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A Review on Travelling Performance of Planetary Rovers

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Abstract—*In designing a planetary rover, it is necessary to evaluate the effect of model size parameters such as weight, diameter/width and grousers of a wheel on its travelling performance. This paper presents an overview of these size parameters and their effect on the travelling performance, concluded from the works of various researchers. This travelling performance depends on the wheel mechanism/track mechanism with no effect from change in rover weight, for tracked mechanism. However, for the wheeled mechanism the travelling performance decreases as the rover weight increases. The wheel diameter rather than wheel width, improves travelling performance. The provision of lugs improves travelling performance. The paper describes the system parameters required and how they are evaluated. The salient observations and inferences on the research carried out by various researchers pertaining to the travelling performance of planetary rovers are also outlined.*

Keywords: *Travelling performance–rovers- slip ratio-drawbar pull-models.*

1. INTRODUCTION

Rovers are mobile robots which aid planetary explorations. While moving on difficult terrain of the Martian planet and lunar surface, these rovers have to negotiate steep slopes and rough terrain. Hence a study on their tractive performance becomes essential. These rovers are of light weight. Small projections on the rim of the wheel, known as lugs or grousers are provided and the performance of the lugged wheel are studied by various researchers. This paper highlights the impact of various size parameters such as wheel weight, diameter of wheel, width of wheel, wheel surface pattern (grousers), grouser height.

2. SLIP RATIO AND DRAWBAR PULL

The rovers tend to slip and the slippage is measured in terms of slip ratio and the drawbar pull.

The wheels of the rover may be rigid or flexible. For rigid wheel, the following conditions apply.

Slip Ratio

Slip ratio can be defined as follows (Wong,2001 and Ding et al.,2011).

$$s = \frac{v_d - v}{v_d} \qquad (1)$$

v_d = circumferential velocity

v = actual travelling velocity of the wheel.

Also,

$$s = \frac{r\omega - v}{r\omega} \qquad (2)$$

ω = angular velocity of the wheel

r= radius of the wheel

v = actual travelling velocity of the wheel.

When no slippage occurs, but, the wheel moves forward, the slip ratio achieves a minimum value of zero (better travelling performance)

When, the wheel moves forward along with slippage, the slip ratio is maximum, and is equal to unity.

Drawbar Pull

The drawbar pull (DP) is the difference between the soil thrust and the external resistance of the soil.

When negotiating a slope, the component of the slope angle also has to be taken into account. As per Wong (2001), the drawbar pull is given by the relationship

$$DP = mg \sin\theta \qquad (3)$$

Where m = mass of the vehicle / rover
g = acceleration due to gravity
and θ = slope angle

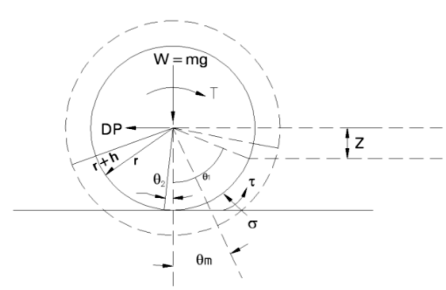

Fig. 1: Wheel-soil interaction diagram

As per Sutoh M. et al, 2010,

$$DP = rb \int_{\theta_2}^{\theta_1} [\tau_s(\theta)\cos\theta - \sigma(\theta)\sin\theta] d\theta \quad (4)$$

Where, b and r, correspond to the size parameters, width and radius of the wheel respectively. ($\boldsymbol{\theta}_m = \boldsymbol{\theta}$, ranging from 0 to $\boldsymbol{\theta}_1$ in Figure 1.) $\boldsymbol{\theta}_1$ is the entry angle; $\boldsymbol{\theta}_2$ is the exit angle of the wheel. τ_s Corresponds to the shear stress and σ corresponds to the normal stress.

As per Setterfield (2013), the above equation was refined as follows. The integration limits correspond to 0 and $\boldsymbol{\theta}_1$. The wheel boundary is in contact with the surface of the soil.

$$DP = rb \left(\int_0^{\theta_1} \tau_s \cos\theta \, d\theta - \int_0^{\theta_1} \sigma \sin\theta \, d\theta\right) \quad (5)$$

As per Sutoh M. et al, 2012, the vertical force is given as follows.

$$F_z = rb \int_{\theta_1}^{\theta_2} [\tau_s(\theta)\sin\theta + \sigma(\theta)\cos\theta] d\theta \quad (6)$$

3. EVALUATION OF STRESSES

(Normal stress and shear stress)

In order to evaluate DP and the vertical force, normal stress σ, shear stress τ_s, σ_{max}, θ_1 and θ_2, need to be calculated.

