CONCEPTUAL DESIGN OF REUSABLE SOUNDING ROCKET

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ABSTRACT

A fully reusable sounding rocket is proposed in ISAS/JAXA. Vehicle systems and ground / flight operations are designed for observations of atmospheric phenomena, micro-gravity experiments and so on. In the present design of the reusable sounding rocket, the vehicle carries a 100kg payload up to 120km altitude. The turnaround time for one flight is less than 24 hours (1 day). In the typical ballistic-flight up to 120km, the total flight time is about 600sec. Maximum Mach number is about 4, and the flight condition of Mach number below 1.0 (subsonic speed) is kept for about 70sec over 110km altitude. In this subsonic flight, the observed atmosphere around the vehicle is not affected by the shock wave. This is desirable for the atmospheric observation. Maximum acceleration in the flight is about 4G in ascent and 7G in descent. For the micro-gravity experiments, the flight environments of acceleration less than 10^{-3}G, 10^{-4}G and 10^{-5}G is able to be made for about 180, 150 and 120sec, respectively.

1. INTRODUCTION

Recently, in spite of existence of many launch demands for scientific researches using sounding rockets, the opportunities of launches are actually restricted because of high-cost of rocket launches, long period of launch preparations, and so on. In order to make the access to space for researches by the sounding rocket much easier (lower cost) and make the opportunities of the rocket launches much frequent, a fully reusable sounding rocket is proposed in ISAS/JAXA. Vehicle systems and ground / flight operations are designed for observations of atmospheric phenomena, micro-gravity experiments and so on.[1]-[4]

The reusable sounding rocket will bring some important changes to scientific observations as follows, (a) subsonic flight without shock wave around instruments, (b) 3-axis attitude control (c) observations at different positions or time with the same instrument, (d) observations from the different launch site, (e) several times observations in one flight campaign, (f) reuse of the instrument – use of expensive instruments / improvements of the instruments, (g) recovery of instrument – big amount of data storage, sample collections and recovery, and so on.

In ISAS, Reusable Vehicle Testing (RVT) campaign in which a small test vehicle was built and flight tested to study design and flight operations of the reusable system is in progress from 1999 for not only testing technical performances but also acquiring ground operation techniques for turnaround of the repeated flight (see fig.1). The precious experiences for designs and operations of the reusable sounding rocket vehicle were obtained through these flight demonstrations. The sounding rocket system is conceptually designed with adopting these experiences now.[5]

In this paper, the present status of the conceptual design of the reusable sounding rocket vehicle is introduced.

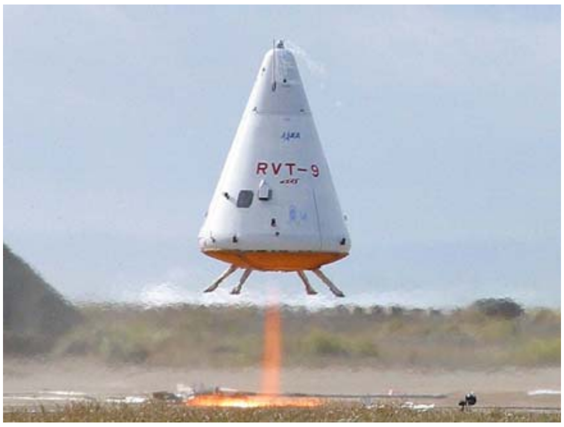

Figure 1. RVT flight campaign.

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3. SYSTEM CONCEPTS OF REUSABLE SOUNDING ROCKET

3.1 Specification of reusable sounding rocket

The specification of the proposed reusable sounding rocket is defined as follows.

1) Summit altitude: 100-150 km
2) Payload weight: 100kg
3) Downrange capability for flight safety: 30kg
4) Reusability of vehicle > 100 times (with some parts exchanges in maintenance)
5) Turnaround time < 24 hours
6) Vertical take-off and vertical landing (lands to the launch site)
7) 1 fail operative and full-time abort (abort capability of safe return to the launch site with one of main engines fail)
8) Ecological (no use of toxic propellant)

In order to satisfy these specifications, system and subsystem designs such as aerodynamics, propulsion systems, structures, etc were conducted, respectively. As these results, the baseline configuration was obtained as shown in Fig.2. A vertical take-off and vertical landing (VTVL) system is adopted because of 1) simple ground support equipments, 2) streamlined flight and ground operations, 3) compact system and light inert weight, and so on. The present vehicle configuration is summarized in Table 1.

