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ScienceDirect

Journal of Terramechanics 68 (2016) 37–49

Journal of Terramechanics

www.elsevier.com/locate/jterra

Traveling and abrasion characteristics of wheels for lunar exploration rover in vacuum

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Received 26 May 2016; received in revised form 3 October 2016; accepted 9 October 2016
Available online 4 November 2016

Abstract

This paper investigates the traveling and abrasion characteristics of rigid wheels for a lunar exploration rover at atmospheric pressure and in a vacuum. For this investigation, a traveling test system that enables the wheel to continuously travel over a long distance was developed. Using this system, tests on traveling performance and abrasion were conducted with the wheel on a lunar regolith simulant surface. In the initial tests, various wheels traveled over different ground conditions and their performances were evaluated based on the relationship between the drawbar pull and slippage. In the later tests, a wheel with grousers traveled a distance of 3 km and the abrasion was analyzed at various intervals. From the traveling performance tests, it was found that for a soft ground condition, the traveling performance of the wheels in vacuum was slightly lower than that in atmosphere. This indicates that ground tests performed in atmosphere overestimate the actual performance on the lunar surface. The abrasion tests suggested that the scratching of wheels occurs more easily in vacuum than in atmosphere. These experiments confirmed that the abrasion of the wheels do not cause any critical problem for a traveling distance of up to 3 km in a simulated lunar environment.

Keywords: Lunar exploration; Wheel; Vacuum; Slippage; Abrasion; Long-distance travel

1. Introduction

International interest in lunar exploration has been growing and Japan Aerospace Exploration Agency, JAXA, is also planning lunar surface exploration missions (Hashimoto et al., 2011). As it is an important technological component required on the missions, JAXA conducts research activities on surface mobility technology using mobile robots, i.e., rovers (see Fig. 1). It is known that the lunar surface is covered with loose regolith consisting of particles that are sharp and jagged, and has a very low pressure, i.e., pressures of 1×10^{-10} Pa at night and 1×10^{-7} Pa in the daytime (Heiken et al., 1991). On such a surface, rovers can easily slip and get stuck; their mobility system can become abraded during their journey, and this could lead to the failure of the mission. Therefore, in the development of surface mobility technology for the Moon, it is necessary to thoroughly investigate the contact and traction mechanics between mobility systems and regolith in conditions simulating those of the Moon.

On loose soil, various conditions of motion behavior of mobility systems have been widely studied, as in Bekker (1960) and Wong (2001). Iagnemma et al. reported on the motion behavior of a wheel based on experiments using a single-wheel testbed (Iagnemma and Dubowsky, 2004). The testbed can provide variable slippages by driving the wheel and carriage at different rates. Although some research groups also use similar systems as in Shirai and Ishigami (2015), Skonieczny et al. (2014) and Ding et al. (2011), in these systems, the wheels are forcibly moved

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http://dx.doi.org/10.1016/j.jterra.2016.10.002
0022-4898/

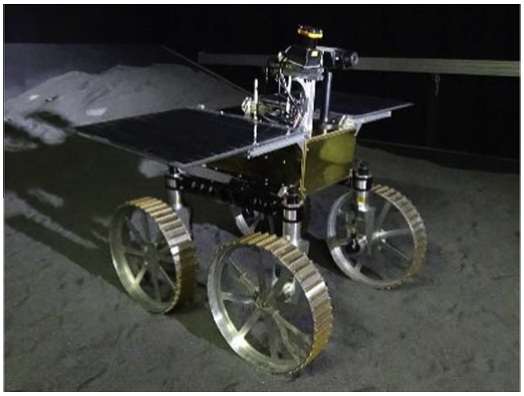

Fig. 1. Lunar rover under development by this research group.

forward even though they do not generate enough force to move. Thus, the motion behavior of the wheel in the testbed can differ from that on the actual rover. To precisely investigate the motion behavior of mobility systems in rovers, our research group utilized a testbed in which a single wheel/track rotates as it generates the required force (Wakabayashi et al., 2009; Narita et al., 2011). Kobayashi et al. reported on the motion behavior of a wheel in low gravity environments using a similar testbed (Kobayashi et al., 2010). These single-wheel/track testbeds are useful for the analysis of the slippage behavior; however, the traveling distance is usually limited (1–2 m) and it is difficult to evaluate the effect of abrasion on the mobility systems during long-distance travel.

