Obstacle-Climbing Capability Analysis of Six-Wheeled Rocker-Bogie Lunar Rover on Loose Soil

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Abstract. Taking six-wheeled rocker-bogie lunar rover as an object, on the basis of force analysis between the wheels and lunar soil, its obstacle-climbing force model on loose soil was established in this paper, and the wheel sinkages were obtained. Based on the method of solving the wheel’s driving torque solution space feasible regions, this paper analyzed the forward obstacle-climbing capability of six-wheeled rocker-bogie lunar rover on loose soil, including single-wheel obstacle-climbing and two wheels obstacle-climbing simultaneously. Simulations show that under the loose soil environment, the wheels have different obstacle-climbing capability, i.e. the rear wheel is the best, the middle one is the worst and the front one is moderate.

Keywords: Obstacle-climbing Capability Analysis, Lunar Rover, Rocker-bogie, Force Analysis, Solution Space Feasible Region.

1 Introduction

Lunar surface is rather complex and rough, which is almost completely covered by a thick loose bed (i.e. lunar soil). Therefore, to complete the exploration mission, it is essential for lunar rover to have a good obstacle-climbing capability on loose soil.

Taking the six-wheeled rocker-bogie lunar rover as an object [1-2], and based on establishing the force model between the wheels and lunar soil, its obstacle-climbing capability on loose soil was analyzed in this paper.

2 Force Model of Lunar Rover on Loose Soil

2.1 Force Analysis of Rigid Wheel on Loose Soil

When the six-wheeled rocker-bogie lunar rover travels on loose soil, the rigid wheels will have a small sinkage. As shown in Fig.1, a vertical load \( W \) and a driving force \( P \) are applied to the wheel; a torque \( T \) is applied at the wheel rotation axis by the motor, \( h \) is the wheel sinkage, as in [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. For the rigid wheel, $\theta_2$ is usually very small, and can be regarded as zero. Their interaction region between the wheel and loose soil can be divided into two zones: $[\theta_m, \theta_1]$ and $[\theta_2, \theta_m]$, where $\theta_m$ is the corresponding central angle of the wheel from the vertical position to the maximum normal stress position, as shown in Fig.1. And $\tau_1, \tau_2$ are the shear stresses of the two zones, $\sigma_1, \sigma_2$ are the normal stress of the two zones.

Based on Karl Iagnemma’s study [4], there are two assumptions. The first assumption is that the angle $\theta_m$ is the average of $\theta_1$ and $\theta_m$, as written in (1).

$$\theta_m = \frac{\theta_1 + \theta_2}{2} .$$

The second assumption is that the maximum shear stress and the maximum normal stress occur at the same position corresponding to $\theta_m$, which has been confirmed by simulation. Based on the above-mentioned assumptions, the maximum normal stress $\sigma_m$ can be written as in (2) and the shear stress is described as in (3).

$$\sigma_m(\theta_m) = \left(k_c + k_\phi b \left(\frac{r}{b}\right)^n\right) \left(\cos \theta_m - \cos \theta_1\right)^n .$$

$$\tau_m(\theta_m) = \left(c + \sigma_m \tan \phi \left(1 - e^{-\gamma \left|\theta - \theta_m - (1-\lambda)\left|\sin \theta - \sin \theta_m\right|\right)}\right) .$$

Where, $k_c$ is the cohesive modulus of lunar soil deformation, $k_\phi$ is the frictional modulus of lunar soil, $n$ is the sinkage coefficient, $b$ is the wheel width, and $r$ is the wheel radius. $c$ is the cohesion of lunar soil, $k$ is the shear deformation modulus of lunar soil, $\phi$ is the internal friction angle of lunar soil, and $\lambda$ is the slip ratio of wheel.

According to the force equilibrium relationship, we can establish the dynamics equations of single wheel, and written in (4) and (5). And as in [5-6], the wheel sinkage $h$ can be calculated in (7).

$$W = rb\int_0^n \sigma(\theta)\cos \theta \cdot d\theta + \int_0^n \tau(\theta)\sin \theta \cdot d\theta .$$

$$P = rb\int_0^n \sigma(\theta)\sin \theta \cdot d\theta - \int_0^n \tau(\theta)\cos \theta \cdot d\theta .$$

$$T = \frac{1}{2} r^2 b \tau_m \theta_1 .$$

$$h = r(1 - \cos \theta_1) .$$

Given that $\theta_m=\theta_1/2$, and the vertical load $W$, the driving force $P$ are known, according to (2)-(6), we can calculate the variables $\theta_1, \sigma_m, \tau_m, \lambda, T$. 

