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Mechanics Analysis and the Simulation for Lunar Rover in Virtual Lunar Environment

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Abstact: In this study, Passive Earth Pressure of soil mechanics, raised by C.A.Coulomb, is applied to explain the mechanics analysis of wheel vane and then the wheel traction force is developed based on the limit equilibrium theory when a set of vane in the soil. In order to obtain the roughness of lunar terrain and the mechanical vibration characteristics of Lunar Rover, we modelled lunar terrain environment by using 3D solid lunar pavement models constructed by UG, Imageware and ADAMS. Lastly, based on power spectrum curve of lunar terrain environment, the spectral characteristic of lunar terrain with different roughness is educed by using reverse engineering algorithm.

Key words: Lunar rover, passive earth pressure, lunar terrain, limit equilibrium theory

INTRODUCTION

The planet vehicle is an important part of the planet exploration and many research institutes have carried out relevant research work (Caruso *et al*., 2007).The lunar rover named Lunakhod was launched by the former Soviet Union in the 1970s. These rovers such as "Sojourner", "Spirit" and "Opportunity" are launched by the United States in 1997 and 2003. All of these demonstrated that the planet rovers played significantly important role in the planetary exploration (Ye and Peng, 2006). The simulation is effective to improve design efficiency and low the total cost. In addition, it's difficult to carry out the mechanics analysis owing to the unknown roughness of the lunar surface, especially when Lunar Rover carries the various precise equipment to implement an unmanned Lunar mission. If the detector response of the rover closes to the natural frequency of the device, it will generate resonance and lead to fatal damage to the equipment. Under the unknown lunar terrain condition, the experiment or simulation results can effectively help to analyze the design parameter. This article is organized as follows. Section 2 introduces the design and traction analysis of semi-step walking wheel. Section 3 describes the terrain spectrum simulation analysis and presents the 3D lunar terrain modeling method for lunar rover landing area. Section 4 has the conclusions.

DESIGN AND TRACTION FORCE ANALYSIS OF SEMI-STEP WALKING WHEEL MODELED ON IMPELLER

The rover may encounter the rough terrain including soft soil, positive or negative obstacles as well as steep hill which will probably make the wheels sink into the lunar soil (Zou *et al*., 2010). In order to prevent lunar rover's sagging, one new type of rover wheels, Semi-step Walking Wheel, is presented in previous work. The particular structure is addressed in reference (Zhao *et al*., 2011).

Mechanics analysis of the vane based on the coulomb's passive earth pressure theory: The passive earth pressure presented in the Coulomb's retaining wall theory is employed to analyze the force interaction between the vane and lunar soil (Wang, 2011). To simplify calculations, here assume lunar surface flat and the part of vane in lunar soft is not curved, as shown in Fig. 1a. The vane sunk H, AB presents the facade of the contact surface between vane and soil, the angle between vane and the vertical direction is α. Wheels squeeze the soil while walking around and then the sliding crack body ABC is formed. The angle between the sliding plane of the body AC and the horizontal plane is θ. Based on the limit equilibrium theory, soil above the sliding plane (the sliding crack area) retains passive limit equilibrium condition. However, the soil beneath the sliding plane maintains an elastic state.

The forces applied on the sliding crack body consist of the following several parts: gravity G of the sliding body ABC which direct vertical downward. The counterforce R acted on the sliding plane forms an angle φ (internal friction angle of lunar soil) with the normal line. Counterforce Pb between the facade of the vane and the sliding crack body ABC, is equal to the passive earth pressure, however, in the opposite direction. The angle δ

