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Experimental Study for Rover Mobility on Lunar Simulant Terrain in Vacuum Condition

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Abstract

In future planetary exploration missions, rovers are required to traverse over very rough terrain. The Moon's surface is covered with soil which is named regolith. Regolith is easy to slide. A stack occurs to the rovers which are running on the regolith. The cause of the stack is not yet clear. At first, this paper investigates kinematics behavior of lunar rovers with a tire-soil traction mechanism where the condition of the moon is a vacuum. In vacuum condition, experiment of the running is carried out, and, air and vacuum conditions are compared. Finally, this paper considers whether experiment of vacuum is effective on the earth.

Keywords

lunar rover, mobility, tire-soil model, vacuum condition

1. INTRODUCTION

Rovers are considered one of the most important mission devices for planetary explorations. Rovers are also expected to move on planetary surfaces to collect precise information regarding the origin and maturing. In the Mars mission by NASA in 1997, the micro rover Sojourner moved and explored on the surface of Mars. Sojourner sent the important data and detailed pictures to the Earth. The mission showed the importance of moving robotics [Kubota, 2003].

In planetary exploration, rovers are required to move on rough terrains such as in craters and cliffs where it is scientifically very important to explore. Further, rovers must avoid a tip-over and stack even though they move on rough terrains.

Some researches have proposed rovers with interaction between wheel and soil on a flat terrain [Yon et al., 1986] [Iagnemma and Dubowsky, 2000]. At first, in this paper, a interaction model between wheel and soil in a slope terrain is carried out. From this model, a important parameter for traversability is distilled. However, running on the moon is not simple, because the environment of the moon is not same as the earth. In this paper, the experiment is carried out in a vacuum condition. And it observes the difference between air and vacuum condition. Moreover, it considers whether the experiment on the earth is effective for lunar rovers.

This paper is organized as follows: in section 2, the important parameters are derived by using a rough model, in section 3, the results of basic experiments are shown, section 4 is for the conclusion of this paper.

2. INTERACTION BETWEEN WHEEL AND SOIL

2.1 Dynamic behavior of soil

Because lunar surface is covered with regolith, the ground of the Moon's surface is soft and it is easy to slide. Regolith is made up of the fragments broken from the Moon and other heavenly bodies. On such a surface, a normal wheel cannot easily produce traction force easily for movement. Therefore exploration rovers need to install "rug" for increasing traction force. In the case of the wheel with rug, to understand the interaction between a wheel and soil, it is necessary to consider the soil's behavior such as subsidence characteristics, shearing force intensity, modification characteristic of shearing, and friction characteristics.

2.2 Wheel model on slope

When rovers explore the Moon, the environment is a vacuum and is exposed to space radiation. Moreover, the temperature difference between day and night is intense. In such an environment, tires which are generally used on the Earth cannot be used for lunar exploration.

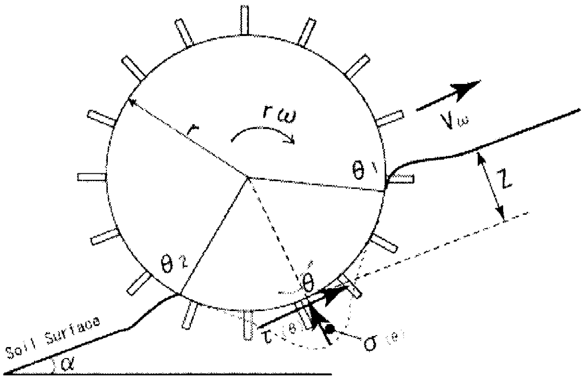

Fig. 1 Wheel model on slope

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Then, usually a metal wheel is used and a wheel can be considered as a rigid body. At the time of running, the interaction between a wheel and soil can be considered by the model shown in Figure 1 [Iagnemma et al., 2002] [Yoshida and Hamano, 2001] [Iizuka et al., 2005].