Payload (instruments for the science observations) is settled in the nose fairing which could be opened for the observations and sampling of the atmosphere. The landing gear can extend in landing phase and can be contracted in the body in other flight phase.

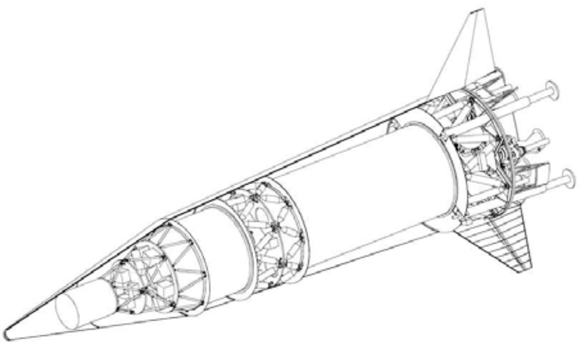


Figure 2. Baseline configuration of vehicle.

Table 1. Present vehicle configuration.

Body length	13.5 m
Body diameter	3.0 m
Take-off mass	10,750 kg
Dry mass	3,814 kg
Engine thrust	41kN×4
Engine Isp	320 sec
Mixture ratio	5.7

3.2. Airframe Shape

Airframe shape of the vehicle was lead from the aerodynamic considerations from the viewpoint of 1) the drag loss in the ascent phase, 2) the downrange capability in descent phase, 3) static stability in equilibrium flight, and so on. According to the system requirement mentioned above, the vehicle must have aerodynamic capability for the satisfaction of the 30km downrange. In order to realize such capability, the L/D of vehicle in the entry flight should be larger than 1.0. From the recent aerodynamic studies, the nose-first entry with a body shape of high fineness ratio can accomplish the relative high L/D. Such slender shape is also beneficial as regarding drag loss in ascent. As a result, the fineness ration of the present vehicle is 4.5 as shown in Fig.2.

3.3. Propulsion Systems

In the design of the propellant system, fault tolerant system architecture was adopted. The important modes of the component faults are thoroughly examined by the hazard analysis in the beginning phase of the system and subsystem designs.

To satisfy the full-time abort requirement, vehicle must have flight capability of the return to the launch site despite the one engine fails. Therefore, the one fail operative rocket system has clustered engines. Main propulsion system in this vehicle is composed of four engines of 4 tons thrust on sea-level, respectively. Each engine has capability of throttling from 60 to 100 %. The attitude control during powered flight is conducted by the gimbaling of the main engines. Expander bleed cycle is adopted to the main engine system.

3.4 Structures

The frame-stringer type structure is adopted as the main structure. A set of structure analysis (stress analysis, buckling analysis, and rigid analysis) and structure design are performed.

4. FLIGHT PERFORMANCES

A schema of typical ballistic-flight of the reusable sounding rocket vehicle up to 120km is as follow (see Fig.3). The vehicle takes-off vertically by the main engine thrust, and cut it off in its ascent phase. Then, the vehicle flies ballistically up to the summit altitude. Around the summit, the flight speed is subsonic because the horizontal speed is low enough in this flight profile. After that, the vehicle entries into atmosphere and decelerated by aerobraking, and vertically lands to the launching site. In the landing phase, the vehicle is decelerated by the main engine thrust for a soft-landing. In the case of the nose-first entry, the "turnover maneuver" must be conducted. This maneuver changes the attitude of the vehicle from the nose-first to the base-first for its deceleration and landing by the main engine thrust.

