Development of a Flexible Wheel That Allows Rovers to Traverse Lunar Soil

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Abstract

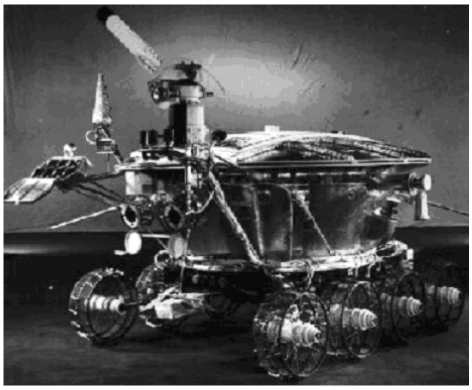
Lunar rovers are required to traverse rough terrains that include craters and rear cliffs, which are scientifically important locations that need to be explored. Recently, wheeled rovers have been gaining popularity for their use in conducting planetary exploration missions. However, there is a problem associated with wheeled rovers in that they are likely to get stuck in soil while traversing such terrains. In this study, we develop a new flexible wheel. This wheel can traverse soft soil. We describe an interaction model between the flexible wheel and soft soil. Then, on the basis of this model, we propose new wheel forms. In addition, to determine the traversability of the proposed wheel on the basis of slip ratio and sinkage, we perform running experiments on soil, similar to regolith.

Keywords

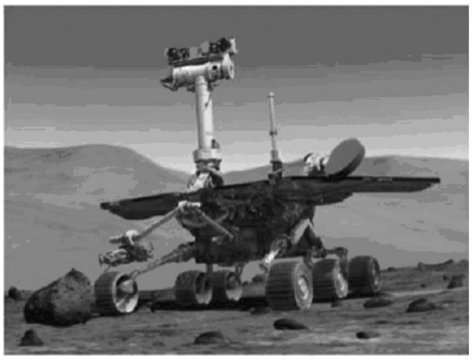
lunar rover, flexible effect, soft soil

1. INTRODUCTION

Robots are considered to be one of the most important mission devices that can be used in planetary explorations; they are expected to traverse planetary surfaces to collect precise information regarding the origin and maturing. The NASA Mars mission in 1997 was accomplished using the micro robot Sojourner that traversed and explored the surface of Mars. Sojourner transmitted important data and detailed pictures to the earth. The Sojourner mission showed the importance of moving exploration [NASA/JPL, 1997]. In planetary explorations, robots are required to traverse rough terrains that include craters and rear cliffs, which are scientifically important locations that need to be explored. Further, while traversing such terrains, robots should not tip over and get stuck in soil. In previous lunar missions, Lunokhod [Russian, 1970] and Lunar Rover Vehicle [NASA, 1971] traveled long distances on regolith in order to carry out explorations. These robots were very large and heavy (approximately 800 [kg]). Such heavy robots are known to have high running performance on soft soil. However, it is not practical to use such robots for conducting future missions because of limitations in payload, cost, and capacity. Therefore, it is essential to downsize future robots. However, it is difficult for small robots such as Sojourner to traverse soil, because it is hard to get effective impulse from soil. In this study, we performed several running experiments on soft soil using a wheel whose size was smaller than that of Lunokhod (Figure 1 (a)) and MER (Figure 1 (b)) [NASA/JPL, 2003]. The size of the rover's body was decided after taking into consideration its use in future lunar missions. The results of these experiments showed that a small-sized wheel had low running performance. If the size of the wheel was smaller than that of the LRV and Lunokhod, the running performance was poor. Theresults of this study showed that a mid-sized wheel (approximately Φ200 mm) can easily sink into soft soil such as regolith. If the wheel sinks to a considerable depth



(a) Lunokhod [Russia]



(b) MER [NASA/JPL]

Fig. 1 Exploration robots

(a) Lunokhod [Russia]

(b) MER [NASA/JPL]

Fig. 2 Wheels for exploration robots

in the soil, the degree of slip increases. Therefore, rovers with small- or mid-sized wheels easily get stuck in soft soil. Therefore, in order to improve the running performance of wheels, a flexible material was used on the surface of the wheels [Iizuka et al., 2008]. The contact area of the flexible wheel with the ground increases. However, if the surface of the wheels is flexible, the surface of the wheel strains by steering. In this study, we propose a new flexible wheel that exhibits high performance without torsion.

