. The comparison showed that the folding type was lighter than the inflating type, especially for long spans. Therefore, the folding type was selected, and the number and positions of the hinges were designed from a planform. Parametric studies were performed on eight input design

variables next. As a result, the battery mass was the only one among these that indicated a tradeoff relationship for the two objective functions of the total mass and the cruising range. The remaining variables simply needed to be maximized, minimized or otherwise set to an optimum value between the two. A range of solutions and typical designs were then developed. The proposed aircraft has a total mass of 7.8 kg and the cruising range of 54 km. In a design with the deployment torque scale  $F$  set to 1, however, the deployment mechanism was heavy and the deployment mechanism mass comprised about 22 % of the total mass. Parametric studies were then performed on technical variables to provide a guideline for research and development in the future. This resulted in the quantitative indication on how the results of technical developments, such as reduction of deployment mechanism mass, could impact airframe specifications. Furthermore, as the consideration for the mission beyond the scope of the assumed various missions, the tradeoff relationships of the dimensions of the airframe, the total mass, the payload mass, as well as the cruising range were clarified and the range of design solutions were presented.

Second, the dynamic behavior of an airplane during aerial deployment of a folding-type wing was analyzed through numerical simulation. The simulation method was developed using the theory of multibody dynamics. The airplane with the folding-type deployable wing was modeled as a three rigid bodies connected by the hinges. The equation of motion for this airplane model was obtained using the theory of the multibody dynamics. The gravity, aerodynamic force, deployment torque, and binding force were acted as external forces and torques. The aerodynamic characteristics were based on the total aerodynamic characteristics of the flat plate at low Reynolds number experiment. The aerodynamic forces were independently acted on the center wing, right wing, left wing, horizontal tail, and vertical tail. This aerodynamic model can be used at low Reynolds number flow and post-stall angle of attack. The dynamic derivatives concerning rotation were approximately and automatically introduced as a nature of the multibody dynamics. Note that the interference of the flow around the wings was ignored.

The constructed simulation method was then validated. The simulation method created by this study was able to correctly calculate flight motion with wings deployed. The result of the verification of multibody motion indicated that there was a close match between the simulation and experiment. Finally, the wing deployment motion of a spring-hinge folding-wing model airplane in free fall was compared with simulation as a verification of multibody motion with aerodynamic forces acting. The simulation condition was modified in the range of the expected error. The results indicate that the created simulation method was able to provide a good representation of wing deployment motion in midair. If the deployment torque scale  $F$  is at least 0.7, this simulation method's aerodynamic model can likely be used for the aerial deployment motion of wings.

The qualitative nature of the behavior was clarified through various conditions of the simulation. Especially, the history of the deployment angles of the right and left wings and the roll motions of the center body was focused on in the analysis. The result of the symmetry analysis indicates that high symmetry deployment by shortening right wing deployment delay time  $T_{SR}$  can reduce the roll motion. The result of the deployment torque analysis indicates that the amount of change of the roll angle increased and the extremal value of the roll rate decreased and the amount of the time required finishing deployment increased as the deployment torque scale  $F$

decreased.

The safe deployment judgment condition was defined. The dynamic behavior of an aerial wing deployment at nominal condition was reported as a successful example. The sensitivity analysis for each single variable was performed. Successful input range, and lower and upper constraints are revealed. The most sensitive condition was the hinge reaction moment. The successful range of the right wing deployment delay time  $T_{SR}$  was narrow. The deployment failed at the cases of the time is both too short and too long. The combinational influences of two variables are also investigated.

Third, suitable design variables for aerial deployment were investigated through a robust optimization method that includes the developed aerial deployment simulation. A multi-objective genetic algorithm was used with objective functions for the robustness of the margin for the safe deployment judgment conditions, and deployment torque strength. Variations in the drop velocity, surrounding gust wind direction and speed, airplane attitude, and height were examined. The results showed that design point with deployment torque scale  $F$  of 0.6 and right wing deployment delay time  $T_{SR}$  of 1.0 second can deploy safely in the low deployment torque condition. This point is able to accomplish both safe deployment and lightweight of the deployment mechanism.

Finally, the collected knowledge was utilized in the conceptual design, and a final design was proposed. First, the effect of the reduction in the deployment torque scale  $F$  on the airplane specifications was revealed. The total mass was reduced, and the range was increased with downscaling. Feasible specifications for a Mars airplane with an aerial deployment mechanism were proposed based on the developed conceptual design method. The total mass and range of the proposed airplane are 16.0 kg and 201 km, respectively. 3D-CAD modeling was performed, and the proposed airplane was shown to fit in the entry capsule well. The nominal behavior of the aerial deployment was examined. The proposed airplane succeeded safe aerial deployment. It was also confirmed that the constructed design method of the deployment mechanism using deployment torque scale  $F$  was still useful even if the scale of the airplane changed.