Available online at www.sciencedirect.com
SCIENCE DIRECT
Journal of Terramechanics 42 (2005) 1–13
Journal of Terramechanics
www.elsevier.com/locate/jterra

An equivalent soil mechanics formulation for rigid wheels in deformable terrain, with application to planetary exploration rovers

H. Shibly [a], K. Iagnemma [b,*], S. Dubowsky [b]

[a] Mechanical Engineering Department, Birzeit University, Palestinian Territories, via Israel
[b] Mechanical Engineering Department, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

Available online 1 July 2004

Abstract

A simplified, closed-form version of the basic mechanics of a driven rigid wheel on low-cohesion deformable terrain is presented. This approach allows the formulation of an on-line terrain parameter estimation algorithm, which has important applications for planetary exploration rovers. Analytical comparisons of the original and simplified equations are presented, and are shown to closely agree. Experimental results from a single-wheel testbed operating in dry sand shows that the simplified equations can be used for mobility prediction with good accuracy. Methods for incorporating the simplified equations into an on-line terrain parameter algorithm are discussed.

Keywords: Rigid wheel mechanics; Deformable terrain; Mobility prediction; Planetary rovers

1. Introduction and related research

During future planetary exploration missions, wheeled mobile robots ("rovers") will be required to negotiate rough-terrain of varying composition [1]. It is well known that wheel–terrain interaction plays a critical role in rough-terrain vehicle mobility [2]. Knowledge of terrain parameters, such as cohesion and internal friction

* Corresponding author. Fax: +1-617-253-9637.
E-mail address: kdi@mit.edu (K. Iagnemma).

0022-4898/$20.00 © 2004 ISTVS. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.jterra.2004.05.002

angle, would lead to improved prediction of wheel–terrain interaction mechanics, which would allow rovers to perform important scientific tasks with increased safety.

It would be desirable to estimate terrain parameters on-line (i.e., while the rover travels), to allow the rover to adapt to changing conditions. This could be accomplished using parameter estimation techniques [3,4]. However, these methods often rely on a closed-form analytical expression relating system inputs to the parameters of interest (e.g., equations relating rover wheel torques and velocities to terrain cohesion and internal friction angle). The complexity of classical wheel–terrain interaction equations prohibits the formulation of closed-form analytical expressions, which makes it difficult to develop on-line terrain parameter estimation algorithms. Thus, we would like to develop a simplified yet accurate form of wheel–terrain interaction equations.

Off-line parameter estimation of Martian soil has previously been performed by the Viking landers and the Sojourner and MER rovers [5,6]. The Viking landers used manipulator arms to conduct trenching experiments. The Sojourner and MER rovers used the rover wheel as a bevameter-type device to identify soil cohesion and internal friction angle. However, neither of these were on-line methods, since both missions used visual cues and off-line analysis techniques to compute soil parameters. Thus, terrain parameter information was not available to enhance the rover's mobility and ability to conduct important scientific tasks on-line.

Here, a simplified, closed-form version of the basic mechanics of a driven rigid wheel on deformable terrain is formulated. The simplification is based on the observation that the shear and normal stress distributions beneath a driven rigid wheel can be approximated by linear functions for a wide range of terrain. Analytical comparison of the original and simplified equations is presented, and are shown to closely agree. This approach allows the formulation of an on-line terrain parameter estimation algorithm. Note that a similar approach has been used to develop an on-line parameter estimation method, with good results [4]. Experimental results from a single-wheel testbed operating in dry sand shows that the simplified equations can be used for mobility prediction with good accuracy for low-cohesion, granular soils. This method can potentially be applied to planetary exploration rovers, since much planetary terrain of interest (e.g., Martian terrain) is known to have low cohesion [6].

2. Analytical background

The interaction mechanics of a rigid wheel on deformable terrain has been studied by many researchers [7–9]. Using the Bekker formulation, the shear stress σ and normal stress τ acting on a point along a wheel rim can be expressed as (see Fig. 1):

$$\sigma(z) = (k_1 + k_2 b)\left(\frac{z}{b}\right)^n, \tag{1}$$

$$\tau(z) = (c + \sigma \tan\phi)\left(1 - \mathrm{e}^{-j/k}\right), \tag{2}$$