DESIGN AND VALIDATION OF A HIGH SPEED, HIGH FLEXIBILITY EXCITATION SAMPLING BRUSH FOR DEEP SPACE SAMPLING

by

Hua-Jun HU[a], Zeng ZHAO[a], Zhong-Xian ZHAO[a], Zhong-Wang YIN[a], Hai-Bin YU[a], Nai ZHANG[a], Yun-Cheng LIN[b], Hong-Ying YUAN[a], and Guo-Xin WANG[a*]

[a] Beijing Spacecrafts Co., Ltd.,
China Academy of Space Technology (CAST), Beijing, China
[b] Beijing Institute of Spacecraft System Engineering, Beijing, China

Original scientific paper
https://doi.org/10.2298/TSCI2502423H

Asteroids are usually sampled by touch due to their small size and weak gravity, and the sampling time is short. Flexible brush high speed excitation sampling is an efficient and reliable sampling method. This paper designs a brush-type symmetrical rotating double-wheel structure brush excitation sampling mechanism for asteroid surface touch sampling in a short time. According to the characteristics of the brush sampling mechanism, a mathematical model for calculating the sampling volume of the sampling mechanism with multiple parameters is established. The sampling volume is verified by discrete element simulation method and microgravity drop tower test. The results show that for different gradations of stellar soil, the theoretical calculation and verification results are relatively consistent. It shows that the theoretical model can be used to estimate the sampling volume during brush excitation sampling. The results of this paper provide a basis for the subsequent asteroid sampling return.

Key words: *brush excitation sampling, high speed, flexibility brush, asteroid sampling, deep space exploration*

Introduction

Asteroids constitute a fundamental component of the solar system. Research indicates that these asteroids contain significant information regarding the genesis, formation, and evolution of the early solar system, as well as crucial insights into the inception of life on Earth, rendering them *living fossils* for the study of our solar system's origins [1, 2]. Investigating asteroids can illuminate the planetary formation process, the primordial environment of the Solar System, and the material origins of planets such as Earth and Mars. Asteroid sampling and return missions can deliver asteroid specimens to Earth for thorough laboratory analysis, yielding far greater scientific insights than current detection techniques. Consequently, asteroid sample and return missions have increasingly emerged as a prominent topic in global deep space exploration research.

Japan's JAXA deployed the Hayabusa1 and Hayabusa 2 asteroid probes, which acquire surface samples by discharging projectiles to agitate surface debris [3, 4]. The NASA

* Corresponding author, e-mail: huhuajun506@126.com

executed the OSIRIS-REx mission investigate the Bennu asteroid, employing an air-blown sampling technique to acquire 121.6 g of samples [5].

Owing to the asteroid's diminutive size and weak gravity, the surfaces of asteroids typically include a limited quantity of samples, primarily including a specific weathering layer. Consequently, asteroid sampling has a limited duration and is typically conducted using contact sampling techniques. The primary sampling methods presently consist of projectile sampling, air blow sampling, wheel brush sampling, drill sampling, electrostatic force sampling, magnetic sampling, combined sweep and grind sampling, and robotic sampling [6-10]. In comparison alternative sample techniques, the high speed flexible brush sampling method offers benefits including reduced sampling duration, increased sampling volume, and enhanced sampling efficiency. Nallapu *et al*. [11] presented a single-brush wheel sample technique for the excavation of small celestial bodies and developed a theoretical model for sampling. Schafer *et al*. [12] examined the impact of pertinent parameters on wheel brush sampling for 2-D particles utilizing smoothed particle hydrodynamics. Wei *et al*. [13] streamlined the asteroid sampling apparatus while preserving the wheel brush and confirmed the quantity of collected particles utilizing soybean particles. Li *et al*. [14] examined the effects of four varieties of brush heads and four configurations of wheel teeth distributions on efficiency. Luo *et al*. [15] developed a dynamic model for wheel brush sampling and examined the dynamic properties throughout the sample process. Sitepu *et al*. [16] introduced a duo of Archimedean screw designs derived from the reverse symmetrical wheel brush.

