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Effects of gravity on rigid rover wheel sinkage and motion resistance assessed using two-dimensional discrete element method

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Abstract

Elucidating the effects of gravity on rover/rover wheel performance is important because it can provide a basis for predicting their performance on extraterrestrial surfaces based on test results obtained on Earth. Results of previous studies by Wong (2012) and by Wong and Kobayashi (2012) indicate that if in conducting performance testing of rovers/rover wheels on Earth with identical mass to that on the extraterrestrial surface, instead of with identical normal load (force) used in the current practice, their performance on the extraterrestrial surface can be predicted based on test results obtained on Earth. As described herein, the effects of gravity on rigid rover wheel sinkage and motion resistance were investigated using the two-dimensional discrete element method. The rover wheel mass is unchanged under various gravity conditions. The results of this study substantiate the findings presented in Wong (2012) and Wong and Kobayashi (2012). Given identical mass, the sinkage of a rigid rover wheel under Earth gravity g is the same as that under a different gravity g_{ex}: $1/6g$–$2g$. It is also shown that the ratio of the motion resistance of a rigid rover wheel under gravity g_{ex} to that under Earth gravity g is equal to the ratio g_{ex}/g.

Keywords: DEM; Gravity effects; Mobility; Sinkage; Motion resistance; Wheel slip; Rover wheel performance; Planetary rover

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1. Introduction

Humans' desire to explore the universe has been a strong motivation for extraterrestrial missions. Surface explorations have so far been realized, for instance, on the Moon by Lunokhod rovers of the Lunokhod program of the USSR [3], by the Lunar Roving Vehicle (LRV) of the Apollo program of the USA [4], and by the 'Yu Tu' rover of the Chang'e 3 mission, PRC [5], and on Mars by several NASA rovers: 'Sojourner', 'Spirit', 'Opportunity', and 'Curiosity' [6].

Before their deployment to the Moon or Mars, tests of the performance of rovers/rover wheels were usually conducted on Earth using soil simulants that were regarded as appropriate to the regolith on extraterrestrial surfaces of interest. In the tests, the soil simulant was subject to Earth gravity, although the regolith on the extraterrestrial body is under a different gravity. Consequently, it is uncertain whether the rover/rover wheel will exhibit the same performance on the extraterrestrial surface as that obtained from tests conducted on Earth. Therefore, elucidating the effects of gravity on performance is important for the development and testing of rovers and their running gear.

Semi-empirical (or parametric analysis) approach [7] has been widely used for the prediction of rover wheel performance on extraterrestrial terrain. Recent examples are apparent in the analyses of the performance of micro-rovers by ESA [8–10]. The computer-aided model Nepean Wheeled Vehicle Performance Model (NWVPM) has been

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Nomenclature

Δt	time step of numerical integration
θ	wheel contact angle, measured from the wheel dead-bottom-center
θ^*	angle between normal contact reaction and horizontal x-axis
μ_p	friction coefficient between soil elements
μ_w	friction coefficient between soil element and wheel element
ρ	mass density of soil element in DEM
ρ_d	mass density of soil in experiments
ϕ	angle of friction between soil elements
ω	angular speed of element or wheel
B_s	soil bin width
B_w	wheel width
C_n	normal damping coefficient between DEM elements
C_t	tangential damping coefficient between DEM elements
D	wheel diameter
e	void ratio of soil
F	gross traction (tractive effort, thrust), $F = \sum_c f_t \cos\theta$
F_d	net traction (drawbar pull, drawbar load), $F_d = F - R_t$
f_n	normal component of reaction on the contact surface between DEM elements
f_t	tangential component of reaction on the contact surface between DEM elements
f_x	x-component of contact reaction between DEM elements
f_y	y-component of contact reaction between DEM elements
g	acceleration of Earth gravity (9.81 m/s^2)
g_{ex}	acceleration of gravity on extraterrestrial surface
g_{ex}/g	gravity ratio
H	height of soil bin
i	wheel slip, $i = 1 - (V/r_w\omega)$
i_e	average wheel slip on Earth
i_{ex}	average wheel slip under gravity g_{ex}
i_R	ratio of average wheel slip at various gravities to that on Earth, $i_R = i_{ex}/i_e$
K_n	normal spring constant between DEM elements
K_t	tangential spring constant between DEM elements
K_ϕ	pressure-sinkage parameter for the modified Reece equation
L	soil bin length
m	mass of soil or wheel element
m_s	mass of soil element with radius of $r = 0.8$ mm
n	exponent of the Reece pressure-sinkage equation
n_e	total number of adjusted soil elements in DEM
P	horizontal load on wheel because of carriage friction on the test facility
R_R	ratio of average wheel motion resistance under various gravities to that on Earth, R_{tex}/R_{te}
R_t	wheel motion resistance, $R_t = \sum_c f_n \sin\theta$
R_{te}	average wheel motion resistance on Earth
R_{tex}	average wheel motion resistance under gravity g_{ex}
r	radius of soil element in DEM
r_w	wheel rolling radius, $r_w = D/2$
V	forward speed of wheel center
W	normal load (force) on wheel
W'	summation of vertical components of f_n and f_t on the contact surface between soil and wheel elements
z	wheel sinkage
z_e	average wheel sinkage on Earth
z_{ex}	average wheel sinkage under gravity g_{ex}
z_R	ratio of average wheel sinkage under various gravities to that on Earth, z_{ex}/z_e

used recently to predict the mobility of various wheel candidates for the LRV of the Apollo program. The predictions have been found to correlate reasonably well with available test data obtained on Earth [11].

Apart from Soviet/Russian work of the Lunokhod era [12] and a US report on dust problem and fender design for a wheel of Apollo LRV [13], experimental data related to rover wheel performance under various gravity conditions have been scarce until recently, when Kobayashi et al. reported the experimentally obtained results of a small rigid wheel performance under reduced gravity conditions experienced during parabolic flights of an airplane [14]. They conducted experiments of two types: one was a partial gravity experiment (PGE) in which the gravity was varied between $1/6g$ to $2g$ (g being the acceleration of gravity on Earth); the other was an on-ground experiment (OGE) in which the vertical load (force) on the wheel was varied.

Soils of two types, a lunar regolith simulant and Toyoura sand, at relative densities 50% and 70%, were used in experiments. The wheel sinkage, torque, and slip were monitored during the tests. Based on test results, they concluded that the change of gravity condition does not affect wheel sinkage. They also found that the traction decreased as the gravity level and/or the wheel load decreased, and that the slippage occurred more easily in low gravity condition than in a $1g$ condition, even if the same sinkage was obtained.