For a wheel travelling on loose soil, the maximum normal stress occurs in the transition zone between the forward and rearward portions. (Wong, 2001)

Normal stress in the forward region (i.e. $\boldsymbol{\theta}$ lies between θ_m and θ_1),

$$\sigma = (k_1 + k_2 b)\left[\frac{r}{b}(\cos\theta - \cos\theta_1)\right] \quad (7)$$

Normal stress in the forward region

(i.e. $\boldsymbol{\theta}$ lies between 0 to θ_m is expressed as

$$\sigma = (k_1 + k_2 b)\left[\frac{r}{b}\left(\cos[\theta_1 - \frac{\theta}{\theta_m}(\theta_1 - \theta_m)] - \cos\theta_1\right)\right]^n \quad (8)$$

where, k_1 and k_2 are pressure-sinkage constants, 'b' is the width of the wheel, 'r' is the radius of the wheel and 'n' is the soil deformation exponent.

As per Ishigami (2007), maximum normal stress can be arrived at from the given normal stress calculated from equation (9).

$$\sigma(\theta) = \sigma_{max}[\cos\theta - \cos\theta_1] \quad (9)$$

$$\sigma_{max} = (ck_c + \rho k_\phi b)\left(\frac{r}{b}\right)^n \quad (10)$$

k_c and k_ϕ are the pressure-sinkage constants, corresponding to the shear parameters, cohesion and friction angle, n denotes soil exponent. c and ρ, are cohesion and bulk density of the soil,respectively.

The entry angle, θ_1 and the exit angle θ_2 of the wheel (for determining DP and vertical stress), depend on λ, the sinkage ratio of the wheel, the ratio of front sinkage to rear sinkage of the wheel, as well as the lug size parameters, height h and radius r.

$$\theta_1 = \cos^{-1}(1 - h/r) \quad (11)$$

$$\theta_2 = \cos^{-1}(1 - \lambda h/r) \quad (12)$$

For a wheel travelling on loose soil, the maximum shear stress is obtained by modifying Mohr's relationship to include the radius of the wheel 'b', shear deformation parameter 'k_s', shear parameters, c and ϕ and the slip 'i'.

$$\text{Slip } i = \frac{\omega r - v}{\omega r} \quad (13)$$

ω is angular velocity of wheel, r is radius of wheel and v is the travel velocity of wheel.

Shear stress (Wong, 2001),

$$\tau_s = (c + \sigma\tan\phi)\left(1 - e^{-\frac{r}{k_s}[(\theta_1 - \theta) - (1-i)(\sin\theta_1 - \sin\theta)]}\right) \quad (14)$$

Ishigami (2007), simplified the shear stress equation by introducing the shear deformation modulus 'k_s' and the soil deformation modulus, j_s, dependent on the wheel angle θ as follows

$$j_s(\theta) = r[\theta_1 - \theta - (1-i)(\sin\theta_1 - \sin\theta)] \quad (15)$$

Hence the modified shear stress equation becomes

$$\tau_s = (c + \sigma(\theta)\tan\phi)[1 - e^{-j_s(\theta)/k_s}] \quad (16)$$

4. EFFECT OF SIZE PARAMETERS ON TRAVELLING PERFORMANCE

Optimization of locomotion performance of vehicles for planetary explorations and design of a reconfigurable mini-rover is described by **Grand et al., (2002).** Velocity based algorithm which improves both the global traction as well as stability performance of a rover is considered. Sensors like inclinometers for pitch and the roll measurements and position sensors for detecting lug mechanism are provided.

Yoshida et al. (2003) uses slip based traction control of a planetary rover over a rough terrain. Experiments were conducted on a test bed, to understand tire-soil interaction. The slip ratio ranges from 0.1 to nearly 1.0 and hence limits excessive tire velocity or force.

