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Experimental study and analysis on driving wheels' performance for planetary exploration rovers moving in deformable soil

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Abstract

Planetary rovers are different from conventional terrestrial vehicles in many respects, making it necessary to investigate the terramechanics with a particular focus on them, which is a hot research topic at the budding stage. Predicting the wheel–soil interaction performance from the knowledge of terramechanics is of great importance to the mechanical design/evaluation/optimization, dynamics simulation, soil parameter identification, and control of planetary rovers. In this study, experiments were performed using a single-wheel testbed for wheels with different radii (135 and 157.35 mm), widths (110 and 165 mm), lug heights (0, 5, 10, and 15 mm), numbers of lugs (30, 24, 15, and 8), and lug inclination angles (0°, 5°, 10°, and 20°) under different slip ratios (0, 0.1, 0.2, 0.3, 0.4, 0.6, etc.). The influences of the vertical load (30 N, 80 N, and 150 N), moving velocity (10, 25, 40, and 55 mm/s), and repetitive passing (four times) were also studied. Experimental results shown with figures and tables and are analyzed to evaluate the wheels' driving performance in deformable soil and to draw conclusions. The driving performance of wheels is analyzed using absolute performance indices such as drawbar pull, driving torque, and wheel sinkage and also using relative indices such as the drawbar pull coefficient, tractive efficiency, and entrance angle. The experimental results and conclusions are useful for optimal wheel design and improvement/verification of wheel–soil interaction mechanics model. The analysis methods used in this paper, such as those considering the relationships among the relative indices, can be referred to for analyzing the performance of wheels of other vehicles.

Keywords: Terramechanics; Planetary exploration rover; Wheel performance; Dimension; Lug; Slip ratio; Performance indices

1. Introduction

Exploring planets such as the Mars and the moon with autonomous wheeled robots (rovers) has already been proved to be an effective method by the successful rovers, including the well-known "Sprit" and "Opportunity" of the US and "Lunakhod" of the former USSR [1,2]. At present, several new rover-based planetary exploration missions are in progress, which require the rovers to travel a much longer distance over more challenging terrain than did earlier missions [3–5]. In order to fulfill complex scientific exploration tasks in rough deformable terrain covered with fine-grained regolith, scientists have been researching and endeavoring to develop high-performance rovers.

Predicting wheel–soil interaction performance from the knowledge of terramechanics is of great importance to mechanical design/evaluation/optimization [6–8], dynamics simulation [9–11], soil parameter identification [12,13], locomotion control [14,15], path following [16], and even to path planning [17] of rovers. Terramechanics theory developed by Bekker et al. [18–22] for conventional terrestrial vehicles was usually directly used for the research on planetary rovers. However, due to the differences between planetary rovers and terrestrial vehicles with regard to the physical dimensions, wheel shape, payload, terrain, running velocity, control mode, and so on, it is necessary to examine the applicability of the conventional theory and improve it so that it can be applied to planetary rovers.

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Nomenclature

$\boldsymbol{W}$	vertical wheel load	z	wheel sinkage
$\boldsymbol{f_{DP}}$	horizontal resistance encountered by a wheel	θ_1	entrance angle of the wheel moving in soil
$\boldsymbol{T}$	driving torque generated by the wheel motor and reduction gears	θ_2	leaving angle of the wheel moving in soil
$\boldsymbol{F_N}$	normal force exerted on the wheel by soil	θ_m	the angular position of the maximum stress exerted on the wheel by soil
$\boldsymbol{F_{DP}}$	drawbar pull exerted on the wheel by soil	c_1, c_2	coefficients used for calculating θ_m
$\boldsymbol{M_R}$	resistance moment exerted on the wheel by soil	s	slip ratio
k_c	cohesive modulus of soil	v	linear velocity of the wheel
k_φ	frictional modulus of soil	ω	angular velocity of the wheel
n	sinkage exponent of soil	n_p	repetitive times for a wheel travelling on the same terrain
c	cohesion of soil	t	time
φ	internal friction angle of soil	PC	drawbar pull coefficient
K	shearing deformation modulus of soil	TC	tractive force coefficient
r	wheel radius	RC	resistance force coefficient
r_s	equivalent shearing radius of the wheel	PE	drawbar pull efficiency
λ_s	coefficient used for calculating r_s	TE	tractive efficiency
b	wheel width	P	effective power of the motor
h	lug height	L	the distance between the tracks generated by two adjacent lugs
β_L	inclination angle of wheel lugs		
n_L	number of wheel lugs		
γ_L	spacing angle of wheel lugs, $\gamma_L = 2\pi/n_L$		

Terramechanics of planetary rovers is a hot research topic at the budding stage, which presents both new challenges and new opportunities to the fields of conventional vehicles and mobile robots [23].

Terramechanics is a subject that closely combines theory and experiments. In order to study the terramechanics of planetary rovers, some testbeds were developed according to the special conditions of planetary rovers [7,24–26] and used to conduct wheel–soil interaction experiments. From the experimental results, the performance of wheels and rovers could be analyzed for understanding the relationships among parameters such as the normal force, drawbar pull, driving torque, wheel sinkage, and slip ratio as well as the influence of wheel parameters (such as the wheel radius/width, and height/number/inclination angle of lugs on wheel performance. The experimental results were also used for deducing, improving, and validating semi-empirical wheel–soil interaction models based on the conventional theory.

Iagnemma et al. simplified conventional stress distribution equations to linear functions according to the observation that stress distributions are approximately linear for most of the natural terrains. By using these simplified equations, they deduced a simplified closed-form formula for wheel–soil interaction mechanics [27]. Further, a linear least-square estimator was adopted to estimate internal cohesion and friction angle on-line by using this formula [28]. The experimental results from a single-wheel testbed [24] confirmed the effectiveness of the simplified equations and the algorithm used for soil parameter estimation. Bauer et al. tested the performance of a wheel with 9 and 18 wheel lugs by using a single-wheel testbed and used the results to validate a dynamic computer simulator [29]. Michaud et al. presented the rover chassis evaluation tools (RCET) and used testbeds to validate the locomotion performance [7,30]. Jizuka et al. developed a pentagon-type wheel for an exploration rover and experimentally studied its slope-climbing performance [31]. Yoshida et al. derived an improved practical model for calculating the drawbar pull as a function of the vertical load and slip ratio on the basis of the Wong–Reece terramechanics formula [32]; in order to analyze the steering performance of a wheel and a rover, the lateral force characteristics of a driving wheel were modeled as a function of the slip ratio and slip angle [33]. The proposed models were validated with reasonable precision by experimental results obtained using a single-wheel testbed [25]. Liu et al. conducted experiments to analyze the effect of slip on the tractive performance of rigid wheels in loose soil [34]. Recommendations for grouser parameters were given: a spacing angle of 15°, grouser height of 10 mm, and grouser thickness of 1.5 mm [35] based on the experiments with a single-wheel testbed [26]. Zou et al. compared the performance of a lugged wheel and a smooth wheel based on experimental results and concluded that the drawbar pull of the former wheel is 5.2 times as that of the latter one [36].

Theoretical prediction of the wheel performance is intrinsically difficult because the wheel–soil interaction process is intricate and is influenced by many factors. The objective of this study is to investigate the effect of several factors on the wheel performance of planetary rovers on the basis of experimental results, including the wheel diameter/width, lug height/number/inclination angle, moving