This work proposes a high speed, very flexible excitation sampler and presents a mathematical model for calculating the sampling mass. Calculations were conducted for single-particle size-graded heavenly soil and gradation A as sampling subjects to determine computed sample mass. The sampling procedure across several gradations was simulated and examined utilizing the discrete element analysis approach to determine the sample collection mass. A microgravity sampling verification system was developed to confirm the sample process across various gradations. Validation study reveals that the theoretical calculations and experimentally derived sampling volumes are congruent, with both surpassing 120 g.

High speed and high flexibility excitation sampler

The brush excitation sampler for asteroid sampling is consisted of two symmetrical axes of rotation, four brush fixed on the rotating shaft, sampler shell and comb grid to prevent large particle size samples. The brush excitation is achieved through the high speed rotation of the brush and its interaction with the sample particles, where kinetic energy excites the

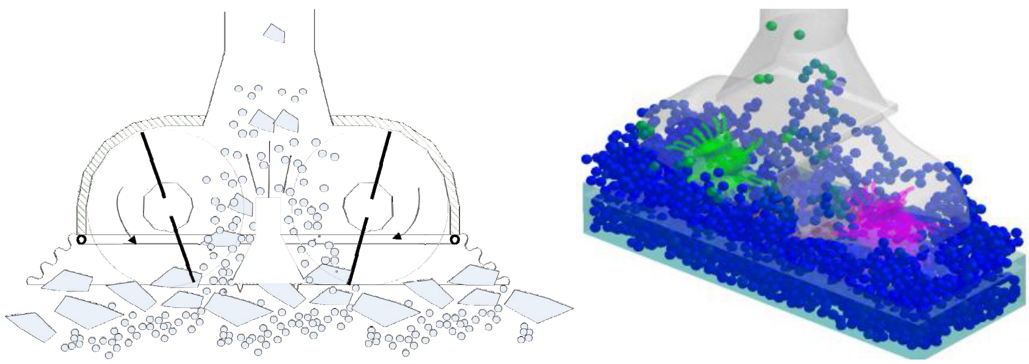

Figure 1. Schematic diagram of brush excitation sampling

particles to move at a velocity, directing them into the sample channel, as illustrated in fig. 1. The sampler features a symmetrical rotating dual-wheel structure, with both rotating shafts turning inward simultaneously. The brushes installed on these shafts are capable of effectively scraping against the weathered layer and small particles, exciting and centrifugally ejecting them. Since gravity does not play a role, the sample particles, constrained by the triangular guiding structure, move towards the direction of the sample channel, facilitating the flow of the sample.

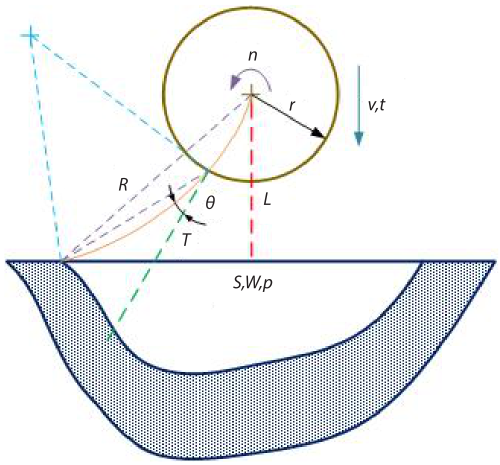

Figure 2. Mathematical model for an individual brush sampling process

Model building

The sampling process of an individual brush is illustrated in fig. 2.

