Experimental Demonstration of Subsurface Sampling Technology for Asteroid Explorations

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ABSTRACT

A new subsurface sampling device is proposed for use in small-body exploration. The proposed device has a multi-stage telescopic structure that can be extended using high-pressure gas. In addition, sampling is also performed through high-pressure gas. Since the proposed device has no actuator, it is expected to be highly reliable. It is experimentally demonstrated that the proposed device can excavate a dummy regolith layer up to a depth of 1 m and collect a sample of 3.88 mg for in-situ analyses and a sample of 0.5 g for sample return. These results indicate that the proposed device is a viable candidate for actual exploration missions.

小惑星掘削・サンプリングデバイスの実験的検証

要旨

本論文では，小惑星地下サンプル(最大深さ 1 m)を採取するための，地下サンプラーのコンセプトと，実証試験結果について報告する．本デバイスは，アクチュエータを使用せず，高圧ガスのみで掘削及びサンプリングを行うことができる．コンセプト実証試験により，模擬レゴリスを深さ 1 m 掘削し，3.88 mg のサンプルを採取できることが確認された．

I. INTRODUCTION

In recent years, several small-body exploration missions, including the return of sampling payloads, have been performed. These missions include Hayabusa, Rosetta/Philae, Hayabusa 2, and OSIRIS-REx. Hayabusa, Hayabusa 2, and OSIRIS-REx are asteroid-sample-return missions (target asteroids: Itokawa, Ryugu, and 1999 RQ36, respectively), and Rosetta/Philae is a comet-exploration mission (target comet: 67P/Churyumov-Gerasimenko). In order to explore a target small body precisely, each spacecraft has a sampling device for collecting materials. These instruments differ dramatically due to differences in mission concept, which include:

- Sample return or in-situ measurement,
- Surface sampling or subsurface sampling,
- Difference in the properties of the target small body.

Precise investigation of the properties of the target small body require the collection of subsurface samples that have not been weathered. Hayabusa 2 and Rosetta/Philae were designed to perform subsurface sampling. In recent years, advanced planetary excavation technologies have been investigated [1]. However, these studies mainly assumed the Moon and Mars as exploration targets. In other words, the surface conditions of these planets are known to some extent, and relatively heavy instruments can be

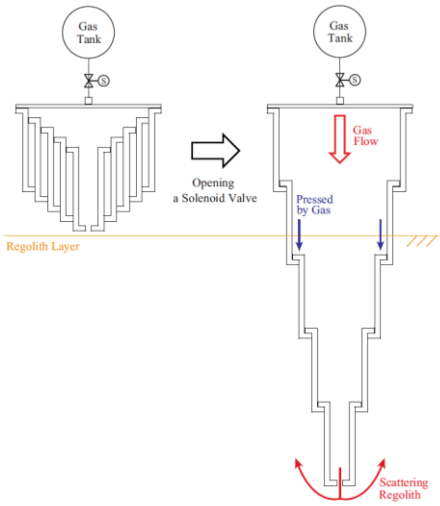

Fig. 1 Concept of Excavation

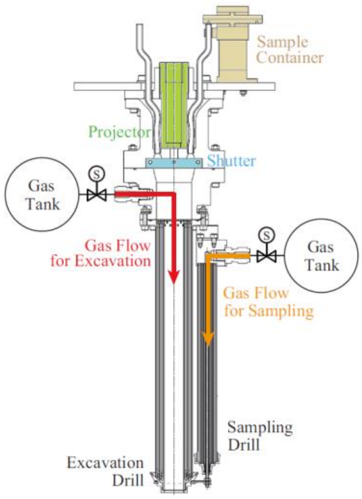

Fig. 2 Concept of Subsurface Sampling Device

used in exploration. However, these assumptions do not hold in small-body exploration, which has stricter restrictions.

In the present paper, we propose a new candidate subsurface sampling strategy for use in small-body exploration, specifically, an integrated excavation/sampling device driven by high-pressure gas. In the following, we present the concept of the proposed device along with some experimental results.