$\frac{1}{2} r^2 b \tau_m \theta_1 = \frac{1}{2} r^2 b \tau_m \theta_1$.
2.2 Force Analysis of Rocker-Bogie Mechanism on Loose Soil

When the lunar rover travels on loose soil, the rigid wheels will have a sinkage $h$, therefore the kinematics of rocker-bogie mechanism will also be changed. Without regard to the normal friction forces, the force analysis is based on the rocker-bogie planes. The two side rocker-bogie mechanisms are selfsame except the displacements and forces at the joints, so their mechanical models are selfsame too. This paper only analyzes the right side rocker-bogie mechanism.

For convenience, it is assumed that they are point-contact between the wheels and lunar soil. The angles $\alpha_1$, $\alpha_2$ and $\alpha_3$ represent the angle between the horizontal plane and the wheel–terrain contact plane. $r$ is the wheel radius, $h_1$, $h_2$ and $h_3$ are sinkages of the rear, middle and front wheels. There is a free pivoting joint at point B, and there is a differential joint at point A, as in [7]. $F_x$, $F_z$ and $M_y$ are the forces and torque at point A. $W_1$, $W_2$, $W_3$ are the normal forces of the wheels. $P_1$, $P_2$, $P_3$ are the driving forces of the wheels, as shown in Fig.2.

\[
\begin{align*}
F_x - W_1 \sin \alpha_1 - W_2 \sin \alpha_2 - W_3 \sin \alpha_3 + P_1 \cos \alpha_1 + P_2 \cos \alpha_2 + P_3 \cos \alpha_3 &= 0 \quad \text{(8)} \\
-F_z + W_1 \cos \alpha_1 + W_2 \cos \alpha_2 + W_3 \cos \alpha_3 + P_1 \sin \alpha_1 + P_2 \sin \alpha_2 + P_3 \sin \alpha_3 &= 0 \quad \text{(9)} \\
M_x + (x_a - x_f)(W_1 \cos \alpha_1 + P_1 \cos \alpha_1) + (z_a - z_f)(W_1 \sin \alpha_1 - P_1 \sin \alpha_1) - T_1 + \\
(x_a - x_m)(W_2 \cos \alpha_2 + P_2 \cos \alpha_2) + (z_a - z_m)(W_2 \sin \alpha_2 - P_2 \sin \alpha_2) - T_2 + \\
(x_a - x_r)(W_3 \cos \alpha_3 + P_3 \cos \alpha_3) + (z_a - z_r)(W_3 \sin \alpha_3 - P_3 \sin \alpha_3) - T_3 &= 0 \quad \text{(10)}
\end{align*}
\]

Where, $x_a, z_a$ are $X$ and $Z$ coordinates of the differential joint at point A, $x_f, z_f, x_m, z_m, x_r, z_r$ are $X$ and $Z$ centre coordinates of the front, middle and rear wheels.
The torque conservation equation at point B can be written as in (11).

\[
(x_B - x_m)(W_2 \cos \alpha_2 + P_2 \sin \alpha_2) + (z_B - z_m)(W_2 \sin \alpha_2 - P_2 \cos \alpha_2) - T_2 + (x_B - x_f)(W_3 \cos \alpha_3 + P_3 \sin \alpha_3) + (z_B - z_f)(W_3 \sin \alpha_3 - P_3 \cos \alpha_3) - T_3 = 0. \tag{11}
\]

Where, \( x_B, z_B \) are the X and Z coordinates of the free pivot at point B.

According to (8)-(11), there are six unknowns implied in the four equilibrium equations, so there are two variable parameters of the rocker-bogie mechanism. It is noted that we can choose the reasonable driving torques to control the whole rocker-bogie mechanism for obtaining a better obstacle-climbing capability.