2.3 Stress at contact surface

It is assumed that soil shows hardening behavior of distortion by a shearing stress when a wheel is moving, the shearing stress in the angle θ can be written as follows.

$$\tau(\theta) = ((c + \sigma(\theta))\tan\phi)(1 - \exp(-\frac{j}{K})) \qquad (1)$$

where

c: adhesive power
j: shearing strain
ϕ: internal friction angle

The normal stress $\sigma(\theta)$ from the surface of soil to a wheel is distributed as shown in a Figure 1 and it can be approximated with a secondary curve.

$$\sigma(\theta) = a(\theta - \theta_1)(\theta - \theta_2) \qquad (2)$$

where
α: characteristic constants
θ_1: angle which wheel ingresses into soil
θ_2: angle which a wheel escapes soil
The slip ratio λ is defined by the following formula here.

$$\lambda = \begin{cases} 1 - \dfrac{V_\omega}{r\omega} : (r\omega \geq V_\omega) \\ 1 - \dfrac{r\omega}{V_\omega} : (r\omega \leq V_\omega) \end{cases} \qquad (3)$$

where
r: the radius of a wheel
ω: angular velocity of a wheel
$V\omega$: moving speed of a wheel
Moreover, the sinkage z can be written as follows, if penetration angle θ_1 is used.

$$z = r(1 - \cos\theta_1) \qquad (4)$$

Shearing distortion j can be expressed by using slip ratio as follows, because it can be described as integration of slip's speed $(r\omega - V_\omega \cos\theta)$.

$$j = r\{(\theta_1 - \theta) - (1 - \lambda)(\sin\theta_1 - \sin\theta)\} \qquad (5)$$

2.4 Force load on wheel

Perpendicular force N can be expressed as perpendicular elements toward the slope of shearing stress $\sigma(\theta)$ and the normal stress $\tau(\theta)$ is intergraded using loading area. In the width direction of a wheel, when stress distribution is fixed, it is expressed as follows using a wheel radius r and wheel width b.

$$N = rb\left\{\int_{\theta_1}^{\theta_2} \sigma(\theta)\cos\theta d\theta + \int_{\theta_1}^{\theta_2} \tau(\theta)\sin\theta d\theta\right\} \qquad (6)$$

The traction DP of a wheel is the total of the turned-up force toward a slope. Therefore traction is expressed as turn-up elements toward a slope of a shearing stress $\tau(\theta)$ and normal stress $\sigma(\theta)$ is intergraded using loading area. Like a perpendicular, in the width direction of a wheel, when stress distribution is fixed, it is expressed as follows:

$$DP = rb\left\{\int_{\theta_1}^{\theta_2} \tau(\theta)\cos\theta d\theta - \int_{\theta_1}^{\theta_2} \sigma(\theta)\sin\theta d\theta\right\} \qquad (7)$$

Moreover, the torque T produced for a wheel is expressed as follows:

$$T = r^2 b\int_{\theta_1}^{\theta_2} \tau(\theta)d\theta \qquad (8)$$

2.5 Parameters for given influence on driving performance of a wheel

On a lunar surface, driving performance of a wheel's robot is not good because the regolith is easy to slide. Therefore the motors used for robots have large torque. When a wheel cannot move, working force in the forward direction is smaller than the opposite force produced from gravity. The traction of a wheel DP becomes a function of the slip ratio λ, the penetration angle θ_1 and the escape angle θ_2. The sinkage becomes a function of the the penetration angle θ_1 and the escape angle θ_2. Therefore the function DP can be expressed as follows:

$$DP = f(\lambda, z) \qquad (9)$$

Shearing stress τ increases simply because the slip ratio increases. Then the increase of slip ratio means the increase of discharged soil by rotation of a wheel. If the sinkage increases, the penetration angle θ_1 and the escape angle θ_2 increase. It is reported that the slip ratio is an important parameter on the traversability of a wheel. The important points for the traversability of rovers involve the behavior of soil. On the moon, the environment is particular and different from the earth. This paper focuses on vacuum condition on the moon.