II. CONCEPT OF THE SUBSURFACE SAMPLING DEVICE

In this section, the concept of the proposed subsurface sampling device is explained. The proposed device has two extension drills, one for excavation and one for sampling. The excavation and sampling strategies using high-pressure gas are first discussed, after which the full configuration of the integrated device is discussed.

In the present study, the target is assumed to be a small body, such as an asteroid or a comet. Several images taken by Hayabusa and Rosetta/Philae indicate that asteroid Itokawa and comet 67P/Churyumov-Gerasimenko are covered with regolith [2-3]. Thus, we herein assume that there is a regolith layer on the surface of the small body considered in the present paper.

Figure 1 shows the concept of the excavation strategy. The excavation is performed using high-pressure gas. The extension structure consists of a multi-stage telescopic structure, and high-pressure gas is used to extend each stage. During this operation, gas is released from the tip of the device. As a result of the interaction between the gas and the surrounding regolith, the surface of the body becomes soft, and the device can be easily extended inside the body. Moreover, due to the gas flow, the regolith cannot enter the device. This guarantees that the collected sample is the subsurface sample at the target depth. The most important feature of this concept is that no actuator is required. In other words, the proposed device can be driven by simply opening a solenoid valve to release the high-pressure gas. In addition, the direction of the counter force is the normal direction with respect to the surface of the small body, which generates no rotational torque. This simplifies the counter-force cancellation mechanism. Note that the normal counter force generated during excavation is assumed to be canceled by thrusters.

As mentioned earlier, excavation is performed using high-pressure gas. In order to be compatible with this excavation concept, it is advantageous to apply the pneumatic drill technique in conjunction with high-pressure-gas sampling. In the sampling strategy, the sample is blown into the sample container by the gas flow, which originates from outside the sample path. This concept has been extensively investigated for use in Moon and Mars exploration missions [4].

By combining these two strategies, we propose a new subsurface sampling device, as shown in Figure 2. The proposed device consists of the following components:

- Excavation Drill
- Sampling Drill
- Shutter
- Sample Container
- Projector

The proposed subsurface sampling procedure is as follows:

Step 1 Excavation is performed using the excavation drill.

Step 2 The shutter is opened.

Step 3 Sampling is performed using the sampling drill.

Step 4 (Backup) If a rock is encountered, the projector is operated to break the rock.

Step 5 (Backup) Sampling is performed again using the sampling drill.

III. VERIFICATION BASED ON EXPERIMENTAL RESULTS

In order to verify the concept of the proposed subsurface sampling device, a demonstration experiment was performed. In the present paper, we consider the nominal operation scenario given as Steps 1 through 3 in Section II.

Figure 3 show a test model of the subsurface sampling device used in this experiment. This device, which constructed primarily of aluminum, has a five-stage excavation drill for excavation to a depth of 1 m. Attached to this structure is a thin sampling drill. The tip of the excavation drill has an orifice (diameter: 10 mm) through which to control the gas flow during excavation. Inside the proposed device is a shutter. The sample passes through the excavation drill and is collected in the sample container. The sample container has a 4-mm cubic sample box for sample collection. The sample box has a metal mesh that traps the samples entering the box. We assume that the device will convey the sample to an in-situ measurement device, such as a mass spectrometer, which would require a sample of at least 1 mg.

