Design and Analysis of Absorption Type Sampler on Star Soil

Ming CHEN¹, Biao CHEN¹,∗ and Shen YIN²

¹North China Institute of Aerospace Engineering, Langfang, Hebei, China
²China Academy of Space Technology, Beijing, China

*Corresponding author

Keywords: Small body sampling, Absorption type sampler, Magnetic vibration, The dense ball bearing shaft.

Abstract. Deep space detection is the result of human exploration of natural intrinsic motivation. To explore the Moon, Mars, target Asteroid soil strata information, meeting the needs of human living space is of great significance. For the mission of celestial bodies, an absorption type sampling method which uses the rotation and pound to burst rock and air flow excitation to obtain samples is put forward. It has characteristics of low reaction force, efficient rock-breaking, light body and low energy consumption. Further, it uses the principle of flywheel energy storage to achieve low energy consumption, passive vibration excitation magnetic control to achieve high efficient rock breaking, and the dense ball bearing shaft inherent function of rush and rotation to achieve structure lightweight. Through ADAMS software, dynamic simulation analysis is ascertained and sampler ground simulation experiment is consolidated according to different hard soil. The results show that the sampling method, can brake rock efficiently, achieve the microgravity sampling function, and provide an effective way for deep space detection.

Introduction

Deep space exploration is an important way for the development and utilization of space resources. The exploration of small objects (asteroids and comets) is necessary to study evolution of the solar system and gather scarce resources on security defense. Up to now, landing, sampling, and other forms of detection are existed. Sampling return can be more effective in studying interspace resources, so the sampling technique determines the small object detection of the breadth and depth [1].

Small bodies is in orbit alternating and solar radiation, so the rocks are dominated by silicon. Its hardness is about 1/20 of the gravity of the earth [2]. To adapt to such an environment, the astral sampler must come up with new requirements. The traditional sampler is not fit for such weakly gravity environment, so a sampling form depending on air intake is proposed.

Absorption Star Soil Sampler Mechanism Scheme

The functions of the absorption sampling mechanism include drilling into the earth, breaking rocks, absorbing samples and structural support [3]. In order to achieve these functions, the sampling consists of Flywheel energy storage facility, Magnetic control actuator, Dense bead drilling mechanism and Air flow absorption channel [4].

The energy storage drive mechanism consists of motors, flywheels, reducers, and coupling. Motor end is connected with the flywheel, willing a higher speed, which has high torque, passing on the bit by drilling device, to overcome the hard rock with reverse torque. The other is joint to the speed reducer, to make sure the millet shaft movement is not too large.

In order to allow dense bead drilling mechanism a continuous vibration impact, and retrench energy, the new type of magnetron drive is adopted. Four strong magnets are put on the supporting plate, with its reverse symmetrical distribution, generating double poloidal field. Two symmetrically identical magnets are assembled on fixed support. When mill bead is into rotary
motion, two strong magnets will be affected by the support of different polarity of cyclical attraction and repulsion. On the contrary, the supporting plate are fixed on a board periodically attraction and repulsion, so as to achieve the effect of continuous vibration impact.

There is a gap between the output shafts of the mechanism, and the drill is subjected to lateral load and longitudinal load when sampling hard rock, causing the drill pipe to throb irregularly. The throbbing is extremely unfavorable to drilling of bit and sampling, so the corresponding measures should be taken to improve the precision of the shaft system and the coaxial degree.

The basic structure of the bearings is composed mainly of the shaft journal, the shaft sleeve, and the radial and axial density of ball bearings. The installation of the compact bead bearing on the pipe can improve the irregular beating of the shafting. The ball on the bearings can guarantee the shaft of the pipe to the clearance and be fixed in the radial direction, thus having higher precision of shafting.

To save space and reduce the sampler overall quality, to take in the middle of the drill bit segregate the dual channel, inflatable by outer channel, channel in smoke gas, to realize the collection of samples under the flow of air.

**Drilling Sample Parameter Design**

**Bit Cutting Force Calculating**

On the process of drilling and sampling, the drill pipe owns the function of penetration under effect of magnetic force. The cutting process is the formation of the rock layers under the action of the tool [5]. Based on hard and brittle rock tensile breakage mechanism, establish a cutting and braking model of star layer. Assuming the crushing is caused by the tensile stress [6], as shown in Figure 1.