In section 2, the interaction between flexible wheels and soft soil is modeled. Then, in section 3, a new flexible wheel is presented. In section 4, the experiment and its results are described. In section 5, the conclusions of this study are provided.

2. INTERACTION BETWEEN WHEEL AND SOFT SOIL

2.1 Running mechanism of circular rigid wheel on soft soil

In this study, the interaction between a wheel in motion and soft soil was examined [Iizuka et al., 2005]. From the experimental results, we clarified that the poor running condition of the wheel was attributed to its sinking behavior.

The running mechanism of the wheel is shown in Figure 3. On a slope, the wheel is subjected to a traction load, which retards its movement. This implies that the wheel slips. Even if the wheel slips, the soil under the wheel is displaced. Displacement of the soil from under the wheel results in the wheel sinking into the soil. When the wheel sinks into the soil, the slope along which the wheel moves increases. When the wheel moves along a steep slope, the applied traction load increases. Under these conditions, the circular rigid wheel experiences high stress. Therefore, circular wheels are known to easily sink into soil. In order solve this problem, typically, either of the following two methods can be used.

(1) A method in which the weight of space robots is decreased.
(2) A method in which the diameter of the wheel is increased.

However, if robots are light in weight, the driving force required to traverse soft soil decreases. Moreover, in order to conduct future missions, it is essential to increase the diameter of the wheel. Therefore, in this study, the feasibility of a flexible wheel for conducting future missions was examined. The performance of the flexible wheel was better than that of the circular wheel.

2.2 Interaction model between flexible wheel and soft soil

We describe an interaction model between a flexible wheel and soft soil. Over the past few years, several studies have been conducted on an interaction model for a circular solid wheel [Bekker, 1955; Yon et al., 1986; Yoshida et al., 2001; Iagnemma et al., 2002; Ishigami et al., 2006]. Moreover, Muro [Muro, 1993] has modeled the interaction between low-stress tires and the ground. The wheels that are to be used on the lunar surface must be made of metal in order to sustain the unique environment on the lunar surface that includes vacuum conditions, radioactive rays, and large variations in temperature. A flexible wheel made of metal can change form. The material used on the surface of a flexible wheel is spring steel. When a wheel made using spring steel is loaded with weight, its form changes such that the part of the wheel that is in contact with the ground becomes flat. The interaction model between a flexible wheel and soft soil is shown in Figure 3. Thesurface of the flexible wheel becomes flat on the ground surface. Traction force is an important factor that must be considered during traversal on ground. In this study, we propose an advanced model. This model is based on that developed by Muro. However, Muro's model does not consider