Bauer et al. (2005) reported good agreement between experimental and simulation results, for, wheel sinkage as a function of slip ratio. Dry sandy soil was used. When 18 lugs were provided on the wheel, approximately 30% increase in drawbar pull was observed from that of a 9 lugged wheel, with relatively little effect on sinkage, AESCO Soft Soil Tire Model (AS^2TM) was able to capture the sinkage vs. slip ratio relationship accurately for both single and multi pass cases.

Wong et al. (2006) evaluated the travelling performance of wheeled vehicle and tracked vehicle. Two computer simulation models, one for wheeled vehicles, NWVPM and other for tracked vehicles, NTVPM are used. Shearing characteristics of the terrain thrust on a wheeled and tracked vehicle are explained. The thrust from both wheeled vehicle and tracked vehicle are compared. For the tracked vehicle,total contact area is usually much larger than that of wheeled vehicle. Hence the traction of a tracked vehicle on cohesive soil is more than the traction of wheeled vehicles.

Michaud et al (2006) carried out optimization of wheel design on a particular soil using Rover Chassis Evaluation Tool (RCET) tool. The travelling performance is expressed in terms of trafficability and terrrainability. Trafficability characteristics include static stability and slope gradeability; Terrainability is in terms of obstacle climbing ability and ground clearance. The optimal rover design is achieved considering the soil properties and wheel load range.

Liu et al. (2008) conducted experiments on small rigid wheel traversing on a soil bin of loose sand. They analyzed the effect of straight lugs on the wheel performance and optimized the wheel configuration of planetary rovers. Experiments were carried out using single-wheel test bed at a free wheel sinkage and 0 to 60% slip. Six transducers, displacement transducer, and torque sensor, towing motor, driving motor and steering motor were made use of. Motion Performance was evaluated by its drawbar pull (DP) and driving torque (DT).Two wheels were considered–one with a diameter of 135 mm and width of 95 mm and another with diameter as 167 mm and width of 105 mm. Based on the study, the optimum lug spacing was 15^o , optimum height was 10 mm and thickness was 1.5 mm. The lug height and slip produced had major effect rather than lug thickness and spacing.

Sutoh et al. (2010) conducted experiments with two-wheeled rover. Numerical simulations were also carried out. Increase in the wheel width, from 50 mm to 150 mm, results in a decrease in the slip ratio to 0.3 (maximum change at slope angle equal to 17^0). Hence, the wheel diameter was increased keeping the width constant, contrary to general belief, as wheel diameter increases, the slip ratio decreases leading to better travelling performance. But, the weight of the wheel is not explicitly mentioned. The above result becomes a possibility if for the same wheel weight and the same width, the diameter alone is increased. In the simulations, as the wheel width increased, the slip ratio decreases as in the case of experiments. The drawbar pull increases. However, in the simulation as width increased, the slip ratio also increased. The effect of variation of diameter was not felt in the simulations carried out.

Ding et al. (2011) conducted experiments using single-wheel test bed for wheels. The parameters varied include wheel diameter,width, lug number, lug heights, and lug inclination angles. Influence of vertical load and moving velocity on wheel driving performance were also studied. Wheel driving performance in terms of performance indices and relative indices are provided. Increase in radius and width results in increase in wheel driving performance; Lug height affects the wheel driving performance more than increase in radius. Optimum number of lugs, were arrived at, to achieve maximum tractive performance. Minimum inclination of lug angle was also determined.

Ishigami et al. (2011) describes a comprehensive model for the traction performance of flexible/rigid wheels driving on deformable terrain calculates wheel deflection as well as wheel sinkage. Simulation results gives the optimal wheel pressure based on wheel load, wheel dimension and terrain stiffness.

Lizuka et al. (2011) carried out investigations on the shape of lugs. Experiments were carried out using single-wheel test bed, to measure slip ratio over various slopes and different shapes of lugs. The ratio between radius of the wheel and lug length is considered. When the lug length is more, the wheel performs better. There is limit on traversing slope on loose soil if the length of lugs, become longer. Wheels with larger radius will have better performance than those with small radius.