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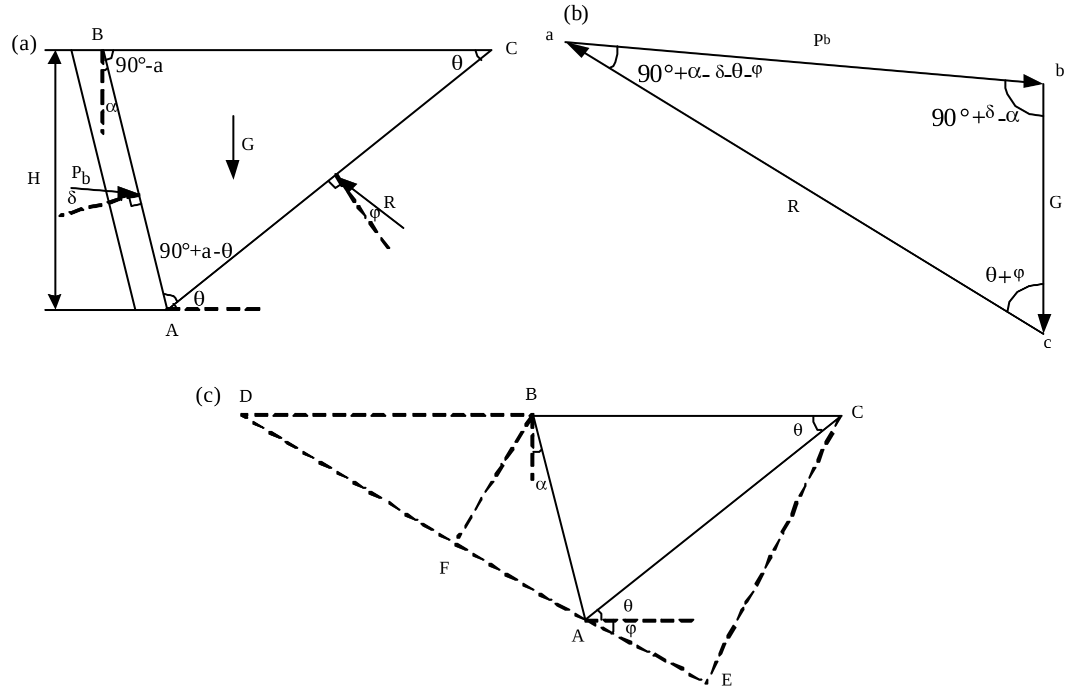

Fig. 1(a-c): Derivation graph of passive earth pressure

is formed by Pb and the normal line of the façade of the vane which means the internal friction angle between lunar soil and the façade.

Since, the sliding crack body stay in balance, the force lines form a closed triangular, as shown in Fig. 1b. A series of assistant lines are needed to deduce the alue of Pb, as shown in Fig. 1c. Here, we have ∠AEC = 90°-αδ and Δabc ≅ ΔCEA. Then:

$$P_b = G.CE/AE \quad (1)$$

The weight of the sliding crack body means area of triangle ABC timed by the volume of the lunar soil γ0:

$$G = \gamma_0.AB.BC.\sin(90°-\alpha)/2 \quad (2)$$

Here, substitute Eq. 1 into 2 which brings:

$$P_b = \gamma_0.AB.BC.CE\ \sin(90°-\alpha)/2AE \quad (3)$$

Triangle   is similar to   which makes AB, BD, BF, AD, DF constants. While the length of AE varies with the length of AC (the length of sliding plane), also varies with the slant angle θ. As a result, passive earth pressure is altered by AE. Based on the extreme value condition $dP_b/dAE = 0$, we have:

$$P_b = \frac{1}{2}\gamma\cdot\frac{AB\cdot BD\cdot BF\cdot(AD+AE-DF)\cdot(AD+AE)}{AE\cdot DF^2}\cdot\sin\left(\frac{\pi}{2}-\alpha\right) \quad (4)$$

The condition of maximum value of the passive earth pressure is depicted here:

$$AE^2 = AD.AF \quad (5)$$

The other unknown values could be calculated by employing sine theorem, then substitute Eq. 5 into 4 to obtain:

$$P_b = \frac{H^2\gamma\cos^2(\alpha+\varphi)}{2\cos^2\alpha\cdot\cos(\delta-\alpha)\left[1-\sqrt{\frac{\sin(\delta+\varphi)\cdot\sin\varphi}{\cos(\delta-\alpha)\cdot\cos\alpha}}\right]^2} \quad (6)$$