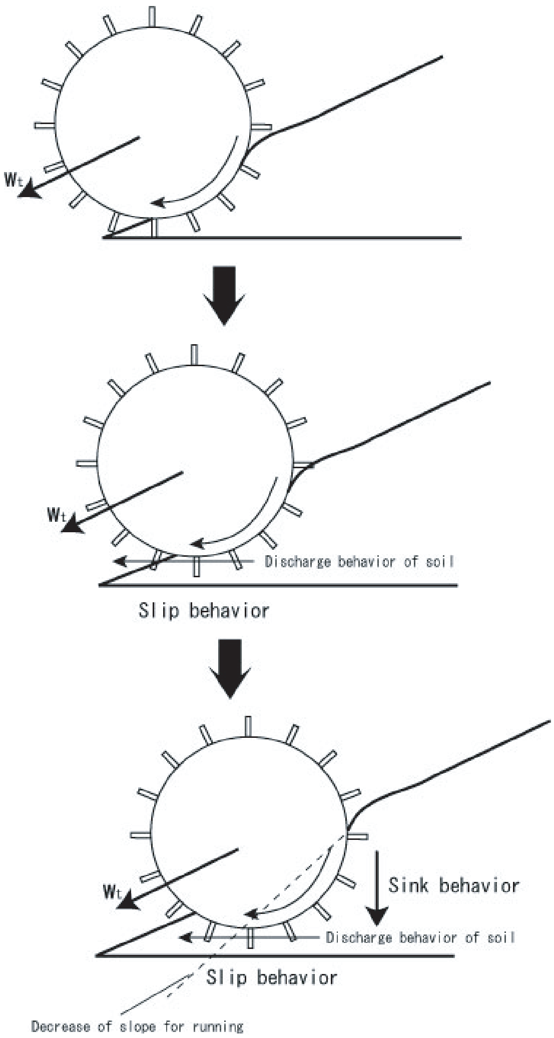


Fig. 3 Running mechanism

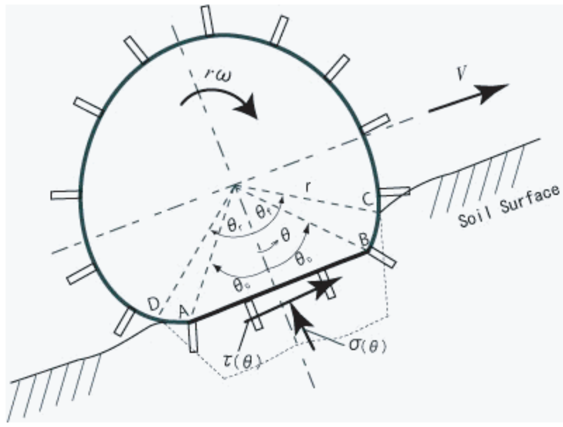


Fig. 4 Interaction model

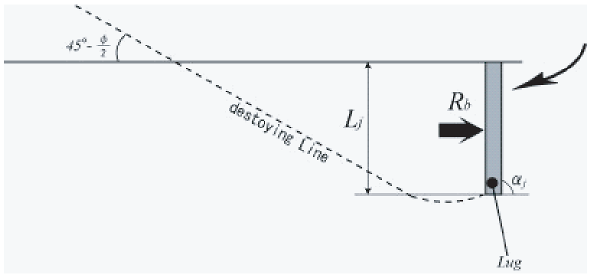


Fig. 5 Lugs model

the effect of lugs on the wheels.

Therefore, in this study, we propose an advanced model that includes the effect of the lugs. The traction force DP is determined using various parameters such as the radius of the wheel, r; the entry angle θ_f ; the exit angle θc; the normal stress $\sigma(\theta)$; the shear stress $\tau(\theta)$; length of flat side between the points A and B, l_{AB}; the reaction stress R_b; the length of the lugs L_j; the width of wheel, b; and the slip ratio λ.

$$DP = rb\left\{\int_{\theta c}^{\theta_f} Ad\theta + \frac{1}{r}\int_{0}^{l_{AB}} \tau(\theta)d\theta + \int_{\theta r}^{\theta_c} Ad\theta\right\} + L_j by\left\{\int_{\theta c}^{\theta_f} Bd\theta + \int_{\theta c}^{\theta_f} B\frac{1}{\cos\theta}d\theta + \int_{\theta r}^{\theta_c} Bd\theta\right\} \quad (1)$$

where

$$A = \tau(\theta)\cos\theta - \sigma(\theta)\sin\theta$$
$$B = R_b \cos\theta$$

When the lugs insert into soil, the wheel can get the reaction stress from soil. The reaction stress is expressed using L_j as follows:

$$R_b = \frac{\sin(\alpha_j + \phi)}{\sin\alpha_j}\left\{L_j c(N_c - \tan\phi) + \frac{1}{2}\gamma L_j^2\left(\frac{2N_r}{\tan\phi} + 1\right)\right. \quad (2)$$

where

α_j: angle of approach

γ: soil density

L_j: lug length

c: cohesion stress

ϕ: friction angle of soil

N_c, N_r: coefficien ts of support force

As observed in Figure 3 (a), in this model, it is important to consider the flat part of the wheel, i.e., the part between points A and B. In this flat part, the reaction force applied by the soil to the wheel and also the lugs is significant.