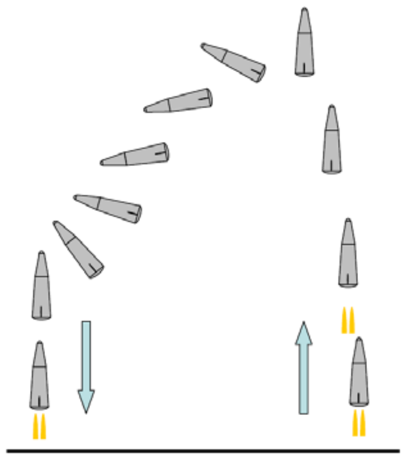


Figure 3. Typical ballistic flight.

Figures 4 and 5 show the profiles of altitude and Mach number, and acceleration in the typical flight, respectively. In the typical ballistic-flight up to 120km, the total flight time is about 600sec. Maximum Mach number is about 4, and the flight condition of Mach number below 1.0 (subsonic speed) is kept for about 70sec over 110km altitude. In this subsonic flight, the observed atmosphere around the vehicle is not affected by the shock wave. This is desirable for the atmospheric observation. Maximum acceleration in the flight is about 7G. For the micro-gravity experiments, the flight environments of acceleration less than 10^{-3}G, 10^{-4}G and 10^{-5}G is able to be made for about 180, 150 and 120sec, respectively.

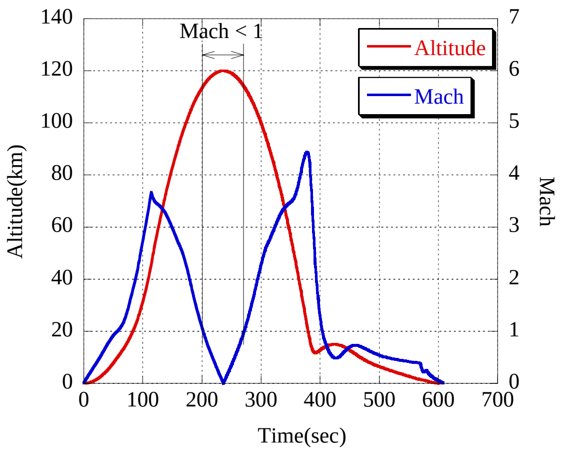


Figure 4. Flight profile: Altitude, Mach number.

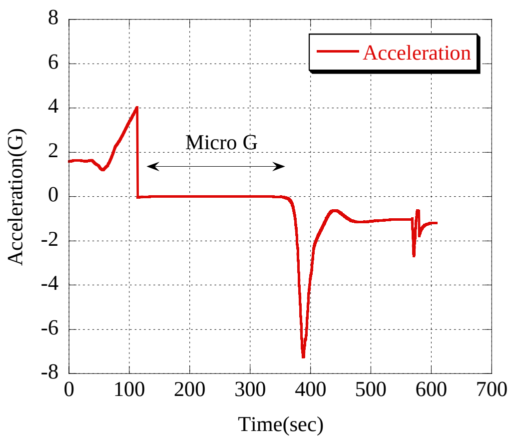


Figure 5. Flight profile: Acceleration.

The exhaust gas from the main engine and RCS thruster is just water vapor, because the vehicle adopts the integrated propulsion system by using hydrogen and oxygen. Depending on the mission objects, the summit altitude, flight velocity, and acceleration can be adjusted by the control of engine propulsive duration time or thrust level on demands. If the vehicle has some trouble in a flight, for example, main-engine fail, control system trouble, and so on, the vehicle can return safely to the launching site, that is, the vehicle has the full-time mission-abort capability.

5. TECHNICAL ISSUES FOR SYSTEM DEVELOPMENT

In order to design an operative reusable sounding rocket, some important technical issues, which are related to aerodynamics in entry flight, propulsion systems, reusable engine system, health management, and so on, are studied in the present. Here, some of these investigations are introduced.