When the wheel scrolls ahead, the wheel generates pressure to the soil. To simplify calculation, it is assumed uniform load q0. Here uniform load can be converted into the height of lunar soil, shown as = q0/γ0. The value H is revised by h0 and substitute (H+ h0) into Eq. 6 to obtain:

$$P_b = \frac{(H+q_0/\gamma)^2\gamma\cos^2(\alpha+\varphi)}{2\cos^2\alpha\cdot\cos(\delta-\alpha)\left[1-\sqrt{\frac{\sin(\delta+\varphi)\cdot\sin\varphi}{\cos(\delta-\alpha)\cdot\cos\alpha}}\right]^2} \quad (7)$$

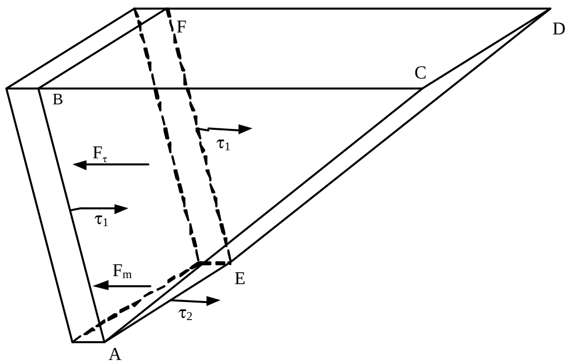

Fig. 2: Force diagram of the bottom surface and side of the vane

While the total passive earth pressure applied on the whole vane is expressed as following:

$$F_b = P_b b_0 = \frac{(H+q_0/\gamma_0)^2\,\gamma_0\cos^2(\alpha+\varphi)\,b_0}{2\cos^2\alpha\cdot\cos(\delta-\alpha)\left[1-\sqrt{\frac{\sin(\delta+\varphi)\cdot\sin\varphi}{\cos(\delta-\alpha)\cdot\cos\alpha}}\right]^2} \quad (8)$$

Besides the above mentioned force, the two sides and bottom of the vane are subjected to shear stress which is expressed by $\tau 1$ and $\tau 2$. In addition, the bottom surface of the vane is subjected to frictional force F_m (Chen and Chen, 1982). The soil thrust is shown in Fig. 2.

The total shearing force F_δ is indicated below:

$$F_\tau = 2S_{\Delta ABC}\tau_1 + S_{ACDE}\tau_2 = 2S_{\Delta ABC}\psi\cdot c + S_{ACDE}\,(c+\rho\tan\varphi)\cdot\left(1-e^{-j/k}\right) \quad (9)$$

Here, c is lunar soil cohesion; ψ is a parameter related to H. When H>b/2, $\psi = 2\sin^2[(\pi+\varphi)/2]^2$, otherwise, $\psi = 1$; ρ is the positive pressure of lunar soil which is equal to $H\gamma_0+q_0$; j is tangential shearing displacement which means the length of AC; b is cross-sectional width of the vane. The horizontal direction of friction force is default and equal to the vertical load multiplied by friction coefficient:

$$F_m = W_0\mu_m \quad (10)$$

In the above equation, μ_m is friction coefficient of lunar soil.

In summary, the maximum thrust which is caused on non-slipping condition, includes the horizontal component of the passive earth pressure, the shearing stress of the lunar soil and friction force F_m. The total thrust is expressed as:

$$F_H = F_b+2F_\tau+F_m \quad (11)$$

Traction force calculation of semi-step walking wheel modeled on impeller: The hypothesis is that lunar surface under the walking wheel is flat, so the slope resistance and steering resistance don't exist. Adherent resistance is greatly reduced due to the special design of the vane which could be ignored. There is no caterpillar thorn resistance here. The resistance F_z includes compaction resistance R_c and bulldozing resistance F_t (Chen, 2009):