2.3 Problem of flexible wheel

In this study, experiments were performed using the flexible wheel [Iizuka et al., 2008]. Figure 6 shows the flexible wheel. The running performance of the flexible wheel was high. The flexible wheel can get the efficient impulsion from soil because of its flat surface at the point of contact with the ground. Moreover, in case of the flexible wheel, the area over which the soil hardens due to the application of the wheel load is wide. However, at torsion, the flexible wheel can-

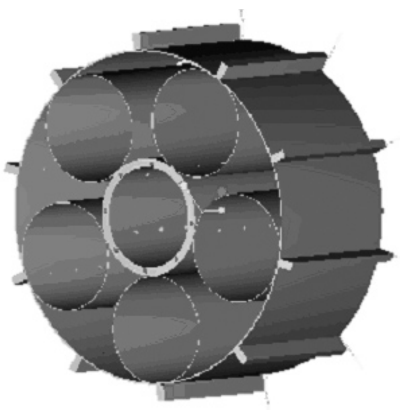


Fig. 6 Flexible wheel [Iizuka, 2007]

not move. The material of the surface of the flexible wheel is soft. Therefore, we need to consider a wheel that is resistant to torsion to effectively benefit from the characteristics of the flexible material.

3. PROPOSED WHEEL

The proposed flexible wheel can be used to easily traverse soft soil. However, the steering movement of this wheel is restricted. On the other hand, a circular rigid wheel does not change its form. Therefore, the circular wheel does not have any torsion during steering. Therefore, we develop a compound wheel as shown Figure 7. The compound wheel is a flexible circular wheel. Two flexible wheels are installed on both the sides of the circular wheel. We believe that the flexible wheel does not sink into the soil while traversing soft ground. The diameter of the wheel is 200 [mm] and its width is 160 [mm] (the portion of the rigid is 100 [mm] and the portion of the flexible are 30 × 2 = 60 [mm]). The rigid portion is made of aluminum. The flexible portion is made of copper beryllium.

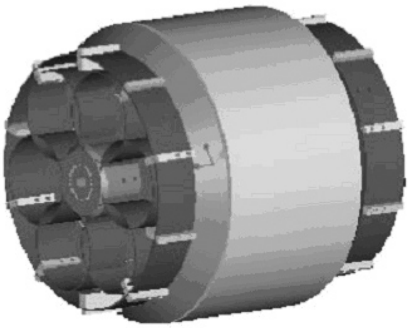


Fig. 7 Proposed wheel

4. EXPERIMENTAL STUDY

4.1 Experiment system

The overview of the experimental system is shown in Figure 8. In this experiment, the simulant was soil, having a particle specific gravity of 2.83, a minimum density of 1.39 [g/cm^3], an adhesive power of 5.0 [kPa], and an internal friction angle of 36.7 [°]. The thickness of the simulated soil was 0.07 [m]. It was dried using a heater. The experimental system comprised some mechanical parts and sensors, as shown in Figure 8. One wheel, a parallel link, stator, guide rail, load balance, and balance box were used for carrying out the simulation. The parallel link was attached between the axis of the wheel and the load balance. The load balance ran on the guide rail. The sensors included a differential transformer and two encoders. The differential transformer was used to measure the horizontal position of the wheel. The maximum distance measurable by the differential transformer is 20 mm. The vertical position of the wheel was calculated using a rotary encoder. The velocity of the wheel was calculated by using the vertical and horizontal positions and the time taken by the wheel to cover a certain distance. The rotation of the wheel was obtained from the encoder. The slip ratio was calculated using the values of velocity and rotation. Sinkage was determined by measuring the depth of the soil before and after performing the running experiments, thereby estimating the difference. The load on the wheel was set by placing an appropriate weight in the balance box.

