Interaction Mechanical Analysis between the Lunar Rover Wheel-Leg Foot and Lunar Soil

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Abstract

Taking the Wheel-leg Foot of the double-half-revolution mechanism of lunar rover as the research objects and considering the mechanics characteristics of lunar soil, the interaction of mechanical behavior between Wheel-leg Foot and lunar soil is presented. Based on the press-sinkage and shear model of soil, established the force balance equation of the Foot and the stress model. By setting the parameters of the foot mechanism and the properties of lunar soil, the stress model was simulated. The relationship curves about the sinkage, the structure parameters of foot, the mechanical performance, slip rate and structure parameters of foot are given.

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1. Introduction

The structure of lunar rover wheel and the interaction mechanical properties between wheel and lunar soil have an important impact on the movement performance of the rover; to understand the above characteristics play an important role in design the rover [1,2]. Some researches about the interaction mechanical properties have been done, one of the basic theory of wheel-terrain which is widely used was proposed by Bekker [3], on that basis, a great number of researches have been done: MIT, Dubowsky et al. [4] derived the closed analytic expression about wheel lunar rover on the level of soft ground; Tohoku University, Ishigami et al. [5] studied obstacle capacity of wheel lunar rover on the soft lunar surface. At the same time, China scholars have proposed some different wheel configuration and done appropriate analysis. HIT, Ji-cheng Liu et al. [6] proposed a drum type wheel and made the interaction mechanical analysis between the wheel and loose sandy soil; HIT, Jian-guo Tao et al. [7] proposed a new wheel with different diameters and done mechanical analysis and experiments of wheel-soil interaction of rolling wheels with different diameters on a lunar rover.

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Wheel-terra mechanics have been deeply studied, while the interaction mechanical properties between the foot of the wheel-legged lunar rover and soft lunar soil are seldom researched, even few can refer to.

With the Wheel-legged Foot of the double-half-revolution mechanism of lunar rover as the research objects in this paper, the interaction mechanical properties of the foot on the soft soil was analyzed when lunar rover in motion and mechanical model of rigid foot in the soft soil movement was established, and then simulation analysis was made.

2. Introduction of single wheel-legged and foot mechanism

![Fig. 1. (a) Single wheel-legged mechanism; (b) Feet mechanism](image)

The single wheel-legged assembly mechanism of wheel-legged lunar rover on the basis of double-half-revolution mechanism shown in figure 1[8,9], it consists of single wheel-legged mechanism and foot mechanism. The simplified model of single wheel-legged mechanism is shown in Fig.1a, it mainly composed of wheel-leg bracket, suspension spring, steering motor, drive motor and double-half-revolution mechanism. Double-half-revolution mechanism composed of first swiveling arm, second swiveling arm and striding rods. The simplified model of foot mechanism is shown in Fig.1b, it composed of steering joint and spherical crown type’s foot. The wheel-legged lunar rover is further designed on the basis of double-half-revolution mechanism lunar rover, the foot mechanism of the wheel-leg overcome the deeper sinkage problem which generated by double-half-revolution mechanism directly as walk mechanism, while contact area with the soft lunar surface and friction are increased, thus drive capability and mobility of lunar rover are increased.

3. The sinkage and compaction resistance analysis

3.1. Interaction mechanical analysis between sinkable rigid foot and lunar soil

In working condition, under the conditions of the sinkage and compaction resistance only are considered, assumptions are presented: 1. the lunar soil deformation under rigid foot is unrecoverable.2. The press-sinkage of soil under the action of rigid wheel and the stress-strain relations of soil under the action of Bekker pressure probe are exactly the same [10]. The most important factor which affects the sinkage of the feet of wheel-legged lunar rover is normal stress, therefore, the mechanical relationship between the rigid foot and lunar soil is researched, the normal stress must be mainly considered, then the mechanical relationship model between the foot and lunar soil is established, as shown in fig.2. \( V \) is the lunar rover velocity, \( W \) is load of a wheel-leg, \( R \) is radius of the spherical crown type’s foot, \( z \) is the maximum sinkage, \( z_0 \) is a sinkage within the scope of the maximum sinkage, \( r \) is radius of dimensions round on the type of spherical crown foot at the sinkage of \( z_0 \), \( A_1 \), \( A_2 \) and \( A_3 \) are there positions respectively at the movement of foot, \( OA_1 \), \( OA_2 \) and \( OA_3 \) are boundaries, in the right side of those boundaries is the interaction area between foot and soil.
3.2. Mechanical model of sinkage and compaction resistance

Known by the assumption 1, interaction area between lunar soil and rigid foot is the right side of those boundaries, equivalent to the right side of the interaction area between stationary foot and lunar soil, so the effective length of the rolling foot is only half of the stationary foot, the effective length can be got by geometric relationship, as written in (1). Where, \( r \) can be got by geometric relationship from the fig.2, as written in (2).

\[
\begin{align*}
b_1 &= \pi \cdot r \\
r &= \sqrt{R^2 - (R - z + z_0)^2}
\end{align*}
\]

Known by the assumption 2, according to the press-sinkage model which is established by Bekker [3], normal stress \( \sigma \) satisfies the following relations, as described in (3).

\[
\sigma = p = \left( \frac{k_c}{b} + k_\varphi \right) z^n
\]

Where, \( k_c \) is the cohesive modulus of lunar soil deformation, \( k_\varphi \) is the frictional modulus of lunar soil; \( b \) is the effective length and equals the \( b_1 \).