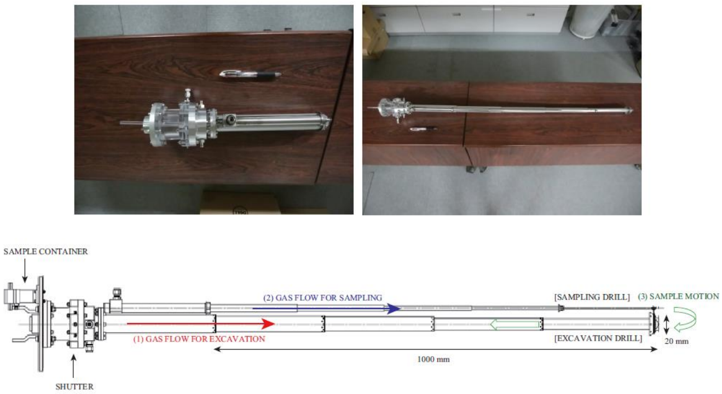

Fig. 3 Test Model

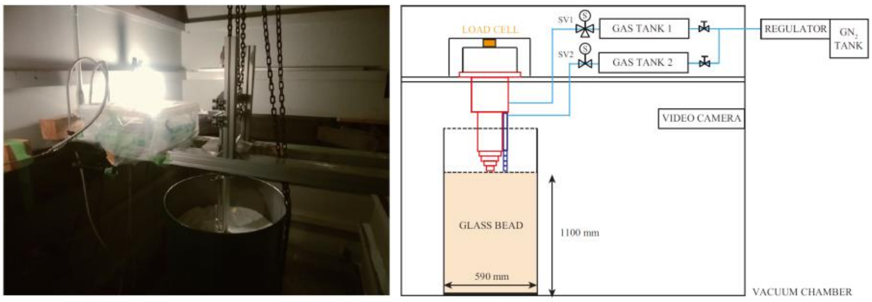

Fig. 4 Experiment Configuration

Figure 4 shows the experimental configuration. This test was performed in a large vacuum chamber. In addition to the sample container, a sample catcher (plastic bag) was used as a reference in order to confirm the sampling capability of the proposed device for the sample return.

The test procedure for this experiment was as follows:

Step 1: Charge high-pressure gas into buffer tank 1.

Step 2: Draw a vacuum.

Step 3: Open SV1 and start excavation.

Step 4: Return the pressure in the vacuum chamber to atmospheric pressure.

Step 5: Take photographs.

Step 6: Open shutter.

Step 7: Charge high-pressure gas into buffer tank 2.

Step 8: Draw a vacuum.

Step 9: Open SV2 and start sampling.

Step 10: Return pressure in the vacuum chamber to the atmospheric pressure.

Table 1 Experimental parameters

Parameter	[unit]	
Dummy Regolith	[-]	Glass Bead (sphere)
Dummy Regolith Size	[um]	180-500
Dummy Regolith Bulk Density	[g/cm^3]	1.5
Gas	[-]	GN_2
Gas Tank 1 Volume	[cm^3]	300
Gas Tank 2 Volume	[cm^3]	30
Gas Tank 1 Pressure	[MPaG]	5.5
Gas Tank 2 Pressure	[MPaG]	3.0
SV1 Opening Duration	[s]	0.4
Vacuum Pressure	[kPa]	1.0

Fig. 5 Excavation Result

Fig. 6 Sampling Result

Table 1 summarizes the experimental parameters used. Glass beads were used as dummy regolith. This set of parameters is only one example, and they should be adjusted for each mission corresponding to the assumed surface conditions of the target body.

In this experiment, excavation to a depth of 1 m was successfully performed, as shown in Figures 5. The excavation took 0.180 s, and the peak reaction force was 136 N. In an actual flight system, this reaction force must be balanced by thrusters.

Figure 6 shows photographs of one sample box at different focuses before and after the experiment. The sample was clearly collected in the sample box. This figure indicates that the sampling was successfully performed. The collected sample weight is summarized in Table 2. The sample box collected a sample having a mass of more than 1 mg, allowing mass spectrometry to be performed. If the pressure in gas tank 2 is increased, more samples can be collected in the sample catcher.

Table 2 Sampling results

Sample Container	[mg]	3.88
Sample Catcher	[g]	0.5

IV. CONCLUSION

A new subsurface sampling device was proposed and experiments were performed to verify the concept. The proposed device uses a very simple sampling strategy involving high-pressure gas driven by opening solenoid valves. Validation experiments were carried out and showed that the proposed device is a feasible candidate for actual exploration missions.

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