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Measurement and modeling for two-dimensional normal stress distribution of wheel on loose soil

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Abstract

On the Moon or Mars, typical target environments for exploration rovers are covered with fine sand, so their wheels easily slip on such weak ground. When wheel slippage occurs, it is hard for the rover to follow its desired route. In the worst case, the rover gets stuck in loose soil and cannot move anymore. To reduce the risk of the rover getting stuck, analysis of the contact mechanics between the soil and wheel is important. Various normal stress distribution models for under the wheel surface have been proposed so far. However, classical models assume a uniform stress distribution in the wheel's width direction. In this study, we measured the two-dimensional normal stress distribution of a wheel in experiments. The results clarified that the stress distribution in the wheel's width direction is a mountain-shape curve with a peak located at the center of the wheel. Based on the results, we constructed a stress distribution model for the wheel's width direction. In this paper, we report our measurements for the two-dimensional stress distribution of a wheel on loose soil and introduce our stress distribution model for the wheel's width direction based on our experimental results.
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Keywords: Planetary rover; Rigid wheel; Stress distribution; Modeling

1. Introduction

In recent years, planetary exploration using lunar/planetary exploration mobile robots (rovers) have been planned and conducted by major developed countries. Typical target environments for such exploration rovers are covered with fine sand, so their wheels easily slip on such weak ground. When wheel slippage occurs, it is hard for the rover to follow its desired route. In the worst case, the rover gets stuck in loose soil and cannot move anymore. For instance, NASA/JPL's Mars Exploration Rover (Spirit), which landed on Mars in 2004, was buried in loose Martian soil in 2009 (Kerr, 2009). In 2010, NASA/JPL gave up trying to free the rover and converted it to a static observation station. Thus, wheel slippage is a serious problem for lunar/planetary surface exploration missions. To avoid such situations, understanding of wheel–soil interaction is essential.

Bekker developed the fundamental terramechanics model of a wheel in the 1960s (Bekker, 1956, 1960, 1969), and Wong, Reece, and others improved upon Bekker's work in their drawbar pull models (Reece, 1965; Onafeko and Reece, 1967; Wong, 2008). These drawbar pull models are based on normal stress distributions generated beneath a wheel and shear stress distributions generated over the same area as the normal stress. Several studies have been conducted on stress distributions that are generated beneath the wheels of lunar/planetary rovers on loose soil.

Hegedus (1963) mounted three pressure sensors on a wheel surface and measured the stress distribution on flat and soft soil in the circumferential direction. He assumed that the normal force acting on a wheel edge was zero

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and deduced the distribution based on the quadratic approximation of three points: the wheel center, near the left edge of the wheel, and the left edge of the wheel; and the wheel center, near the right edge of the wheel, and the right edge of the wheel. He performed experiments using the wheels and demonstrated that the shape of the normal stress distribution in the wheel circumferential direction corresponds to the slip ratio.

In a previous study, we mounted four thin pressure sensors on the rover's wheel surface and measured the normal stress distributions (Nagatani et al., 2009). In our experiments, we confirmed that the stress distribution in the width direction of the wheel is not uniform. However, the mean of the sensors' output was used because of the low resolution. We reported that (1) the slip ratio increases with the wheel slippage, (2) a normal stress distribution is generated at the front portion of the wheel, and (3) the generation region moves forward as the wheel slippage increases.

In other research related to the measurement of the normal stress distribution generated beneath the wheel, Krick (1969) and Senatore and Iagnemma (2014) measured normal and tangential stresses using strain gages. Oida et al. (1991) measured three-dimensional stress distributions using a three-axial force transducer on tire surface. In addition, Iizuka and Kubota (2010) and Narita et al. (2011) measured the stress distributions for an elastic wheel.

Several researchers have observed the sand particles beneath a wheel directly to analyze the normal stress distribution. In typical cases, the sand particles were observed with camera devices (Fukami et al., 2006; Moreland et al., 2012; Vlahinic et al., 2012). A half cut model of the wheel would be developed, and the cut surface would be placed on a clear glass or plastic plate to observe the movement of the sand particles while the wheel rotated. In contrast, Kinugasa et al. successfully tracked the three-dimensional movement of soil particles beneath a wheel by using a radioactive isotope tracking system (Kinugasa et al., 2013).

