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Influence of atmosphere on lunar rover performance analysis based on soil parameter identification

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Abstract

This paper outlines an analysis of the traveling performance of a lunar rover. The analysis is in the form of numerical simulations and it uses soil properties, identified in vacuum, and mechanics of wheel-based travel. The wheel-to-ground contact model and soil parameters are determined first so they could be used in the numerical simulation. A soil test device is introduced and the soil parameters are identified from plate-pressing and shear tests. Finally, numerical simulations are conducted using the parameters identified and their results are discussed along with those of the traveling tests conducted in vacuum. The soil tests indicated that the wheel sinkage into the ground can increase in vacuum and that the shear stress acting beneath the wheel in vacuum is almost the same as that in the atmosphere. Because of these trends, the simulations and traveling tests showed that the traveling performance of the wheel can decrease in vacuum. Although it has been widely considered that the vacuum environments enhance the traveling performance of the wheel, this study confirmed that it is not always the case.

Keywords: Lunar exploration; Rover; Traveling performance; Vacuum; Soil parameter identification

1. Introduction

The Japan Aerospace Exploration Agency (JAXA) considers rover mobility as an important technology in lunar exploration (Hashimoto et al., 2011). In order to develop the technology, it is essential to thoroughly understand the influence of the unique lunar environment on the rover. The surface of the Moon is covered with loose regolith on which wheels of the rovers can easily slip or get stuck. In addition, this hazardous loose regolith is in lunar low gravity and vacuum environment.

In the 1940s, soil mechanics was first systematized by Terzaghi (1943). In the 1960s, based on observed effect, Bekker and Wong et al. developed empirical models that dealt with the interaction between vehicle and terrain (Bekker, 1960; Wong and Reece, 1967). In the early 2000s, Iagnemma et al., applied these models to planetary exploration rovers and estimated the traveling performance of the rovers traveling on loose ground (Iagnemma et al., 2004). In their studies, the vertical force and drawbar pull developed by a wheel were analyzed along with wheel slippage. Ishigami et al., added a sideforce generated by a wheel into these models (Ishigami et al., 2007). Recently, the latter model is widely used in characterizing traveling performance of planetary rovers in Trease et al. (2011), Inotsume et al. (2013). For rover design, Sutoh et al., and Ding et al., reported the influences of wheel parameters (e.g., wheel diameter, width, and grouser geometry) on the traveling performance of rovers based on experiments conducted using various wheels (Sutoh et al., 2012; Ding et al., 2011).

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In addition to rover wheel parameters, there exist various reports on the influence of the lunar/Martian environment on exploration rovers. Jiang et al., considered the influence of the lunar gravity and vacuum environment on motion behaviors of a wheel or a cutting blade and proposed mathematical models to describe it (Jiang et al., 2014, 2017). In their model, an increase in Van der Waals force in vacuum was considered as a typical difference between the soil behavior in the atmosphere and that in vacuum. Regarding the influence of the low gravity on the wheel performance, Kobayashi et al., conducted experiments in reduced gravity environments (Kobayashi et al., 2010). Wong et al., proposed wheel-to-ground contact models, based on these experimental data, that considered the gravitational effects (Wong, 2012; Wong and Kobayashi, 2012). On the influence of vacuum environment, Iizuka et al. reported experiments conducted using a small-sized rover in a vacuum chamber (Iizuka et al., 2006). Our research group also evaluated the influence of the pressure level based on experiments using various wheels and ground conditions in vacuum (Sutoh et al., 2016). In these studies, traveling performance of a wheel in the atmosphere and vacuum was discussed. However, the studies did not include any soil tests to identify the soil properties that explain the difference between phenomena observed in the atmosphere and those in vacuum.

Edwards et al., estimated pressure – sinkage and shear behaviors, which were regarded as the soil parameters that represented the ground by using bevameters and discussed the traveling performance of Mars rovers (Edwards et al., 2017). A bevameter, which stands for Bekker-Value-Meter, is a device for measuring the Bekker values that represent the soil characteristics. Apfelbeck et al., also conducted tests using various bevameters of various geometries and discussed the influence of the bevameter size and shape on the estimation of traveling performance (Apfelbeck et al., 2011). Their tests were all conducted in the atmosphere and they did not discuss the soil behaviors in vacuum. Meanwhile, the soil behaviors in vacuum were reported in various reports in Bernett et al. (1964), Johnson et al. (1970), and Walton (2007). However, there was no discussion on the vacuum influence on the traveling performance of exploration rovers.

The objective of this study is to analyze the influence of a vacuum environment on the traveling performance of exploration rovers by conducting numerical simulations and experiments in vacuum. To this end, soil tests, i.e., plate-pressing and shear tests, were first conducted and sinkage and shear behaviors were identified as the soil parameters that represent the ground. The traveling performance of a wheel was then evaluated based on a numerical simulation using the soil parameters identified. The traveling tests were also conducted using wheels and their results were discussed along with the trend obtained in the numerical simulation.

2. Wheel – ground contact model

In this study, traveling performance of a wheel is theoretically discussed based on the wheel-to-ground contact model proposed by Wong (2001). In this section, the wheel-to-ground contact model is described and soil parameters needed in the model are summarized along with the parameter identification methodologies.

2.1. Vertical force and drawbar pull

For a wheel to travel on ground, a vertical force is required for the ground to support the wheel load. Meanwhile, when the wheel travels over a slope, it must generate a drawbar pull to pull its own weight along the slope. Normal and shear stresses, σ and τ, act beneath the wheel traveling on ground, as shown in Fig. 2. The vertical force, F_z, and drawbar pull, F_x, are modeled using these stresses:

$$F_z = rb\int_{\theta_r}^{\theta_f} \{\tau(\theta)\sin\theta + \sigma(\theta)\cos\theta\}d\theta, \tag{1}$$

$$F_x = rb\int_{\theta_r}^{\theta_f} \{\tau(\theta)\cos\theta - \sigma(\theta)\sin\theta\}d\theta. \tag{2}$$

Here, r and b denote the wheel radius and width, respectively, as (Wong, 2001). θ_f and θ_r are the entry and departure angles of the wheel, respectively, and are derived using the wheel sinkage, h, as presented in Ishigami et al. (2007) and Wong and Reece (1967).

2.2. Normal stress: σ

Wong and Reece (1967) modeled a normal stress distribution, $\sigma(\theta)$, beneath the wheel as,

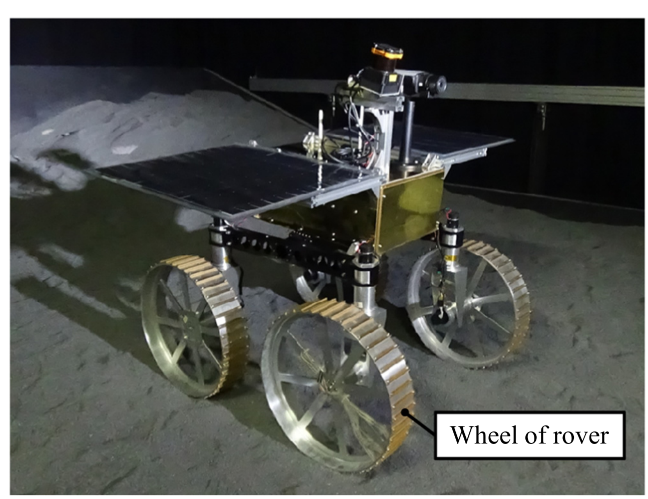

Fig. 1. Lunar rover under development by this research group.