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Journal of Terramechanics 74 (2017) 45–56

Journal of Terramechanics

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Longitudinal skid model for wheels of planetary rovers based on improved wheel sinkage considering soil bulldozing effect

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Received 14 December 2016; received in revised form 14 June 2017; accepted 15 October 2017
Available online 6 November 2017

Abstract

To successfully deploy a wheeled mobile robot on deformable rough terrains, the wheel-terrain interaction mechanics should be considered. Skid terramechanics is an essential part of the wheel terramechanics and has been studied by the authors based on the wheel sinkage obtained using a linear displacement sensor that does not consider soil bulldozing effect. The sinkage measured by a newly developed wheel via detecting the entrance angle is about 2 times of that measured by the linear displacement sensor. On the basis of the wheel sinkage that takes the soil bulldozing effect into account, a linear function is proposed to the sinkage exponent. Soil flow in the rear region of wheel-soil interface is considered in the calculation of soil shear displacement, and its average velocity is assumed to be equal to the tangential velocity component of the transition point of shear stress. To compute the normal stress in the rear region directly, the connection of the entrance and leaving points is supposed as the reference of wheel sinkage. The wheel performance can be accurately estimated using the proposed model by comparing the simulation results against the experimental data obtained using two wheels and on two types of sands.

Keywords: Terramechanics; Wheeled mobile robots; Longitudinal skid model; Soil bulldozing effect; Sinkage exponent

1. Introduction

The analysis of wheel-soil interaction mechanics has implications for the system's design, sensing subsystem, and estimation and control algorithms (Iagnemma et al., 2001, 2010; Ding et al., 2011). Usually, this interaction is assumed to follow the simple Coulomb friction law, and the effects of such phenomena as wheel slippage and sinkage are ignored (Yu et al., 2010). Although such an approach may be sufficient for some applications, operation near a system's performance limits, e.g. on challenging terrains, often requires more sophisticated analyses of robot-terrain interaction. Sandy terrains are widely distributed across terrestrial, lunar and Martian surfaces, which are difficult to traverse, and their access presents an ongoing challenge for mobile robots (Yang et al., 2014).

Slip and skid terramechanics are two essential components of the wheel-soil interaction mechanics (Ding et al., 2009). Bekker (1960) and Wong and Reece (1967a) predicted the performance of a driving rigid wheel of terrestrial vehicles based on the stress analysis. Irani et al. (2011) established a validated dynamic terramechanics model for a driving rigid wheel with grousers of wheeled mobile robots operating on loose sandy soil to capture and predict the dynamic oscillations observed in the experimental data from a single-wheel test-bed. Lyasko (2010)

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https://doi.org/10.1016/j.jterra.2017.10.004
0022-4898/

Nomenclature

W	vertical load of wheel (N)
F_{DP}	drawbar pull exerted on the wheel (N)
F_N	normal force exerted on the wheel (N)
F_P	pushing force exerted on the wheel (N)
F_R	resistance force from the soil (N)
T_D	wheel driving torque (Nm)
T_B	braking torque (Nm)
K	shear deformation modulus of soil (mm)
K_e	equivalent shear deformation module of soil (mm)
V_h	horizontal velocity component of a random point in wheel rim (mm/s)
V_s	soil flowing velocity (mm/s)
V_r	relative velocity of soil to wheel rim in the tangential direction (mm/s)
V_t	tangential velocity component of a random point in wheel rim (mm/s)
K_v	coefficient of flow velocity
s, s_d	slip and skid ratio
v	forward velocity of wheel (mm/s)
z_1	wheel sinkage (mm)
z_σ	wheel sinakge referred to the new reference (mm)
z_2	rebounding height of soil (mm)
f_{DP}	horizontal resistance encountered by the wheel (N)
k_{eq}	equivalent deformation modulus of soil (Pa/m^n)
n	sinkage exponent of soil
k_c	cohesive modulus of soil (Pa/m^{n-1})
k_φ	frictional modulus of soil (Pa/m^n)
b, r	wheel width and radius (mm)
c	cohesion of soil (Pa)
c_e	adhesion between wheel rim and soil (Pa)
c_1, c_2	coefficients used for calculating θ_m
d_1, d_2	coefficients used for calculating θ_0
j, j_f, j_r	shear deformation distance relative to wheel rim (mm)
n_0, n_1, n_2	coefficients used for computing n
ω	wheel angular velocity (rad/s)
θ_1,θ_2	wheel-soil contact angle (°)
θ_m	angular position of the maximum radial stress (°)
θ_0	angular position of the transition point of tangential stress (°)
τ	tangential stress (Pa)
φ	internal friction angle of soil (°)
φ_e	surface friction angle between wheel rim and soil (°)
σ	radial stress (Pa)
σ_1	radial stress in the front region (Pa)
σ_2	radial stress in the rear region (Pa)

developed an effective analytical formula that takes into consideration the slip-sinkage effect, which was validated on different soil conditions and compared with other formulae used in terramechanics. To arise the drawbar pull, Yang et al. characterized the normal and tangential forces acting on a single lug during translational motion by changing the running variables (Yang et al., 2014), and tuning the sinkage length of active lugs (Yang et al., 2014).

As for the skid terramechanics, Wong and Reece (1967b) predicted the performance of a towed rigid wheel of terrestrial vehicles based on the analysis of normal and shear stress. However, there are many differences between wheeled mobile robots and terrestrial vehicles (Ding et al., 2011), which makes it necessary to consider the skid terramechanics aiming at the wheeled mobile robots.

Ishigami et al. (2007) and Ding et al. (2012) introduced terramechanics models of a wheel moving forward with slip and lateral skid during the process of steering or moving on the challenging terrain. Besides, the authors established a longitudinal skid terramechanics model for wheeled mobile robots based on the assumptions that there exists a misalignment between the angular position of the maximum radial stress and the angular position of the shear stress transition point, and the sinakge exponent is not a constant but a proposed quadratic function about the skid ratio based on the sinkage measured using a linear displacement sensor (Gao et al., 2013).

The limitations of the previously established model mainly lie in: (1) the soil bulldozing effect was not reflected (Wong and Reece, 1967b; Gao et al., 2013); (2) the soil flow velocity in the rear region of the wheel-soil interface was neglected (Wong and Reece, 1967b; Gao et al., 2013); (3) the normal stress in the rear region cannot be computed directly using the wheel sinkage (Wong and Reece, 1967a, 1967b; Gao et al., 2013; Sutoh et al., 2012; Iagnemma et al., 2004a; Ding et al., 2014).

Based on the wheel sinkage that takes the soil bulldozing effect into account, a linear equation for computing the sinkage exponent is proposed. The soil flow velocity is assumed to be equal to the tangential velocity component of the transition point of the shear stress, and the connection of the entrance point and leaving point is supposed to be the reference of wheel sinkage. The accuracy of the proposed longitudinal skid model is verified by the experimental data obtained using two wheels and on two types of sands.

The rest of this paper mainly consists of four parts. Part 2 concentrates on the introduction of traditional wheel-soil