Simulation analysis and experiment of sampling process of wheel brush sampler based on discrete element method

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Abstract. In order to study the brush sweep sampling process through simulation analysis, the structure of the asteroid sampler is simplified on the basis of retaining the wheel brush. Soybean particles are selected as the verification sampling particles, and the physical and contact parameters of calibrated soybean particles are applied to the discrete element simulation software EDEM and the relationship between the sampling wheel brush speed and torque is analysed. At the same time, a set of wheel brush asteroid sample ground torque test system is built to verify the accuracy of the discrete element simulation results. The results show that the driving torque of the sampling wheel brush is mutational in the process of sampling, and the faster the rotation speed of the sampling wheel brush, the more the mass of the collected particles, and the greater the driving torque required for the sampling wheel brush. This research provides a method basis for the structure selection and parameter optimization design of the asteroid sampler.

1. Introduction
Asteroid sampling mission is an important part of deep space exploration mission[1]. Researchers have designed and proposed many sampling detection technology solutions, and the wheel brush sampling technology is one example. The wheel brush sampling technology is a Touch-And-Go (TAG) mode sampling technology, as shown in Figure 1. When the probe is lowered to a certain height from the surface of the asteroid, the robotic arm expands and makes contact with the surface of the asteroid, and at this time, the two sampling wheel brushes will rotate symmetrically to sweep the asteroid surface sample into the collector[2].

It is difficult to realize a microgravity environment on the ground. Therefore, in the process of space equipment research and development, numerical simulation is often used to iteratively optimize space equipment[3], which can help it successfully complete the established sampling task.
2. **Wheel brush asteroid sampler and its simplified model**

The structure of the sampling head part of the wheel brush asteroid sampler is shown in Figure 2. The main structure includes the sampling wheel brush, the sampler shell and the sample chamber. By the way of brushing the sampling wheel, the particle material on the asteroid surface is rolled up and passed through a specially shaped shell into a cylindrical sample chamber to complete the sampling process.

![Figure 2. The structure diagram of the wheel brush sampler](image)

The structure of real space equipment is complicated, and it needs to be simplified before the simulation analysis. The exploded assembly drawing of the simplified model is shown in Figure 3. Among them, the sampling box and the sampler shell are made of the PLA materials through 3D printing technology; the sampling wheel brush is made of aluminum alloy, which is simplified to a certain extent on the basis of retaining the appearance; the bearing blocks are the standard piece made of aluminum alloy used to secure the sampler shell to the sampling wheel brush.

![Figure 3. The exploded assembly drawing of the wheel brush sampler simplified model](image)

3. **Simulation analysis of sweep sampling process based on DEM**

3.1 **Introduction of Discrete Element Method**

Discrete Element Method (DEM) is a numerical calculation method to simulate the dynamics of discontinuous media and its related processes, which is helpful for constructing the model of particles on the asteroid surface[4]. In this paper, soybean particles will be selected as the preliminary verification sampling particles. The discrete element appearance model of soybean particles can be established by using four-sphere model, as shown in Figure 4. The three-axis dimensions of the length, width, and height are 6.833, 6.292, and 6.884 mm, respectively. The four-sphere model conforms to the appearance characteristics of soybean particles.
Figure 4. The discrete element model of soybean particles

Physical parameters of particle materials and sampler prototype materials are determined by consulting the literature and material manuals[5], as shown in Table 1.

| Material  | Elastic Modulus (GPa) | Poisson's ratio | Density (kg m$^{-3}$) |
|-----------|-----------------------|-----------------|-----------------------|
| Soybean   | 0.16                  | 0.25            | 1212                  |
| Aluminum  | 72                    | 0.33            | 2740                  |
| PLA       | 3.6                   | 0.27            | 1260                  |

Contact parameters of the soybean particles to other objects are determined through the parameter calibration test[6], as shown in Table 2.

| Material               | Coefficient of Restitution | Coefficient of Static Friction | Coefficient of Rolling Friction |
|------------------------|----------------------------|-------------------------------|--------------------------------|
| Soybean to Aluminum    | 0.312                      | 0.466                         | 0.08                           |
| Soybean to PLA         | 0.472                      | 0.425                         | 0.05                           |
| Soybean to Soybean     | 0.323                      | 0.394                         | 0.07                           |

3.2 Simulation and analysis of wheel brush asteroid sampler

Based on the discrete element simulation analysis software EDEM and multi-body dynamics simulation software Adams, this article simulates and analyses the sampling process of the sampler, and provides guidance for the design selection and structural optimization of the wheel brush sampler.