$$F_R = R_c+F_t \quad (12)$$

$$R_c = \left[\frac{3W}{(3-n)\sqrt{D}}\right]^{\frac{2n+2}{2n+1}}\cdot\frac{1}{(n+1)\left(k_c+b_0k_\varphi\right)^{\frac{1}{2n+1}}} \quad (13)$$

$$F_t = \frac{b_0\sin(\alpha_0+\varphi_0)}{2\sin\alpha_0\cos\varphi_0}\left(2h_0c_0K_c+\gamma_0h_0^2K_\gamma\right)+\frac{\pi l^3\gamma_0\left(90^\circ-\varphi_0\right)}{540}+\frac{c_0\pi l^2}{180}+c_0l^2\tan\left(\frac{\pi+\varphi_0}{2}\right) \quad (14)$$

There $\varphi 0$ is the soil internal friction angle; c0 is the soil cohesion; Nc and Nγ are the coefficient related to friction angle. Here $K_c = (N_c-\tan\varphi_0)\cos^2\varphi_0$:

$$K_\gamma = \left(\frac{2N\gamma}{\tan\varphi_0}+1\right)\cos^2\varphi_0,\ l = h_0\tan^2\left(45^\circ\frac{\varphi_0}{2}\right)$$

In summary, the traction force formula of Semi-step Walking Wheel modeled on Impeller is:

$$F_{DP} = F_H-F_R \quad (15)$$

Here introduce the ADAMS model of CE-3-X suspension (Yang *et al*., 2010). Overall quality of the vehicle is 120 kg and uniformly distributed above the six wheels. The diameter of the wheel is 300 mm.The width is 140 mm. The effective width of the vane is 122.5 mm. The acceleration of gravity is 1/6 g. The previous article simulates the movement of the lunar rover, under these three conditions: Straight driving, one-side surmounting obstacle and two-sides surmounting obstacle (Wang, 2011).

TERRAIN SPECTRUM SIMULATION ANALYSIS OF LUNAR ROVER

The response characteristics of the lunar terrain excitation is acquired at the installing location of each device in the cabin which can provide necessary technical references for design improvements or installation method of cabin equipment. Referring to the literature about lunar surface roughness and road spectrum, we develop 3D solid lunar surface models with different roughness constructed by UG, Imageware and ADAMS.

Power spectrum of three different types of lunar surface: The literature (NASA, 1969) show the power spectral curve of three different type of lunar surface. Based on this, multi-point curve fitting method is applied to establish mathematical model of power spectrum on three different types of lunar surface.

Figure 3a shows the surface power spectral curve of smooth mare based on the mathematical model. Figure 3b shows the surface power spectral curve of rough mare based on the mathematical model.

Applying inverse Fourier transform to get three different types of lunar surface roughness (Zhang and Zhang, 2006; Chen and He, 2012; Zhang *et al*., 2011; Samaras *et al*., 1985), as is shown in Fig.4

3D lunar surface modeling and ADAMS simulation analysis: Using Imageware and UG to construct 3D solid model with different roughness for three types of lunar surface (Zhao *et al*., 2011). The width of solid model is 5 m, the length is 10m and the resolution of is 50 mm. Importing 3D lunar surface solid model and the rover model into ADAMS to simulate operation condition, in that the rover travels at 200 and 100 km h^{-1}, respectively.

The acceleration curves show that: when the rover travels on the smooth mare, rough mare and rough upland at the same speed, the maximum acceleration value of centroid becomes larger and larger. The maximum acceleration of centroid increases with the raising of the