Sutoh M et al. (2011) conducted experiments using lightweight two-wheeled rover. The number of lugs, lug heights were varied; in a sand box the influence of lugs on the travelling performance of planetary rovers was assessed. From experimental results, it was found that although lugs have some effect on the travelling performance over gentle slopes (for slopes less than 8^0), they have more effect on the travelling performance over steep slopes (slopes more than 8^0). On gentle slopes, when no of lugs are small, increase in lug height (from 5 mm to 15 mm) results in decreasing travelling performance whereas an increase in the no of lugs with an increase in lug height results in increase in traveling performance. On the other hand, increase in lug height and increase in no of lugs contributes high travelling performance of wheels over steep slopes. Wheels with lugs have higher travelling performance than wheels with diameter.

Sutoh et al. (2012) has used the linear travelling speed model. The wheel had lugs. Guidelines for determining a suitable lug interval are described., Terramechanical stress models were given. This study was aimed at optimizing the lug interval. When the number of lugs was increased from 3 to 12, the speed of the rover periodically changes whereas for lugs more than 12, speed remains constant. Still research needs to be carried out, for large number of lugs on wheels for better results.

Sutoh M et al., (2012), conducted experiments using a mono-track rover and an inline four-wheeled rover with different rover weights in order to evaluate its travelling performance based on the influence of rover weights, wheel diameter/width (diameters considered are 116 mm, 202 mm, 327 mm and widths are 50 mm, 100 mm, 150 mm). Numerical simulation and comparisons with with experimental results are carried out.For tracked mechanism, there is no effect due to increase in rover weight ;in wheeled mechanism, decrease in travelling performance occurred with increase in rover weight. Wheel diameter (327 mm) rather than wheel width (150 mm), contributes to better travelling performance. The increase in the number of lugs will improve the travelling performance than having large diameter.

Skonieczny et al. (2012) proposed an expression for determining appropriate lug(grouser) spacing for rigid wheels. Experiments were conducted using test bed with different no of lugs on wheel and with various heights of grousers resulting in an increase in grousers beyond the minimum number do not improve performance. The proposed expression relates the geometric wheel parameters (such as wheel radius, lug height and spacing) and operating parameters (such as slip and sinkage), and predicts the maximum allowable lug spacing which is given in below.

$$\phi < \frac{1}{(1-i)}\left(\sqrt{((1+h)^2-(1-z)^2)}-\sqrt{1-(1-z)^2}\right)$$

Where ϕ is angular grouser spacing, h is grouser height, z is wheel sinkage and i is wheel slip.

$i = 1 - \frac{v}{r\omega}$; where v is wheel linear velocity, ω is wheel angular velocity and r is radius of the wheel.

Ding et al. (2012) carried out studies on slip ratio of a lugged wheel. Wheel-soil interaction experiments were carried out varying wheel diameter, lug height.. Sensors are used to determine drawbar pull, torque and wheel sinkage. If the slip ratio is zero, the soil can cause little resistance force on the smooth wheel. It also results, wheels with different lug heights to verify this, the driving torques were also same if the slip ratio was zero.

Sutoh et al. (2013) provided a fundamental guideline for determining the lug interval on a wheel. Linear travelling speed model is proposed for wheeled vehicle first and, to verify this model, travelling tests were performed using two-wheeled rover with wheels of different lug intervals and with different lug heights. Maximum allowed lug interval can be determined for a given wheel using the angle derived from static sinkage of wheel. From experimental results it was found that, for a wheel to have high travelling performance there should be more than two lugs between the vertical and the surface of the soil on a wheel.

Sreenivasulu and S.Jayalekshmi(2014) provide a comprehensive review of the terramechanics on lunar soil mechanics.

Sreenivasulu(2014) prepared a lunar soil simulant: TRI-1(Tiruchirappalli -1) and characterization of the same and wheel-soil interaction studies were carried out on TRI - 1

Yamamoto et al. (2014) examine about influence of lug motion, the soil reaction forces acting on a single actuated lug (without wheel) in various motion scenarios. The parameters of lug's motion, such as inclination angle, moving velocity and sinkage length of the lug were assessed. Both the bulldozing force and vertical force are independent of horizontal moving velocity of the lug. Bull dozing force achieved its maximum value around 120^0 whereas vertical force achieved its maximum value around 130^0.

5. CONCLUSIONS

This paper presents a review on the travelling performance of planetary rovers carried out by various researchers. It is inferred from the review that ample scope exits for wheel soil interaction studies.

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