According to the mathematical model for an individual brush sampling process, the sample mass can be expressed:

$$P = 2\frac{R_1 - r}{2\theta}\sin\theta$$
$$\cos(\pi - \theta) = \frac{r^2 + P^2 - R^2}{2rP}$$
$$S = 2\left(\frac{1}{2}R^2\text{acos}\left(\frac{h_1 + h_2}{R}\right) - \frac{L\sqrt{R^2 - (h_1 + h_2)^2}}{2}\right) \tag{1}$$
$$m_t = 2SW\rho$$
$$m_a = m_t\eta_1\eta_2\eta_3$$

where P is the chord length corresponding to the deformed section of the brush, R_1 – the radius of gyration of brush in its free state, r – the radius of rotational axis, θ – the deflection angle of the brush under force bending, S – the cross-sectional area of the sapling region, W – the width of the sapling region, ρ – the equivalent bulk density of the sapling region, h_1 – the distance between the rotation center and the sample surface when the brush reaches its maximum sweeping depth, h_2 – the sinking distance of the sampling mechanism, L – the distance between the rotation center and the sampling surface, m_t – the theoretical sample mass, m_a – the actual sample mass, η_1 – the sampling efficiency of sweeping sample, η_2 – the transmission efficiency during comb, and η_3 – the transmission efficiency after combing.

In fact, eq. (1) can be simplified:

$$P = \frac{(R_1 - r)\sin\theta}{\theta}$$
$$R = \sqrt{r^2 + P^2 + 2rP\cos\theta}$$
$$S = R^2\text{acos}\left(\frac{h_1 + h_2}{R}\right) - L\sqrt{R^2 - (h_1 + h_2)^2} \tag{2}$$
$$m_a = 2SW\rho\eta_1\eta_2\eta_3$$

It can be clearly seen from eq. (2) that the actual sample mass m_t will be affected by radius of rotational axis, radius of gyration of brush in its free state, deflection angle of the brush under force bending, width of the sampling region, distance between the rotation center and the sampling surface, equivalent bulk density of the sampling region, sampling efficiency of sweeping sample, transmission efficiency during comb and transmission efficiency after combing.

Design example

According to the sample model proposed in this paper, we design a brush sample mechanism that frequently used for regolith sampling of extraterrestrial asteroid. The design parameters and sample condition for sampling mechanism is list in tab. 1.

Table 1. Parameters and sample condition of sampling mechanism

Sample condition	Parameters								
	r [mm]	R_1 [mm]	W [mm]	h_1 [mm]	θ [rad]	ρ [gmm^{-3}]	η_1	η_1	η_1
Single particle size sample (10 mm)	15	55	66	29	0.314	0.00296	85%	85%	85%
Gradation A	15	55	66	29	0.785	0.0018	70%	70%	70%

The sample mass considering different sample condition and some key parameters are calculated using the analytical model with the design parameters. For the celestial sample gradation consisting of a single particle size of 10 mm, the calculated sample mass is 634.3 g. When the sampling subject with Gradation A, the calculated sample mass is 135.7 g.

Verification

In order to validate the model of sample mass, the brush excitation sampling performance with time is implemented using commercial DEM package EDEM, which is competent for simulation and analysis of granular materials. In the simulation model, a ball pool with dimensions of 500 mm in length, 400 mm in width, and approximately 150 mm in thickness was established. The cohesive strength between particle was considered to be 3 kPa. The set rotational speed of the bristle brush was 1000 rpm, and the data acquisition duration was 1.5 seconds. The simulation for the single particle size of 10mm and gradation A are illustrated in figs. 3 and 4, respectively.