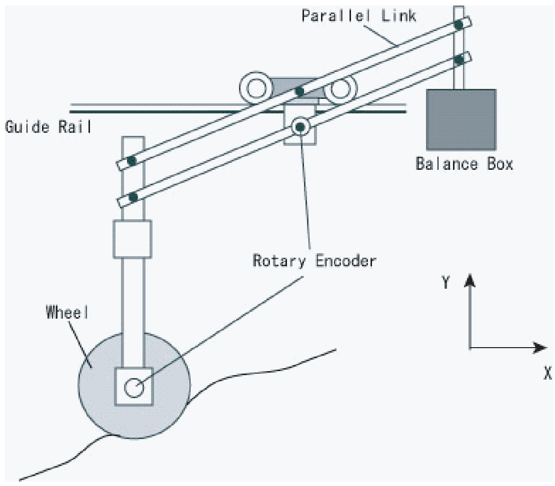


Fig. 8 Experiment system

4.2 Experimental conditions

In the parameters experiment, the wheel load and slope angle could be varied. The experimental parameters are listed in Table 1.

Table 1 Experimental parameters

	Value	Unit
Load	3.0	kg
Speed	0.1	m/s
Slope	0, 5, 10, 15, 20, 25	°

4.3 Results and discussion

Figure 9 shows the photograph of the running experiment. The wheel with a flexible effect can traverse soft soil. Table 2 lists the experimental results. A rigid circular wheel traversed soft soil along a slope ranging from 0 to 15 [°]. However, when the circular wheel traversed soft soil along a slope of 20 [°], the slip ratio and the sinkage of the circular wheel increased. In the case of the circular wheel, there are not floating elements from soil. When the wheel sinks into the soil, it exhibits high resistance. Therefore, the circular wheel has limitations in terms of traversing soft soil along a slope. On the other hand, the flexible wheel can traverse soft soil along a slope ranging from 0 to 20 [°]. Figure 10 shows the results of the running experiment performed at a slope of 0 [°]. Both the abovementioned wheels had high performance. At a slope of 0 [°], the wheels did not have high resistance and gravity influence.

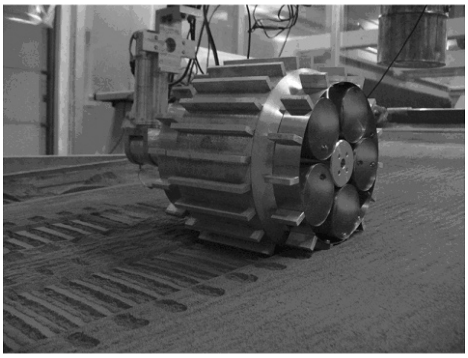


Fig. 9 Photograph of running experiment

Table 2 Results of experiment

	Slope Angle [°]					
Flexible effect	0	5	10	15	20	25
With (Proposed)	○	○	○	○	○	
Without (Circular)	○	○	○	○	×	×

Note: Dimensions of the wheel: diameter 200 [mm], width 160 [mm]

Figures 11-12 show the results of the running experiment performed at slopes of 5 and 10 [°]. Along both these slopes, the values of the slip ratio were small and the running condition was good.

Figure 13 shows the result of the running experiment performed at a slope of 15 [°]. The value of the slip ratios of both the wheels were approximately 0.6. When the value of the slip ratio is 0.6, the wheel sinks easily. If the wheel continues to traverse soft soil along a slope, the value of the slip ratio increases.