3 Analysis of the Driving Force and Wheel Sinkages

3.1 Analysis of the Driving Force

Given the vertical load \( W \), the wheel will have the maximum driving force \( P_{\text{max}} \) when the slip ratio \( \lambda = 1 \), and at that time the actual wheel center velocity is zero, namely the wheel will get stuck in loose soil, the motor will do useless work. In practice, the slip ratio \( \lambda < 1 \), and \( \lambda_{\text{max}} \) is needed to be given. The wheel will have the minimum driving force when the driving torque \( T \) is dropped to zero, denoted as \( P_{\text{min}} \). Under the loose soil environment, When \( W \) and \( P \) are given and \( \lambda_{\text{max}} = 0.9 \), the driving torque \( T \) is determined according to (1)-(7), and the relationship curve of \( T, P, \) and \( W \) is shown in Fig.3.

3.2 Analysis of the Wheel Sinkages

When the normal forces \( W \) and the driving force \( P \) are given, the wheel sinkage \( h \) is determined according to (1)-(7), and their relationship curve is shown in Fig.4.

4 Obstacle-Climbing Capability Analysis

Whether the lunar rover travels forward or backward, their obstacle-climbing capabilities are almost consistent. This paper only analyzes the forward obstacle-climbing capability. The wheels and lunar soil characteristic parameters are given in Table 1, as in [8].
Table 1. Simulation parameters

| Wheel radius $r$ (mm) | Wheel width $b$ (mm) | Frictional modulus $k_f$ (N·m$^{-1}$(n+2)) | Cohesive modulus $k_c$ (N·m$^{-1}$(n+1)) | Shear deformation modulus $k$ (m) | Cohesion $c$ (kPa) | Internal friction angle $\phi$ (°) | Sinkage coefficient $n$ |
|------------------------|----------------------|---------------------------------------------|---------------------------------------------|---------------------------------|-----------------|-------------------------------|------------------|
| 130                    | 130                  | 814370                                      | 1379                                        | 0.01778                        | 0.172           | 40                            | 1.0              |

4.1 Analysis of Single-Wheel Obstacle-Climbing

Taking the right wheel 3 for example, given that the obstacle is a 40° slope, the height of obstacle is 100-200mm, i.e. $\alpha = [0 0 40^\circ 0 0 0]$, $Z = [0 0 100-200 0 0 0]$. When giving the obstacle heights of 100mm, 150mm and 200mm, the solution space feasible regions of the driving torque $T_1$, $T_2$ and $T_3$ are shown in Fig.5. Simulation shows that as the obstacle height increasing, the right solution space feasible regions have the gradually decreasing trend while the left solution space feasible regions changed little.

![Fig. 5. The solution space feasible regions of the right wheel 3](image)

4.2 Analysis of Two Wheels Obstacle-Climbing Simultaneously

**Wheel 3 and wheel 6 obstacle-climbing simultaneously.** Given that the obstacle is a 40° slope, the height of obstacle is 100-200mm, i.e. $\alpha = [0 0 40^\circ 0 0 40^\circ]$, $Z = [0 0 100-200 0 0-200]$. When giving the obstacle heights of 100mm, 150mm and 200mm, the solution space feasible regions of driving torque $T_1$, $T_2$ and $T_3$ are shown in Fig.6.

**Wheel 2 and wheel 5 obstacle-climbing simultaneously.** Given that the obstacle is a 40° slope, the height of obstacle is 0mm, i.e. $\alpha = [0 0 0 40^\circ 0 0 40^\circ]$, $Z = [0 0 0 0 0 0]$, there is no solution by simulation. Fig.7 shows the solution space feasible regions of wheel 2 and wheel 5 when giving $\alpha = [0 30^\circ 0 0 30^\circ 0]$, $Z = [0 0-100 0 0-100 0]$. 

![Fig. 6. The solution space feasible regions of wheel 3 and wheel 6](image)

![Fig. 7. The solution space feasible regions of wheel 2 and wheel 5](image)
The Fig.6 and Fig.7 shows that with the increase of obstacle height, the size of the feasible region has no obvious change except its shape and position.

![Fig. 6. The solution space feasible regions of wheel 3 and wheel 6](image1)

![Fig. 7. The solution space feasible regions of wheel 2 and wheel 5](image2)

5 Conclusions

On the basis of force analysis between the wheels and lunar soil, this paper established the obstacle-climbing force model of six-wheeled rocker-bogie lunar rover on loose soil. From the above analysis, we may draw the conclusion that when the lunar rover goes forward, with the same obstacle heights and slope angles, the obstacle-climbing capability of the wheels are different, namely the rear wheel is the best, the middle one is the worst, and the front one is moderate.

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