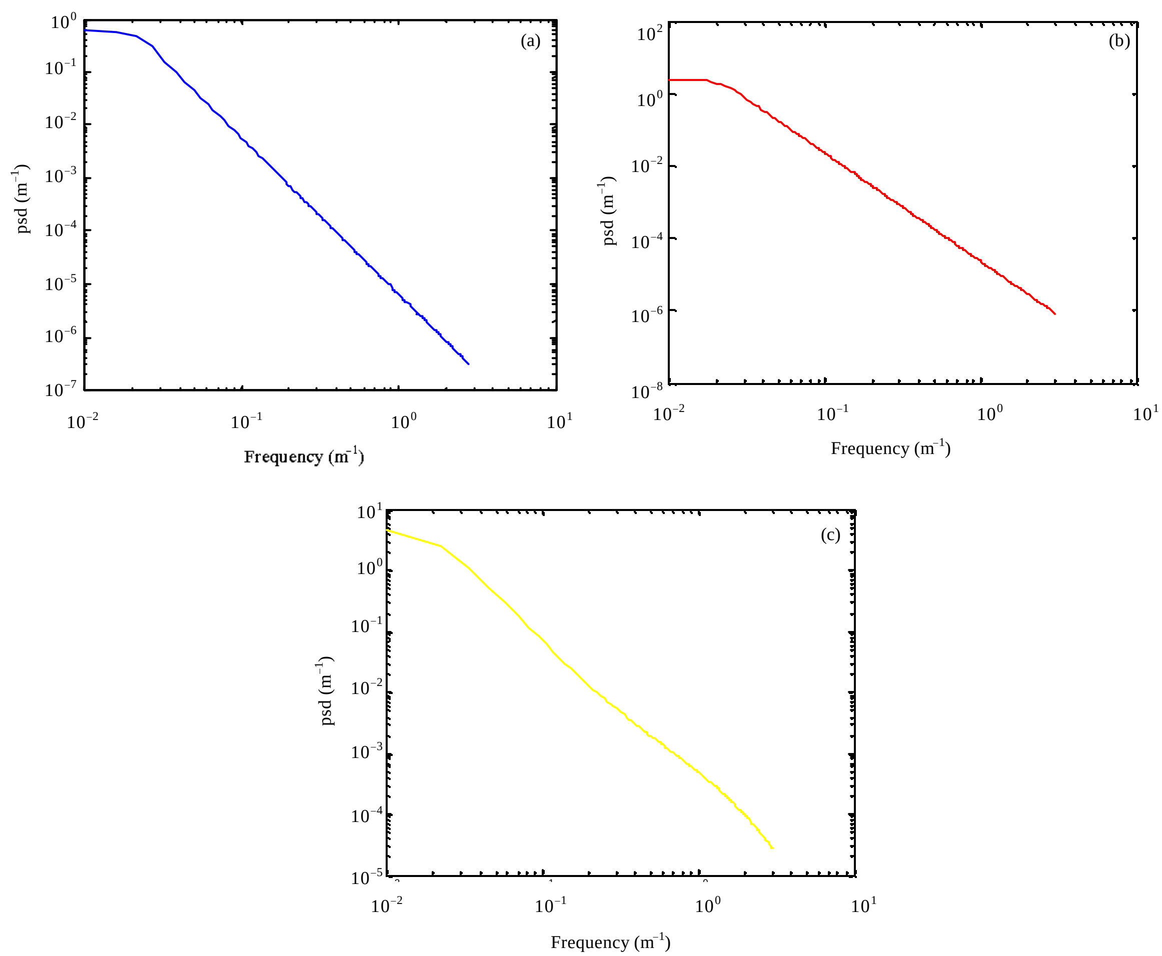

Fig. 3(a-c): Surface power spectral curve related to different lunar surface (a) Smooth mare, (b) Rough mare and (c) Rough upland