![Figure 1. Mechanical model of cutting rock formation.](image)

The force of the solid nucleus impacting on the rock is as Eq. 1 as

\[
R = 2\int_{0}^{\pi/4} a \sigma_c \cos \theta d \theta = 2\sqrt{2} a \sigma_c. \tag{1}
\]

In this form, \(\sigma_c\) is single axial compressive strength of rock formation and \(\theta\) is normal pressure infinitesimal angle of nucleus and layer. As the force is large enough, the rock strata will break along the arc line of \(ABC\) under the influence of tensile stress [7]. The tensile strength of the rock formation, as Eq. 2 as

\[
T = \sigma_t r \int_{\phi}^{\pi/2} \cos \beta d \beta = 2\sigma_t r \sin \phi = \frac{\sigma_t h}{\sin \phi}. \tag{2}
\]

In this form, \(T\) is the limit tensile stress of the unit width strata, \(\sigma_t\) is single axial tensile strength of strata, \(\phi\) is rock’s breaking angle and \(h\) is cutting depth of the axis.

By the equilibrium condition of the point C moment, the limit tensile stress \(T\) of the broken rock is combined with the solid nucleus as Eq. 3 as

\[
271
\]
$$R \left[ \frac{\sqrt{2}}{2} a + \frac{h}{\sin\phi} \cos \left( \phi + \frac{\pi}{4} \right) \right] - T \frac{h}{2\sin\phi} = 0.$$  \quad (3)

Due to the small star is more of weathering soil, and its hard is only 1/6 of the earth layers, and the current data on small celestial star soil is relatively scarce, so the simulation calculation here take JSC Mars -1 Martian soil mechanics parameters [8].

So we can plug this data to get the $F_h = 98 \, \text{N}$, $F_v = 120 \, \text{N}$, $\phi = 44.2 \, ^\circ$, $M = 0.48 \, \text{N} \cdot \text{m}$. With the expected nominal torque difference, the amount of torque is sufficient when astral rock formation is close to JSC Mars-1.

**Calculation of Bit Turning Parameter**

The interplay of the drill blade and rock formation will produce the broken pit, and the hit frequency is related to the speed and rotary speed of the drill, as Eq. 4 as

$$f = \frac{2\pi \cdot D \cdot n \cdot \tan \phi}{60h}.$$  \quad (4)

The torque and impact frequency satisfy the following relations as Eq. 5 as

$$M = 0.81D^2 \cdot f^{0.8} \cdot K_p.$$  \quad (5)

In this form, $K_p$ is correction factor and numbered 0.93. According to verticals, calculate a bit diameter $D = 10 \, \text{mm}$, $h = 0.02 \, \text{mm}$, and the impact frequency and turn rotational speed is $f = 10 \, \text{Hz}$, $n = 186 \, \text{r/min}$.

The drill is expected to be between 100 and 200 rpm, so the speed is feasible.

**Magnetic Force and Axial Force Computation**

When sampling is taken by the sampler, the axial drilling drive is provided by the magnetic force, which is supported by the bearings of the compact beads, and the vibration impact is achieved [9]. The magnetic force is calculated with the empirical formula of NDB ferromagnetism as Eq. 6 as

$$F = 2 \left( \frac{B_p}{4956} \right)^2 \cdot S.$$  \quad (6)

In this form, $B_p$ is magnetic flux density of the permanent magnet and its unit is Gauss, and $S$ is magnetic area of the permanent magnet.

The needed NDB ferromagnetism can be known for its diameter of 5 mm, thickness of 1 mm, remanence $Br$ of 14500 T (Tesla) and calculated $F = 6.23 \, \text{Kgf}$. Getting magnetic $F$ prime is equal to 62.3 N. In the case of mechanism, there are two pairs of magnets, so the total force is $2F' = 124.6 \, \text{N}$.

The maximum axial cutting force is 120 N, so the drilling driving force provided by the magnetic force can meet the requirements.

**Parameter Design of Motor and Flywheel**

Sampler in rotary motion, electricity is to drive flywheel of high-speed rotation, then achieve and maintain a constant one. To get a big moment of inertia of the flywheel, electrical energy is stored in the form of kinetic energy of flywheel, thus completing the process of electrical energy to mechanical energy conversion of energy storage.