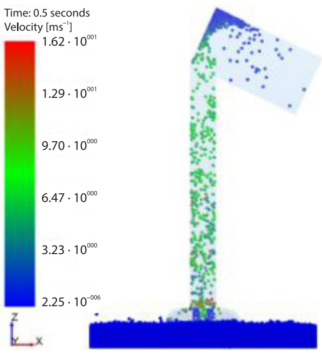

Figure 3. Simulation of a single particle size of 10 mm

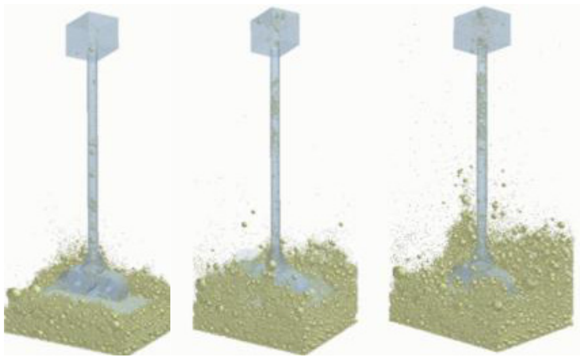

Figure 4. Simulation of gradation A

The prototype of high speed and high flexibility excitation sampling brush mechanism is also manufactured, and the experimental system used to obtain the sample mass is set-up, as shown in fig. 5, to validate the sample mass performance. The microgravity sampling experiment system mainly comprises a single-cabin drop capsule, an excitation sampling and collection system, a vacuum test system, simulated extraterrestrial soil, an experiment controller, and an imaging measuring system.

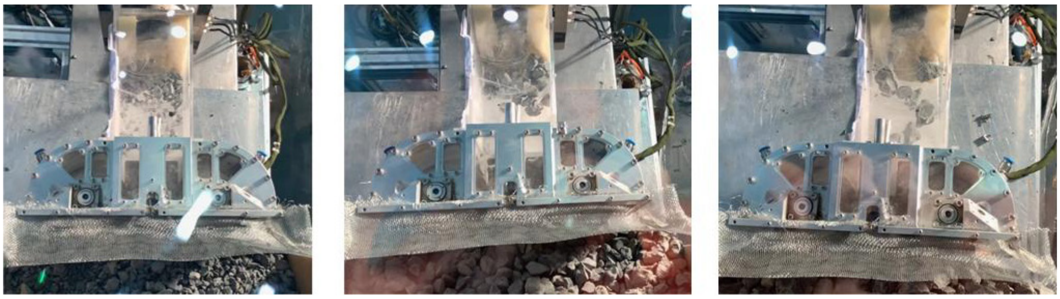

Figure 5. The experimental system of a brush excitation sample

Result and discussion

The simulation findings indicate that aiming a particle size of 10 mm constitutes one of the optimal conditions for maximizing sample volume. In the 0 g sampling scenario, the sampling volume for a singular particle size of 10 mm is 693 g. In the simulation of astronomical soil Gradation A with mixed particle sizes, the 5 seconds sampling volume is 156.97 g, and the collected sample particle sizes are ≤20 mm. The precise dimensions and weights of the particles in tab. 2.

Table 2. Simulation result of gradation A

Particle size [mm]	3	7	10	15	20	25	>25
Number	1428	23	38	8	0	0	0
Mass [g]	54.31	11.11	53.52	38.03	0	0	0

The drop tower microgravity experiment results indicate that for a single particle size of 10 mm, the sample collection volume is 682 g for a microgravity sampling duration of 3.2 seconds. Under Condition A, the sample collection volume under microgravity conditions for various particle size gradations is 150.8 g.

The theoretical calculations, simulation analyses, and test results exhibit a high degree of consistency with little discrepancies. The theoretical model can approximate the sample volume of brush excitation a specific degree. The varying gradation conditions of star soil significantly influence the sampling volume. Optimal working conditions for a uniform particle size can yield an increased sampling volume. The sampling volume of star soils with varying gradation particle sizes will diminish due to the screening action of the comb grid.

Conclusion

This work presents a high speed, highly adaptable brush excitation sampling method that collects extraterrestrial soil samples by brief, rapid brush sweeps. The correlation between the brush sweep sampling volume and the geometric dimensions of the sampler is established, allowing for the analysis of the sampling volume under varying heavenly soil gradation conditions. Simulation analysis and microgravity testing have proven that the brush sampler can gather celestial soil at high rotational speeds, with a sampling volume exceeding 120 g under the assessed celestial soil conditions.