Figure 14 shows the result of the running experiment performed at a slope of 20 [°]. The value of the slip

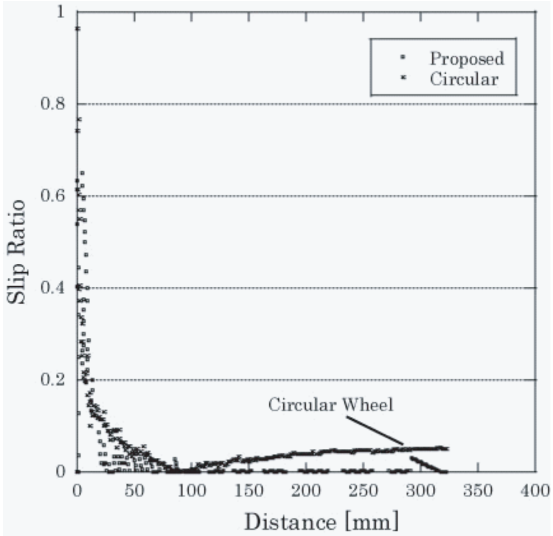


Fig. 10 Experiment result of slip ratio (0 [°])

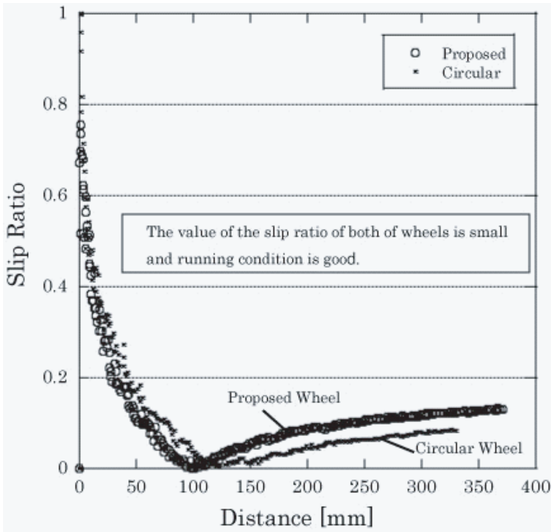


Fig. 11 Experiment result of slip ratio (5 [°])

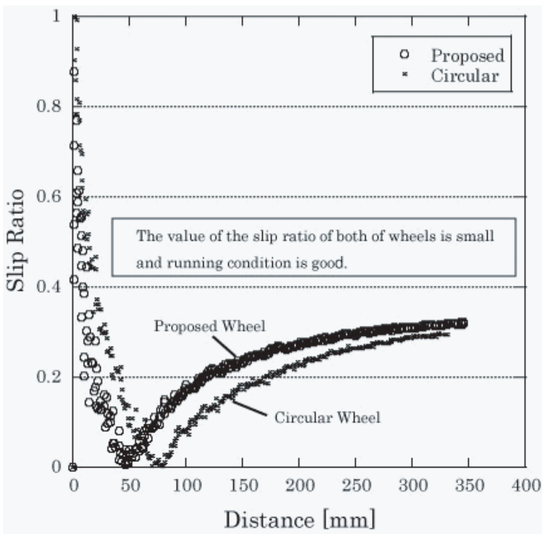


Fig. 12 Experiment result of slip ratio (10 [°])

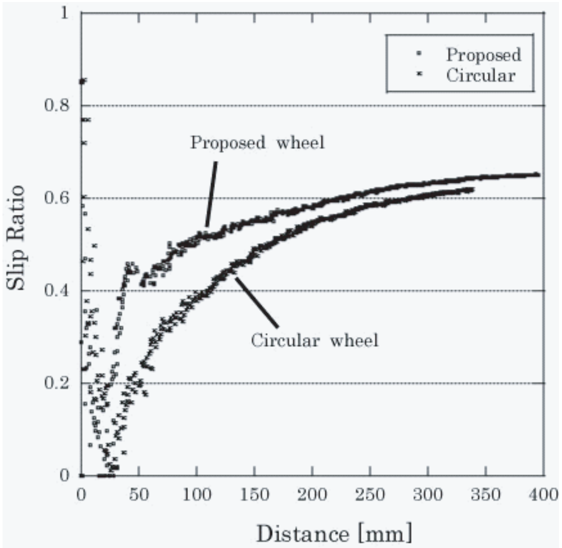


Fig. 13 Experiment result of slip ratio (15 [°])