Although some researchers have examined the normal stress distribution of wheels on weak soil, in almost all cases the normal stress distribution in the width direction of the wheel was assumed to be uniform, as shown in Fig. 1. However, the stress distribution shape generated beneath a wheel is actually a mountain-shaped curve. Therefore, we concluded that the uniform stress distribution models are inadequate for analysis of the contact mechanics for the interaction between the wheel and loose soil. In order to obtain the normal stress distribution precisely, an array sensor of the stress, in the width direction of the wheel, is needed. However, this approach is currently difficult because commercially available array sensors are expensive. Moreover, the space and force resolutions of these array sensors are too low to measure the normal stress distribution precisely. Therefore, we measured the two-dimensional (2D) normal stress distribution by using a six-axis force/torque (F/T) sensor. This sensor cannot measure the normal stress distribution in all areas simultaneously but can measure the normal stress distribution at a

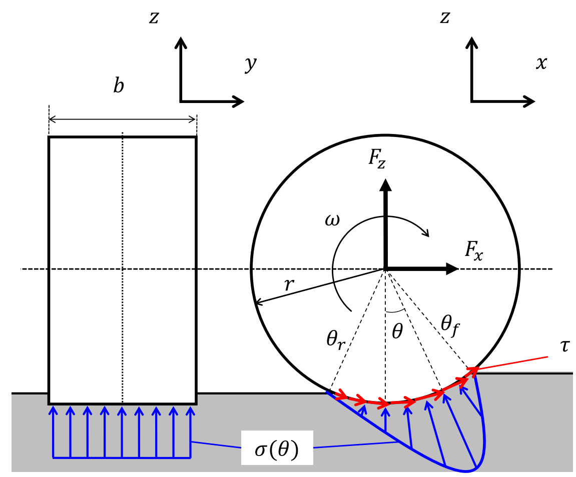

Fig. 1. Force acting on wheel on loose soil, where r is wheel radius, b is wheel width, ω is angular velocity, θ is wheel rotational angle with wheel bottom defined as zero, θ_f is entry angle to soil, θ_r is departure angle from soil, $\sigma(\theta)$ is normal stress, $\tau(\theta)$ is shear stress, F_x is traction force (i.e., drawbar pull), and F_z is vertical force.

specific point in the wheel width direction precisely. Therefore, we can repeat the measurement of the normal stress distribution in the wheel circumferential direction while changing the measurement point in the wheel width direction. We then superimpose all of the normal stress distribution data. With this, we can obtain a result similar to that using the array sensor.

In an actual field, online estimation of the normal stress distribution of the wheel is needed in order to predict the risk for rover immobilization. Knowing the normal stress distribution allows the forces acting on the wheel (e.g., drawbar pull) to be estimated. To do so, precise measurement of the entire normal stress distribution of the wheel is essential. However, in the actual field, changing the measurement point in the wheel width direction of the sensor is impossible. Hence, we can measure the 2D normal stress distribution of the wheel using a six-axis F/T sensor a priori and model the normal stress distribution in the wheel width direction. With this, we can estimate the normal stress distribution of the wheel precisely by substituting the normal stress distribution data in the wheel circumferential direction at several points into the model.

In this study, our aim was to reconstruct the 2D normal stress distribution beneath a wheel based on a normal stress distribution model in the wheel width direction and a few pressure sensors mounted on the wheel. To achieve this goal, understanding and constructing a model of the 2D normal stress distribution beneath the target wheel are necessary. Therefore, we first measured the 2D stress distribution beneath the wheel in detail. Next, we approximated the stress distribution along the wheel's width direction to construct a stress distribution model in the wheel width direction. Finally, we reconstructed the wheel's 2D normal stress distribution using two points' experimental data.

This paper is organized as follows. Section 2 presents the strategy of our approach. In Section 3, we report our

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