Acknowledgment

This work was financially supported by the Civil Space Program of the Aerospace Science and Technology Corporation, and the Key Project of the National Natural Science Foundation of China (U21B2072).

Nomenclature

m_a – actual sample mass, [g]
m_t – theoretical sample mass, [g]
P – chord length, [mm]
R_1 – radius of gyration, [mm]
r – radius of rotational axis, [mm]
S – cross-sectional area,[mm^2]
W – width of the sapling region, [mm]

Greek symbols

θ – deflection angle, [rad]
ρ – equivalent bulk density, [gmm^{-3}]

References

[1] Yu, H. M., *et al*., Conceptual Design of China's Small Celestial Body Exploration Mission, *Space International*, *9* (2021), 3, pp. 4-9
[2] Zhang, R. Q., e*t al*., The Development Overview of Asteroid Exploration, *Journal of Deep Space Exploration*, *6* (2019), 5, pp. 417-423
[3] Yada, T., *et al*., Hayabusa-Returned Sample Curation in The Planetary Material Sample Curation Facility of JAXA, *Meteoritics and Planetary Science*, *49* (2014), 2, pp. 135-153
[4] Tsuda, Y., et al., System Design of The Hayabusa 2 – Asteroid Sample Return Mission 1999 JU3, *Acta Astronautica*, *91* (2013), 2, pp.356-362
[5] Lauretta, D. S., *et al*., OSIRIS-REx: Sample Return from Asteroid (101955) Bennu, *Space Science Reviews*, *212* (2017), 1, pp. 925-984
[6] Bonitz, R., The Brush Wheel Sampler – A Sampling Device for Small-Body Touch-and-Go Missions, *Proceedings*, IEEE Aerospace Conference, Big Sky, Mont., USA, 2012, pp.1-6
[7] Zhang, J., *et al*., A Sweeping and Grinding Combined Hybrid Sampler for Asteroid Sample Return Mission, *Acta Astronautica*, *198* (2022), 3, pp. 329-346
[8] Kato, H., *et al*., Subsurface Sampling Robot for Time-limited Asteroid Exploration, *Proceeding*s, IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Las Vegas, New., USA, 2020, pp. 1925-1932
[9] Zhang, W., *et al*., Inchworm Drilling System for Planetary Subsurface Exploration, *IEEE/ASME Transactions on Mechatronics*, *25* (2020), 2, pp. 837-847
[10] Kawamoto, H., Sampling of Small Regolith Particles from Asteroids Utilizing an Alternative Electrostatic Field and Electrostatic Traveling Wave, *Journal of Aerospace Engineering*, *27* (2014), 3, pp. 631-635
[11] Nallapu, R. T., *et al.*, Optimized Bucket Wheel Design for Asteroid Excavation, *Proceedings*, International Astronautical Congress, Guadalajura, Mexico, 2016
[12] Schafer, C. M., *et al*., Numerical Simulations of Regolith Sampling Processes, *Planetary and Space Science*, *141* (2017), 2, pp. 35-44
[13] Wei, Q., *et al*., Simulation Analysis and Experiment of Sampling Process of Wheel Brush Sampler Based on Discrete Element Method, *Journal of Physics: Conference Series*, *2137* (2021), 1, 012058
[14] Li, J., *et al*., A Multisite and Anti-Cross-Contamination Brief Touch Sampler for Asteroid Sample Return Mission, *Acta Astronautica*, *201* (2022), Dec., pp. 317-328
[15] Luo, H., *et al*., Numerical Simulation and Experimental Research on the Wheel Brush Sampling Process of an Asteroid Sampler, *Frontiers of Mechanical Engineering*, *18* (2023), 2, ID16
[16] Sitepu, E., *et al*., Granular Sample Collection Simulation Via Counter Rotating Wheels Sampler for Small-Sized System at Reduced Gravity Environment, *Planetary and Space Science*, *237* (2023), 2, ID105778

Paper submitted: November 26, 2024
Paper revised: November 30, 2024
Paper accepted: December 11, 2024