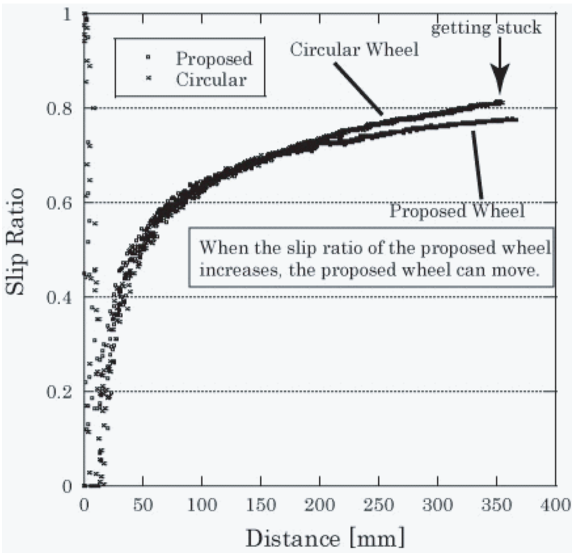


Fig. 14 Experiment result of slip ratio (20 [°])

ratio of the flexible wheel was smaller than that of the circular wheel. The circular wheel could not traverse soft soil along a slope of 20 [°]. While traversing along this slope, the circular wheel would get stuck in soil. On the other hand, if the value of the slip ratio of the flexible wheel is large (approximately 0.6), the wheel can traverse soft soil along a slope.

Figures 15-16 show the results of the current experiment performed at slopes of 15 and 20 [°]. At a slope of 15 [°], the current value of the flexible wheel is stable. However, that of the circular wheel tends to increase. Moreover, at a slope of 20 [°], the current value of the circular wheel is not stable. This implies that the resistance of the circular wheel in motion increases.

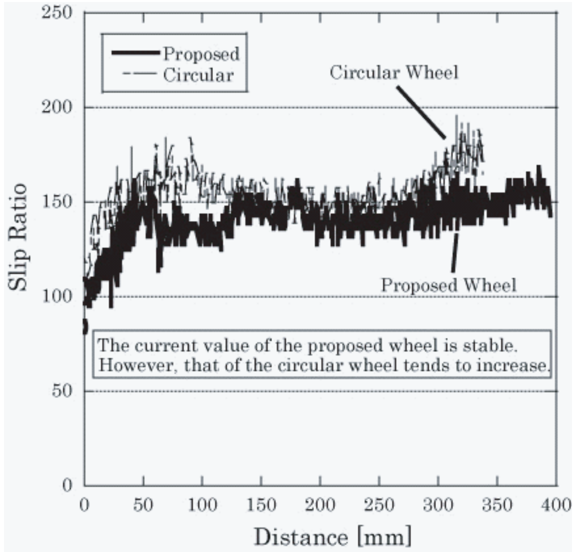


Fig. 15 Current data (15[°])

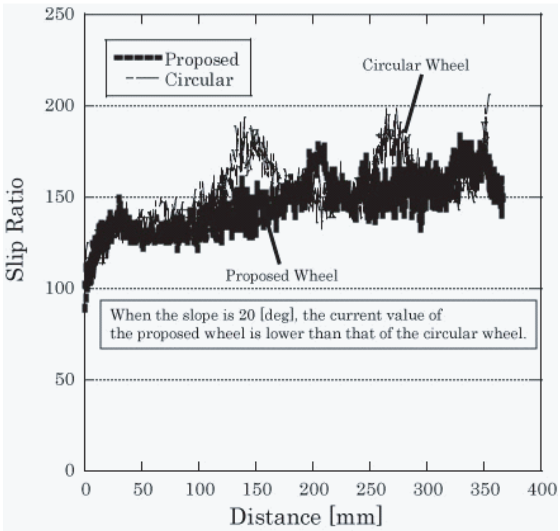


Fig. 16 Current data (15 [°])

5. CONCLUSION

In this paper, we described a wheel that can be used in lunar rovers. We proposed a new flexible wheel. The experimental results showed that the flexible wheel had a high running performance.

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