The slip ratio of the traversability is not clear on vacuum codition. If the environment becomes in vacuum condition, the particles of soil occur different behavior. In vacuum condition, the friction of the particles of soil is large and hardening effect of soil is appeared more and more because air between the the particles of soil lose. However these influence is not clear.

So, in the earth, vacuum condition is made, and the running experiment will be carried out.

3. EXPERIMENTAL STUDY

The interaction between wheel and soil focused in Section 2 where the slip ratio is as important parameter for the traversability of the wheel.

The experiment verifies whether the situation of vacuum actually gives some influence to the traversability.

3.1 Experimental system

The vacuum chamber is shown in Figure 2. The diameter of the vacuum chamber is 1.0[m] and length is 2.5[m]. The material of the chamber is stainless steel. Inside condition can be seen from front small a window. The vacuum condition is made by a vacuum pump. The vacuum system has two devices. One type is grease diffusion. The other is grease revolution. The vacuum condition is made by combining these types of devices.

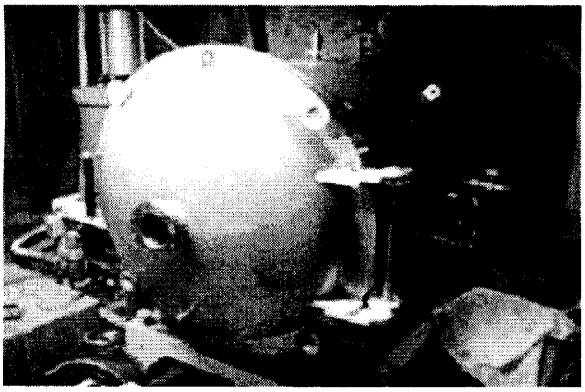

Fig. 2 Vacuum chamber

In this experiment, a soil simulant is used, whose particle specific gravity is 2.83, the minimum density is 1.39[g/cm^3], adhesive power is 5.0[kPa] and internal friction angle 36.7[deg]. The depth of the simulant is 0.20[m].

As a test bed, the running robot used is a small model rover (Figure 3). The specifications of small model rover are shown in Table.1. When the chamber is in vacuum condition, the rover can't be released all heat. Therefore CPU of rover can start program as soon as the rover has a power supply. Also, the rover has two CPU. Each CPU controls one side wheel (each front and rear wheel).

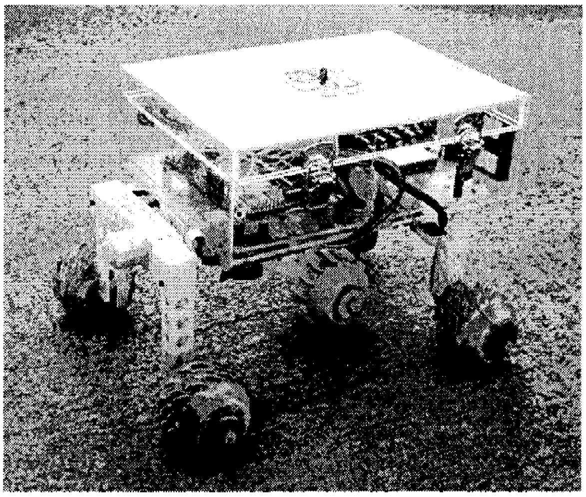

Fig. 3 Small model rover

Table 1 Specifications of small model rover

Body length	0.21[m]
Body width	0.17[m]
Whole length	0.26[m]
Whole width	0.22[m]
Vehicle high	0.10[m]
Wheel diameter	0.05[m]
Wheel Width	0.05[m]
Mass	1.3[kg]
Mobility System	4WD
Maximum Speed	0.80[m/s]
Motor	Maxon RE13
Gear	Maxon GP13A

The motors of the wheel are moved by PID control. Control CPU installed outside vacuum chamber controls operation (receive and trance of data) of rover. The system interaction inside and outside of the vacuum chamber is shown in Figure 4. The experimental system is composed of some sensors: cameras for measured distance, and two encoders. The measurable distance by cameras is within 0.5[m]. To see value of encoder calculates revolution of each wheel. The velocity of the wheel is calculated too. Rugs are attached at a height of 0.123[m], width of 0.15[m] and 22.5[deg] intervals. In the experiment the traversability is investigated by changes in the speed of a wheel and the slope of simulant surface.