5.1 Turnover maneuver and vertical landing

As mentioned above, the vehicle has to turn its attitude over before the landing. Some typical concepts can be considered for such inversion maneuver of the vertical landing rocket vehicle. The aerodynamic turnover maneuver, which is one of the most adoptable methods, is schematically shown in Fig.6. The vehicle begins the maneuver by using the instable aerodynamic characteristics due to the configuration change such as a retraction or an expansion of aerodynamic control surfaces. Aerodynamic moments cause the vehicle pitch up initially and pitch down finally. Control torque of a reaction control system (RCS) stabilizes the vehicle in a tail-first attitude and maintains an angle of attack of 180 deg before a re-ignition of main engines.

In order to demonstrate the aerodynamic turnover maneuver, flight tests gliding from a balloon or helicopter by using a small scale model is planed and prepared by wind tunnel tests and numerical analysis in the present. As a preliminary test before the balloon or helicopter experiment, a glide test by a small styrofoam model was conducted from 30m height (see Fig.7). The vehicle shape and the center of gravity must be considered to accomplish the turnover maneuver.[6[,[7]

In the landing phase after the turnover maneuver, the vehicle is decelerated by re-ignited main engine thrust and lands softly to the ground site. Then its aerodynamic characteristics are affected by the interaction between the

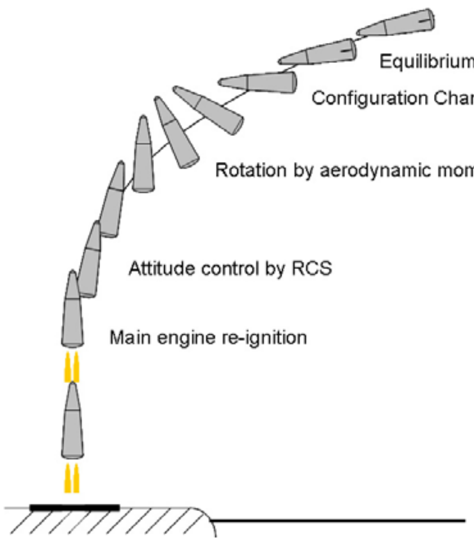


Figure 6. Turnover maneuver.

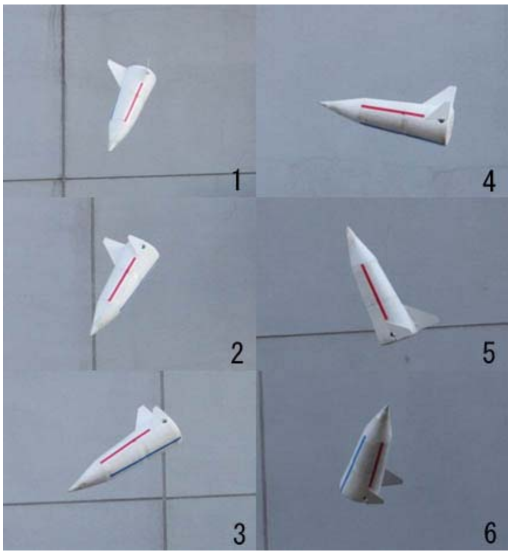
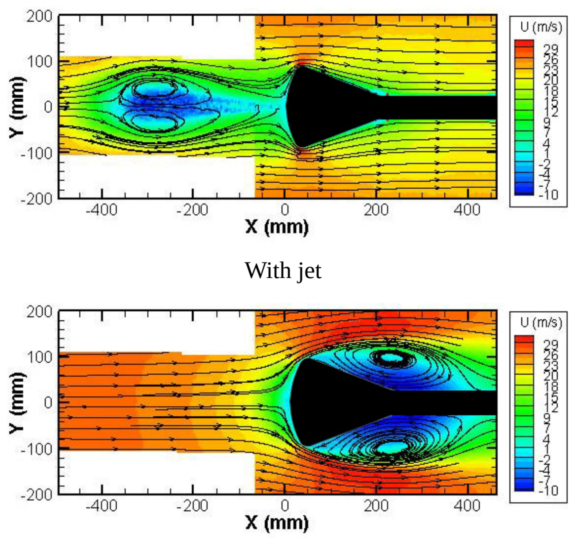


Figure 7. Small model fight test.

engine plume and the subsonic free-stream against the vehicle. In order to investigate the influence of such interaction, wind tunnel tests were conducted. Flowfield around the vehicle model was visualized by using Particle Image Velocimetry (PIV) method (see Fig. 8). As a result, the drag force and pitching moment acting the vehicle were affected by the change of pressure distribution due to the jet/free-stream interaction. Since the interaction region has high nonlinear characteristics and great unsteady motion observed, we have to be very careful in designing the vehicle flight scheme from this view point.[8]-[10]



With jet

Without jet

Figure 8. Jet/free-steam interaction in landing.