When load effects, the flywheel motor in high speed rotating flywheels round body, will decrease the flywheel kinetic energy into a load, with the effect of kinetic energy to electrical energy to kinetic energy transformation, namely the flywheel reduced portion of the kinetic energy is "transplanted" to the load, completed the flywheel kinetic energy release [10].
Calculating the torque of flywheel can be converted to flywheel by the equal power condition, and the power conversion efficiency is added. The speed on the reducer 1st axis is met by the rotational speed of 2nd. Reduction gear reduction ratio \( i = 3.7 \), the power conversion efficiency \( \varepsilon = 0.8 \), can calculate the flywheel torque \( M_F = 0.162 \text{N·m} \).

Regardless of the transmission efficiency, according to the drilling speed and transmission ratio, can calculate the motor speed between 680 ~ 700 rpm, so can select motor model for M28GXR, the motor and reducer, level of reduction ratio is 3.7, so it meets the requirements.

The drilling mechanism is used as the equivalent component. According to the equal kinetic energy conditions, can obtain the rotary inertia of flywheel as Eq. 7 as

\[
J_F = \frac{J_L}{i^2} - \frac{J_2}{i^2} - J_m - J_1
\]

In this form, \( J_L = 2.492 \times 10^{-7} \text{kg·m}^2 \), \( J_1 = 1.42 \times 10^{-9} \text{kg·m}^2 \), \( J_2 = 1.42 \times 10^{-9} \text{kg·m}^2 \), \( J_m = 3.12 \times 10^{-5} \text{kg·m}^2 \), so the \( J_F \) can be calculated for \( J_F = 2.15 \times 10^{-6} \text{kg·m}^2 \).

**Drilling Mechanism Dynamics Analysis**

The main content of drilling mechanism dynamics analysis is the impact of the drill, the analysis of torque and the change of the internal force of the drill. Using ADAMS to analyze the various institutions to verify the rationality of the organization [11].

Based on the theoretical analysis and calculation, in front of the bit impact is driven by magnetic effects, but as the drill pipe rotation, the impact will cause a unstable wave, so it is necessary to analyze the impact of the drill bit. To improve the simulation speed, the 3D model is simplified and then imported into ADAMS software. The properties of the material and the moving pairs are set up, and the external load and drive torque (10,000 times magnification) are applied to simulate the motion simulation. Calculate the impact of the drill bit as shown in Figure 2, with an impact average of 125N.

![Figure 2. The impact of the bit changes over time.](image)

![Figure 3. The bit torque varies over time.](image)

The torque of the drill will also change with the time of the cutting strata, so the analysis of torque is also necessary. When the motor drives the flywheel rotation, rotation movement will also drive the drilling mechanism, and bit will start from zero growth. When the speed reached a peak, immediately shock rock, at this time will be affected by rock greatly reverse torque, so the torque bit instantly at greatly reduced, and stable cutting rock formations, will be relatively stable, present a rapid increase, and then fell sharply, and then a relatively stable fluctuations, as shown in Figure 3.

As an institution of drilling, internal stress analysis is also indispensable. In ADAMS, the analysis of internal stress should be bit as flexible body analyzed. According to the finite element theory, it needs to be discrete components into a certain number of units. The more numbers, and the higher calculation precision, however, the greater high meshing component deformation. So it should choose the selected. The inner stress of the drill is shown in Figure 4. The drill has to vibrate at the same time as the cutting rock, so the drill is necessary to be analyzed for vibration. The analysis of the strain modal analysis of the natural frequency is shown in Figure 5.
Conclusion

In this paper, the absorbing type star soil sampler consists of Flywheel energy storage mechanism, Magnetic drive mechanism, Dense bead drilling mechanism and Air flow channel of intake, with light body small to meet the needs of small objects sampling under low gravity environment. Based on the analysis of this paper, the sample size is less than 2 mm, the sampling mechanism can reach 120 N, the lateral cutting force can reach 98 N, and the torque is 0.48 N. By ADAMS software to the impact of the drill bit, torque and internal stress are simulated, the results show that under the proper setting of parameters, the sampler can complete the sampling work with stability, simply and effectively, and provide a reference for subsequent small objects sampling technology.

References

[10] Denghui Xu, Motor and shafting design in flywheel energy storage system [D], Zhejiang University, 2016.