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Advances in Space Research 56 (2015) 2515–2526

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)

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# A mechanical model for deformable and mesh pattern wheel of lunar roving vehicle

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Received 12 April 2015; received in revised form 8 October 2015; accepted 12 October 2015
Available online 19 October 2015

**Abstract**

As an indispensable tool for astronauts on lunar surface, the lunar roving vehicle (LRV) is of great significance for manned lunar exploration. An LRV moves on loose and soft lunar soil, so the mechanical property of its wheels directly affects the mobility performance. The wheels used for LRV have deformable and mesh pattern, therefore, the existing mechanical theory of vehicle wheel cannot be used directly for analyzing the property of LRV wheels. In this paper, a new mechanical model for LRV wheel is proposed. At first, a mechanical model for a rigid normal wheel is presented, which involves in multiple conventional parameters such as vertical load, tangential traction force, lateral force, and slip ratio. Secondly, six equivalent coefficients are introduced to amend the rigid normal wheel model to fit for the wheels with deformable and mesh-pattern in LRV application. Thirdly, the values of the six equivalent coefficients are identified by using experimental data obtained in an LRV's single wheel testing. Finally, the identified mechanical model for LRV's wheel with deformable and mesh pattern are further verified and validated by using additional experimental results.

*Keywords:* Lunar roving vehicle; Wheel with deformable and mesh pattern; Terramechanics; Interaction between wheel and soil

## 1. Introduction

Rich material and space resources on the moon have attracted many countries to develop plans of lunar exploration. As the first step of space exploration, lunar exploration can help people to know earth, solar system, as well as the whole universe well. With the development of the technologies for space exploration, the conventional unmanned lunar exploration is shifting to the manned one, and finally lunar base construction and residence on the moon will be accomplished (Ouyang et al., 2010; Yu, 2010).

Manned lunar exploration is an inevitable trend of the development of planet exploration, and it also lays the foundation for building lunar base and astronomical station on the moon (Yu et al., 2012; Tomas et al., 2012; Xu et al., 2014). Furthermore, the moon will be the first station to improve exploring the mars and other planets (Fong et al., 2010; Connolly et al., 2012), and accomplish manned mars exploration (Kramer et al., 2013; Sanders and Larson, 2012; Zhang et al., 2014).

Lunar roving vehicle (LRV) is an important and indispensable detection tool that can travel far away from the lunar module and transport astronauts to complete a variety of detection missions more efficiently (Liang et al., 2014). As a specialized electric vehicle suitable for traveling on lunar surfaces, LRVs are required to work under extraordinary circumstances. To this end, the

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http://dx.doi.org/10.1016/j.asr.2015.10.019
0273-1177/

designer must be aware of its movement performance and adaptability during the design stage. All LRV designs must take into account terramechanics dealing with the interactions between wheels and the lunar soil. The existing theories on interactions between wheel and lunar soil are suitable for rigid wheels, whereas the wheels of LRV have deformable and mesh pattern. Therefore, it is necessary to develop appropriate theory to model the wheels of LRV.

A typical LRV running on the lunar surface is designed to take two passengers. The large temperature difference between day and night on the moon requires the wheels to be made of metal, and the driving comfort of the astronauts needs the wheels to have deformable property. A wheel for LRV usually has deformable mesh pattern, with surface covered a series of herringbone sheet metals. The surface of LRV's wheel can be penetrated by soil, and the property of soil will be changed after being passed by. Therefore, unlike the normal rigid wheel which can modeled and analyzed using most existing theories, the LRV's wheel cannot be properly modeled by existing theories.

In this paper we proposed an LRV's wheel model by modifying normal rigid wheel model with six equivalent coefficients. The mechanical model of a normal rigid wheel is presented firstly, in which the relationship of vertical load, tangential traction force, lateral force and slip ratio of the wheel is deduced. Secondly, six equivalent coefficients are added to model of the normal rigid wheel to reflect the effects of deformable and mesh pattern. Thirdly, an experiment of an LRV's wheel in with deformable and mesh pattern is conducted. Finally the testing data are used to identify the six equivalent coefficients and verify the mechanical model.

As this paper contains many equations, a definition of the quantities and variables is provided in the Appendix A.

## 2. Mechanical model of normal rigid wheel

### 2.1. Tangential force model of normal rigid wheel

Many methods have been used to establish the mechanical models of a wheel running on ground, such as experimental method (Sandu et al., 2008), empirical method (Durham, 1976), semi-empirical method (Bekker, 1969; Janosi and Hanamoto, 1961), finite element method (Shoop et al., 2002, 2006) and discrete element method (Koizumi et al., 2008; Zhang and Li, 2006). The semi-empirical method is used in this paper as this method has been most widely used due to its rapid computing speed, clear physical interpretation, and high accuracy.

The slip ratio of a normal rigid wheel to be modeled is defined as follows:

$$s = \frac{r\omega - v}{r\omega} \tag{1}$$

According to the pressure-sinkage model introduced by Bekker (1969), the normal stress of the wheel can be calculated as follows:

$$\sigma = (k_c/b + k_\varphi)z_w^n \tag{2}$$

According to the shear stress model of soil introduced by Janosi and Hanamoto (1961), the shear stress beneath the wheel can be calculated as follows:

$$\tau = \tau_{\max}\left(1 - e^{-j/j_0}\right) = (c + \sigma\tan\varphi)\left(1 - e^{-j/j_0}\right) \tag{3}$$

The tangential traction force of the wheel, $F_{DP}$, is defined as,

$$F_{DP} = \frac{T - T_f}{r} \tag{4}$$

$F_{DP}$ has the following relationship with other forces acting on the wheel,

$$F_{DP} - f_R - f_G = m_{wh}a_{wh} \tag{5}$$

The tangential traction force $F_{DP}$ is equal to the sum of the total resistance $f_R + f_G$, and the inertia force $m_{wh}a_{wh}$ in Eq. (5). The vertical load $W$, the tangential traction force $F_{DP}$, and the driving torque $T$ are balanced by the pressure and the shear stress of the soil beneath the wheel, as shown in Fig. 1. Generally, in forced-slip state (Liang et al., 2014), $F_{DP}$ and $W$ are given as known values, whereas $s$ and $z_w$ need to be solved.

The following equations can be obtained by using geometric analysis of the wheel,

$$z_w = r(1 - \cos\theta_1) \tag{6}$$

$$j = r[(\theta_1 - \theta) - (1 - s)(\sin\theta_1 - \sin\theta)] \tag{7}$$

In Fig. 1, the peak pressure is not located vertically beneath the wheel axle due to the slip of a moving wheel. The offset angle of the peak pressure $\theta_m$ is given as (Shibly et al., 2005):

$$\theta_m = (c_1 + c_2|s|)\theta_1 \tag{8}$$

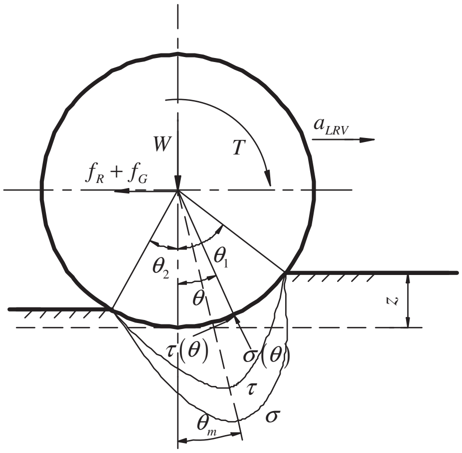

Fig. 1. Stress distribution between wheel and soil.