Known the normal stress on the rigid foot under the conditions of the lunar rover is moving and the sinkage is \( z_0 \), which is generated by interaction of rigid foot and lunar soil, as described in (4).

\[
\sigma_1(z_0) = \pi \sqrt{R^2 - (R - z + z_0)^2} \left( \frac{k_c}{\pi \sqrt{R^2 - (R - z + z_0)^2}} + k_\varphi \right) z_0^n
\]

Thus, in the vertical direction, the supporting force of the entire foot is \( N_1 \), as described in (5).

\[
N_1 = \int_0^{z_0} \sigma_1(z_0) \frac{R - z + z_0}{R} dz_0
\]

\[
= \int_0^{z_0} \pi \sqrt{R^2 - (R - z + z_0)^2} \left( \frac{k_c}{\pi \sqrt{R^2 - (R - z + z_0)^2}} + k_\varphi \right) z_0^n \frac{R - z + z_0}{R} dz_0
\]

In the horizontal direction, the compaction resistance of the rigid foot which lunar soil applied on is \( F_{rc} \), as described in (6).

\[
F_{rc} = \int_0^{z_0} \sigma_1(z_0) \frac{R - z + z_0}{R} dz_0
\]

\[
= \int_0^{z_0} \pi \sqrt{R^2 - (R - z + z_0)^2} \left( \frac{k_c}{\pi \sqrt{R^2 - (R - z + z_0)^2}} + k_\varphi \right) z_0^n \frac{R - z + z_0}{R} dz_0
\]

4. Contact stress analysis—the relationship between the rigid foot and lunar soil in the level
In working condition, under the conditions of the interaction contact stress is analyzed, assumption is presented: the maximum stress isn’t prepositive along with the rigid wheel rolling over on the ground. The interaction stress model between the rigid foot and the lunar soil is established, as shown in fig.3. $\theta_1$ is the approach angle, which is the corresponding central angle of the wheel from the vertical position to the first touchdown position; $\theta_2$ is the departure angle, which is the corresponding central angle of the wheel from the vertical position to the lift-off position. Their interaction region between the foot and soil can be divided into two zones: $[0, \theta_1]$ and $[0, \theta_2]$. $\theta$ is a angle between the two zones. The above assumption is that the maximum normal stress and shear stress occur at the same position corresponding to 0. $\sigma_1, \sigma_2$ are the normal stress of the two zones, $\tau_1, \tau_2$ are the shear stress of the two zones, $z_0$ is sinkage at the position of angle $\theta$, $z$ is the maximum sinkage at the position of $[0, \theta_1]$, $z_1$ is the maximum sinkage at the position of $[0, \theta_2]$, $V$ is the lunar rover velocity, $\omega$ is rotation angle velocity of wheel-leg and foot, $T$ is a torque, $F_{DP}$ is horizontal force, that is driving force.

![Fig. 3. contact stress analysis](image)

Based on the Bekker press-sinkage model and Janosi shear model, the contact stress model of the foot can be established, and written in (7) and (8).

\[
\begin{align*}
\sigma_1(\theta) &= \left(\frac{k_1}{b} + k_v\right)R^n(\cos \theta - \cos \theta_1)^s & 0 \leq \theta \leq \theta_1 \\
\sigma_2(\theta) &= \left(\frac{k_2}{b} + k_v\right)R^n(\cos \theta - \cos \theta_1)^s & 0 \leq \theta \leq \theta_2
\end{align*}
\]

(7)

\[
\tau(\theta) = (c + \sigma_0 \tan \phi)(1 - e^{-\frac{\theta}{\tau_0(\theta_1 - \theta)(\sin \theta_1 - \sin \theta)}})
\]

(8)

Where, $n$ is the cohesion of lunar soil, $k$ is the shear deformation modulus of lunar soil, $\phi$ is the internal friction angle of lunar soil, $s$ is the slip ratio of feet. $k_c, k_v, \phi$ consistent with the above.