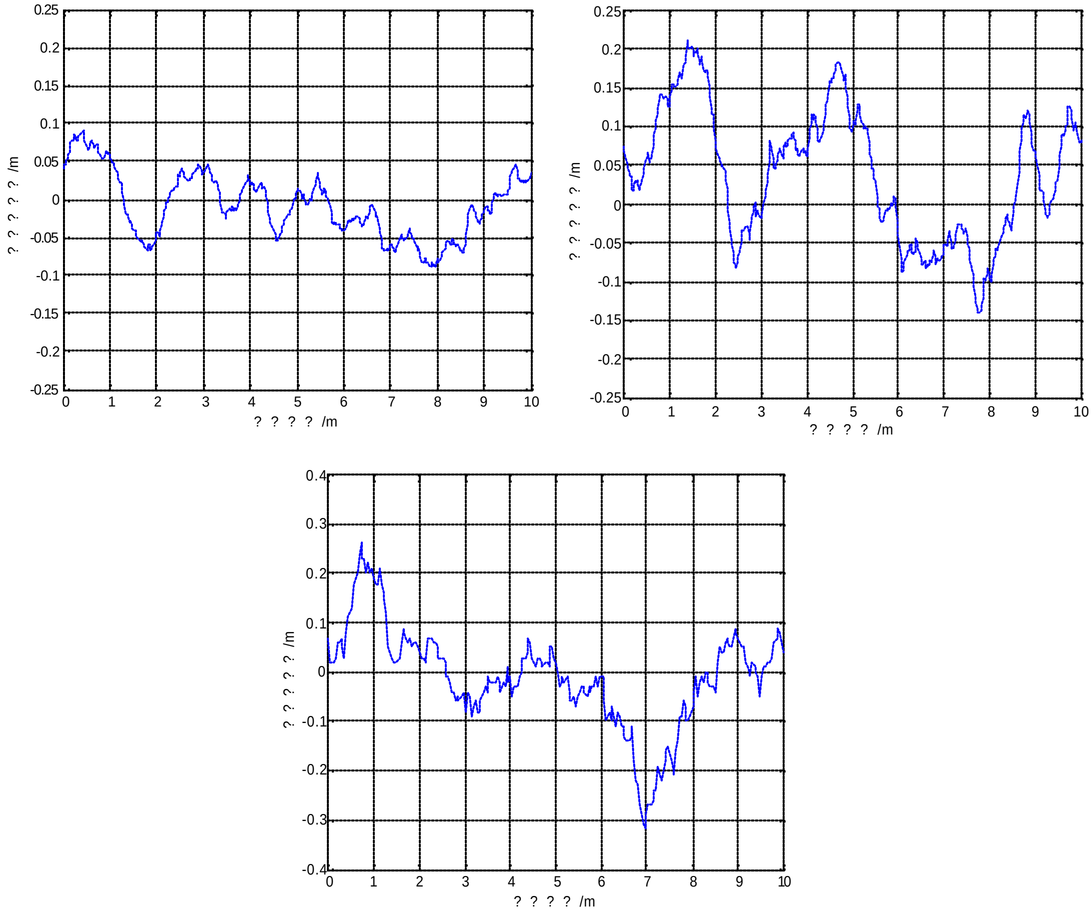

Fig. 4(a-c): Roughness curve related to different lunar surface, (a) Smooth mare, (b) Rough mare and (c) Rough upland

rover speed on certain roughness surface. The maximum acceleration of centroid when traveling at 200 m h^{-1} on the smooth mare, rough mare and rough upland approximates 0.5, 1.5 and 1.8 g, respectively.

CONCLUSION

Based on the new type of Semi-step Walking Wheel modeled on Impeller, the Coulomb theory of passive earth pressure is employed to obtain the traction formula of the walking wheel. Then, the wheel traction force is developed based on the limit equilibrium theory when a set of vane in the soil. There are still some shortcomings in this study, such as analysis of only one group vane's force and the theory of soil mechanics is still in primary stage, so the next step is to depth theoretical exploration.

This study presents how to obtain the roughness of lunar terrain and the mechanical vibration characteristics of Lunar Rover, we modelled lunar terrain environment by using 3D solid lunar pavement models constructed by UG, Imageware and ADAMS. Using reverse engineering software to construct the lunar landing terrain and fulfill Lunar Rover kinematics and dynamics simulation. American literature provides power spectrum curve of lunar terrain environment, for reference, the spectral characteristic of three different lunar terrain roughness is educed. Simulation results demonstrate the dominate frequency of vibration mechanics properties for different roughness surface.

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