Several studies have conducted experiments on soil mechanics in low-pressure conditions, as in Kleinhenz and Wilkinson (2014), Kleinhenz and Wilkinson (2012) and Craven et al. (2009); however, few studies have been carried out on the motion behavior of a wheel in such conditions. Iizuka et al. investigated the traveling performance of a small rover in a low pressure based on tests conducted in a vacuum chamber (Iizuka et al., 2006). In their study, small wheels having a diameter of 5 cm were used; the behavior may differ from that of large-sized wheels. Regarding abrasion (wear) on a wheel, Siebert et al. reported on abrasion on a wheel surface in a Martian environment (Siebert et al., 1998; Ferguson et al., 1999). In their study, the effect of abrasion during a moderate traveling distance of the wheel was investigated, but its effect over a long distance, e.g., more than a few kilometers, was beyond the scope of the study.

The objective of this study was to investigate traveling and abrasion characteristics of rigid wheels at various pressure levels. For this investigation, a traveling test system that enables the wheel to continuously travel for a long distance was developed, and various experiments were conducted using the system. In the traveling performance evaluation tests, the motion behavior of the wheel was investigated for various ground and drawbar pull conditions. In abrasion evaluation tests, during a 3 km travel distance of the wheel, the change in appearance of the wheel surface was examined. All the tests were conducted at atmospheric pressure and low pressure, and the differences in results are discussed in detail. Note that the low-pressure condition is hereinafter referred to as "vacuum" in this study.

This paper is organized as follows. The following section, Section 2, introduces the traveling test system developed. Sections 3 and 4 present the traveling performance and abrasion evaluations, respectively. Section 5 presents the conclusions of this study and recommendations for future studies.

2. Traveling test system

In this section, a traveling test system developed is described in detail.

2.1. Overview of traveling test system

Figs. 2 and 3 show photographs and schematic illustrations of the traveling test system, respectively. This system consists of three units: the vacuum chamber and soil bed unit; the wheel driving and leveling unit; and the motion control and measuring unit. The vacuum chamber and soil bed unit consists of the vacuum chamber equipped with the soil bed inside it, and the pressure inside the vacuum chamber can be controlled. The wheel driving and leveling units are also positioned inside the chamber and the wheel continuously travels in a circular motion as it pulls the leveling unit in the soil bed. The motion control and measuring unit is located outside the chamber. It controls the wheel rotation and measures the drawbar pull caused by the leveling unit. In the following subsections, the functions of each unit are described in detail.

2.2. Vacuum chamber and soil bed unit

The vacuum chamber and soil bed unit simulates the lunar environment by reducing the pressure of the vacuum chamber equipped with the soil bed. The vacuum chamber dimensions in Figs. 2(a) are Ø 1.5 × 1.2 m. A soil bed with the dimensions of 1.2 × 1.2 × 0.25 m is located inside the chamber. A lunar regolith simulant (Fuji Japanese Simulant 1, FJS-1; Shimizu Corp.) (Kanamori et al., 1998), which emulates the physical properties of the lunar regolith, is fillled to a thickness of 0.15 m in this soil bed. The properties of the simulant are listed in Table 1. The pressure of the chamber is reduced using dry and turbo molecular pumps and measured using Pirani and cold-cathode ionization gauges in the low and high vacuum ranges, respectively. With soil/material in the bed, the unit can reduce the pressure to lower than 1.0×10^{-2} Pa. It has previously been reported that if the pressure inside a vacuum chamber equipped with a soil bed is reduced only from the top of the bed, the gases trapped inside the soil bubbles up and the surface of the ground becomes disturbed