According to the force equilibrium relationship, the dynamics equations of the single rigid foot can be established, and written in (9), (10) and (11). $W_2$ is the supporting force.

\[
W_2 = \pi R \left[ \int_0^{\theta_1} (\sigma_1(\theta) \sin \theta \cos \theta + \tau(\theta) \sin^2 \theta) d\theta + \int_0^{\theta_2} (\sigma_2(\theta) \sin \theta \cos \theta + \tau(\theta) \sin^2 \theta) d\theta \right]
\]

(9)

\[
F_{DP} = \pi R \left[ \int_0^{\theta_1} \tau(\theta) \sin \theta \cos \theta - \sigma_1(\theta) \sin^2 \theta d\theta + \int_0^{\theta_2} \tau(\theta) \sin \theta \cos \theta - \sigma_2(\theta) \sin^2 \theta d\theta \right]
\]

(10)

\[
T = \pi R (R + l_k) \int_0^{\theta_1} \tau(\theta) \sin \theta d\theta
\]

(11)

Where, $l_k$ is the length of striding rod. By simplified mechanical model, according to (7) - (11), the variables $W_2, F_{DP}$ and $T$ can be calculated.

5. Simulation analysis
In order to analyze the mechanical properties of the foot of the double-half-revolution wheel-legged lunar rover, the mechanical parameters of the foot is simulated and calculated by MATLAB programming simulation. Lunar soil characteristic parameters are given in Table 1, as in [11]. The weight of single wheel-leg is about 15kg.

<table>
<thead>
<tr>
<th>Acceleration g(m/s²)</th>
<th>Sinkage coefficient n</th>
<th>Frictional modulus k,(N·mⁿ⁻²)</th>
<th>Cohesive modulus kc(N·mⁿ⁻¹)</th>
<th>Shear deformation modulusk(m)</th>
<th>Cohesion c(kPa)</th>
<th>Internal friction angle φ(°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.6333</td>
<td>1.0</td>
<td>814370</td>
<td>1379</td>
<td>0.01778</td>
<td>0.172</td>
<td>40</td>
</tr>
</tbody>
</table>

5.1. Feet sinkage analysis

Given the vertical load \(W\) and different radius R (such as 40mm, 45mm, 50mm), the foot sinkage \(z\) is determined according to (1)-(5), and their relationship curve is shown in Fig.4.(a). Simulation shows: when the lunar rover velocity \(V\) is certain, as the vertical load \(W\) increasing, the sinkage \(z\) is increasing; when the load is certain, as the foot radius R increasing, the sinkage \(z\) is decreasing.

5.2. Analysis of driving force

Given the slip ratio \(s\) and the vertical load \(W_i\), the driving force \(F_{DP}\) is determined according to (7)-(10), and their relationship curve is shown in Fig.4.(b). Simulation shows: when the lunar rover velocity \(V\) is certain, as the load \(W_i\) increasing, the driving force \(F_{DP}\) is increasing; when the load \(W_i\) is certain, as the slip ratio \(s\) increasing, the driving force \(F_{DP}\) is decreasing. Given the slip ratio \(s\) and the foot radius R, the driving force \(F_{DP}\) is determined according to (7)-(8) and (10), and their relationship curve is shown in Fig.4.(c). Simulation shows: as the slip ratio \(s\) increasing, the driving force \(F_{DP}\) is increasing; when the slip ratio \(s\) is less than 0.2, as the foot radius R increasing, the driving force \(F_{DP}\) is decreasing, when the slip ratio \(s\) is more than or equal to 0.2, as the foot radius R increasing, the driving force \(F_{DP}\) is increasing.

5.3. Analysis of the driving torque

Given the slip ratio \(s\) and the foot radius R, the driving torque \(T\) is determined according to (7)-(8) and (11), and their relationship curve is shown in Fig.4.(d). Simulation shows: when the lunar rover velocity \(V\) and the single wheel-leg load \(W_1\) is certain, as the slip ratio \(s\) increasing, the driving torque \(T\) is increasing; when the slip ratio \(s\) is less than 0.1, as the foot radius R increasing, the driving torque \(T\) is decreasing, when the slip ratio \(s\) is more than or equal to 0.1, as the foot radius R increasing, the driving force \(F_{DP}\) is increasing.

6. Conclusions

Based on the traditional theory of the terramechanics, interaction mechanical properties between the feet of wheel-legged lunar rover are analyzed. The sinkage and compaction resistance mechanical model and the interaction mechanical model between the foot and lunar rover are established respectively, dynamic formulas for calculating mechanical parameters are derived. By given some relative parameters of the foot and lunar soil, mechanical parameters are calculation and analyzed. Simulation shows: in certain conditions, as the load increasing, the foot sinkage is increasing; as the load, the slip ratio and the foot radius increasing, driving force is increasing; as the slip ratio and the foot radius increasing, the driving torque is increasing.
Fig. 4. (a) Relationship curve of $W$, $R$ and $z$; (b) Relationship curve of $W$, $S$ and $F_{DP}$; (c) Relationship curve of $s$, $R$ and $F_{DP}$; (d) Relationship curve of $s$, $R$ and $T$

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References