The changes of torque and mass in the process of brushing and sampling at a certain time are shown in Figure 5. After the simulation of brush sweep sampling starts, the left brush wheel of the brush sweep mechanism rotates counter clockwise at a certain speed, and the right brush wheel rotates clockwise at the same speed. Under the brushing action of the sampling wheel brush, the particles enter the upper sample chamber along the guide cover, and enter the particle collection boxes on both sides through the top guide angle to complete the particle collection.
Figure 5. Brush sampling process of the wheel brush asteroid sampler

For the rotation speed of the sampling wheel brush, the low-speed group of 180 rpm, the medium-speed group of 360 rpm and the high-speed group of 540 rpm are respectively set as parameter variables, and record the sampling mass of the wheel brush sampler at different speeds, as shown in Figure 6. It can be seen that as the rotation speed of the sampling wheel brush increases, the quality of the collected particles is increasing, that is, the sampling efficiency is increasing.

4. Torque analysis and experimental verification of the brush wheel sampler

In order to ensure the reliability of the simulation analysis, the corresponding ground test prototype is designed to verify the results of the simulation analysis. According to the simplified ground model of the wheel brush asteroid sampler, a set of ground torque test system for the wheel brush asteroid sampler was designed and built, as shown in Figure 7, which can measure the real-time change of the torque of the sampling wheel brush of the brush wheel asteroid sampler in the process of sampling.

Figure 7. Ground torque test system of wheel brush sampler

In the experiment, the low-speed, medium-speed and high-speed groups are respectively set to simulate the working conditions of simulation analysis. The acceleration and deceleration stage are removed, and only the uniform rotation part of 1s~5s is taken to check the simulation results, and the simulation and test torque curves under different rotational speeds are obtained, as shown in Figure 8.
Figure 8. Comparison of the torque of wheel brushes with different speeds

It can be seen that the torques of the two sampling wheel brushes of the wheel brush asteroid sampler are symmetrical, and the torque curve obtained from test and simulation is close to the trend and extreme value. This proves that it is feasible to simulate the asteroid sampling process through the DEM.

Besides, Figure 8 also shows that the variation of torque of the sampling wheel brush is abrupt. Specifically, the torque is close to zero at this moment and may fluctuate greatly at the next moment. This may be because the collision of particulate matter with the sampling wheel brush is random, and the torque change is also random. At the same time, with the increase of the sampling wheel brush speed, the value of the torque extreme value also increases, that is, high speed brings a higher instantaneous torque, while the high instantaneous torque will cause harm to the motor. Therefore, the wheel brush sampler cannot pursue an excessively high rotation speed, and the balance between sampling efficiency and instantaneous torque need to be achieved.
5. Conclusion
According to the need of asteroid sampling, a simplified model of the asteroid rotary symmetrical sampling brush mechanism is carried out in this paper. The soybean particles are used as the preliminary verification sampling particles, and obtain various contact parameters of the soybean particles. Through the discrete element method, the process of sampling soybean particles by the wheel brush asteroid sampler is simulated and analysed, and a corresponding ground test system is built to verify the feasibility of the simulation results.

The results show that the DEM simulation is feasible, and can be used to simulate and analyse the real samplers in space microgravity environment. Besides, with the increase of the speed of the sampling wheel brush, the sampling effect is getting better and better, but the extreme value of the torque of the sampling wheel brush is also getting larger and larger, and the sudden change of torque will have a negative impact on the motor. Therefore, it is necessary to find a suitable rotation speed for the wheel brush asteroid sampler to balance the relationship between the sampling efficiency and the torque.

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