5.2 Sloshing of liquid propellant

Engine restart in the present flight configuration is planned to be conducted after the ballistic flight and the equilibrium glide as mentioned above. From a view of propellant management, it becomes very difficult to keep the liquid propellant in desirable position in the tank under low-gravity condition during the ballistic flight. And also, during the period from the occurrence of engine failure to the second one shut down, the attitude of the vehicle would change largely due to the misalignment of the thrust vector. From a view of propellant management, the lateral acceleration could be induced and act on the propellant in the tanks at the same time. If the large amount of bubbles should be sucked through the outlet port located on the bottom of the tank and reach at the igniter in the combustion chamber, it might result in the failure of re-ignition sequence. Therefore, suppression of sloshing and avoiding vapor-suction would be important problem.

To establish the fundamental technology for propellant management in space transportation systems, a numerical method, called 'CIP-LSM', is under development in University of Tokyo, which is designed to simulate three-dimensional free-surface flows under various gravity conditions. As the preliminary investigation, to acquire the dynamic behavior of liquid in the environment during the ballistic flight, the sloshing motion in the small vessel was experimentally observed. The series of experiments also aimed at obtaining the visualized data for the check of correlation with the numerical results. Figure 9 shows the sloshing simulation for confirming effect of baffle plate in the fuel tank.[11]

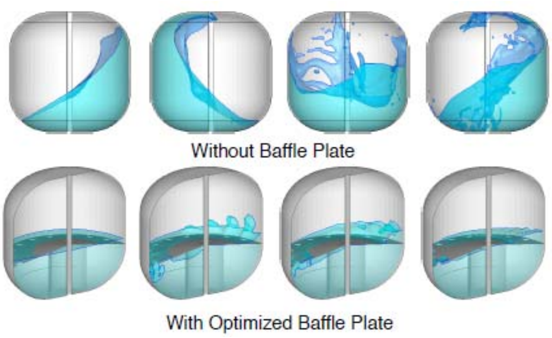


Figure 9. Sloshing simulation.

6. EXPECTED SCIENCE MISSIONS BY REUSABLE SOUNDING ROCKET

The demands of the proposed reusable sounding rocket for the science researches were investigated. As principal themes of the science studies, 1) Atmospheric physics, and 2) Micro gravity science are expected. The proposed reusable sounding rocket will help to solve outstanding problems of the middle atmosphere, lower thermosphere, and ionosphere. Examples of the expected science missions by the reusable sounding rocket with unique characteristics such as repetitive daily flight, hovering, sampling, and so on, are summarized as follows.

Atmospheric physics

In the middle atmosphere;

- Dynamical and photochemical processes around the mesopause.
- Space and time variation of minor constituents (O_3, greenhouse gases, etc.).
- Distributions of meteoric dust and noctilucent cloud (NLC) particles.

In the lower thermosphere and ionosphere;

- Neutral wind dynamics (tidal and planetary waves, etc.)
- Magnetic perturbations by polar or equatorial electrojets
- Mechanism of field aligned irregularities (FAIs) in the E-region
- Horizontal distribution of metallic ions in sporadic E-layer (Es)

Micro gravity experiments;

- Late access to sample before launch
- Quick access to returned sample after the experiment

etc.

7. SUMMARY

The conceptual system design of the reusable sounding rocket and related technical studies are summarized. The reusable sounding rocket with unique characteristics such as sampling, repeated daily flight etc will bring the great changes of the scientific observation of atmosphere and micro G experiments, and so on. Such reusable sounding rocket is effective not only for science missions but also for the research and development of the future space transportation systems. These activities will accelerate such studies and lead to the next step.

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