Table 2 shows the experiment parameters.

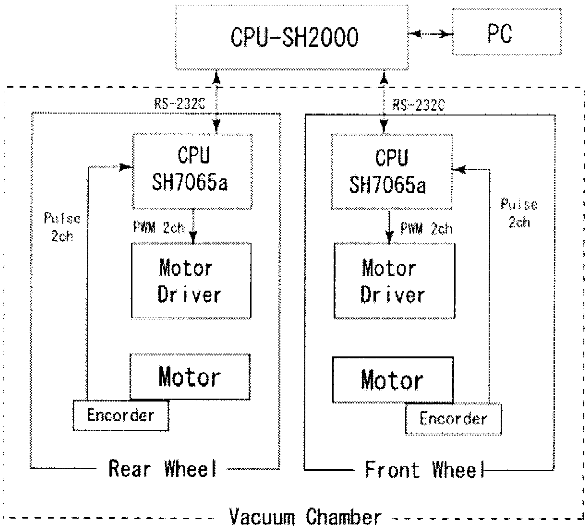

Fig. 4 Block diagram of hardware interface for scale model rover

Table 2 Experiment parameter

Air Pressure	760, 1.0×10^{-7} [torr]
Speed	0.1, 0.4 [m/sec]
Slope	0, 15, 20 [deg]

3.2 Experimental process

The first condition of the experiment is shown in Figure 3 and experimental process shows the following:

(1) Door of chamber is opened and soil is raked.
(2) Door of the chamber is closed and inside of chamber will be made into a vacuum condition.
(3) When the chamber becomes a vacuum condition, rover achieved power supply and the wheel rotates.
(4) When distance which rover runs is 0.40[m], the running of rover is finished.

Measurements are repeated (1)-(4).

3.3 Experimental results

Figure 5 shows the experimental results. Figure 5 shows values of slip ratio at slope. On vacuum condition, the speed 0.1[m/s] is a solid line and 0.4[m/s] is a dash line. On air condition, the speed 0.1[m/s] is a dotted line, and 0.4[m/s] is a broken line. When the inclination of a slope becomes larger, both slip ratios (air and vacuum) increase. But slip ratio of vacuum condition is a little better than air condition because the air between soil and soil was lost by vacuum and soil was not easy to move. The shearing force decreases. However, slip ratio of air and vacuum condition is not large difference. Moreover, the influence of vacuum condition is small. Therefore the running of the air condition can show same traversability of the vacuum condition.

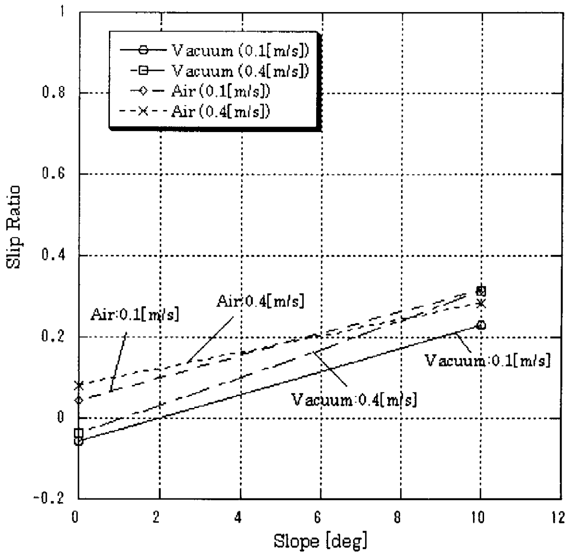

Fig. 5 Slip ratio of air and vacuum conditions

4. CONCLUSION

This paper has presented the rover mobility on the slope of regolith in a vacuum condition. Both air and vacuum conditions were compared. As a result, traversability in both conditions is not very different. Therefore, experiments on the earth (air condition) are effective for lunar rover.

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