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Journal of Terramechanics 55 (2014) 47–59
Journal of Terramechanics
www.elsevier.com/locate/jterra

Characteristics of normal and tangential forces acting on a single lug during translational motion in sandy soil

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Received 3 March 2014; received in revised form 30 April 2014; accepted 27 May 2014
Available online 12 July 2014

Abstract

Lugs (i.e., grousers) are routinely attached to the surfaces of wheels/tracks of mobile robots to enhance their ability to traverse loose sandy terrain. Much previous work has focused on how lug shape, e.g., height, affects performance; however, the goal of this study is to experimentally confirm the effects of lug motion on lug–soil forces. We measured normal and tangential forces acting on a single lug as functions of inclination angle, moving direction angle, sinkage length, horizontal displacement, and traveling speed. The experimental results were mathematically fitted by using least square method to facilitate quantitative analyses on effects of changes in these motion parameters. Moreover, we compared the measured tangential forces to values calculated from a conventional tangential force model to evaluate the effects of the lug-tip surface, which is generally ignored in existing terramechanics models. The conclusions from this study would be useful for estimating the traveling performance of locomotive mechanisms equipped with lugs, modeling interaction mechanics between lugged wheels and soil, etc.

Keywords: Terramechanics; Sandy terrain; Lug motion; Normal force; Tangential force

1. Introduction

Due to poor trafficability, terrains covered by loose granular sand present an ongoing challenge for mobile robots. Many robots have been developed for planetary explorations and for geological investigations in environments that are hazardous to humans (e.g., active volcanoes) or that are difficult for humans to access (e.g., Martian surfaces). Examples include wheeled vehicles [1], track-based crawlers [2], and robots based on hybrid mechanisms [3].

Significant efforts have been made to improve the mobility of terrestrial robots. One simple and effective method is to add protrusions or convex patterns called lugs (i.e., grousers) to wheels/tracks to reduce slippage. The wheels of the Lunakhod I vehicle were formed by wire mesh with sixteen 20-mm-high lugs to aid traction [4]. On the Apollo rover, titanium chevrons were adopted to provide traction [5]. In Micro5, special tires with spiral fins were utilized to ease turning [6]. These applications confirm that lugs significantly influence the traveling performance of lightweight vehicles. Hence, many experimental investigations have been performed to further evaluate the effects of lugs. Ding et al. reported the effects of lug height and inclination angle on the performance of driving wheels [7]. The effects of lug interval on the linear speed of the vehicle have been measured by South et al. [8]. In addition to wheeled robots, they also investigated the effects of lugs on the traveling performance of tracked rovers [9]. These studies mainly focused on the effects of lug shape on the traveling performance of the robots.

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http://dx.doi.org/10.1016/j.jterra.2014.05.006
0022-4898/

Unlike the shapes of lugs, which are generally determined during the design stage, lug trajectories change as a robot performs its tasks. Actual trajectories of the lug are influenced by many factors such as slip ratio, posture of the robot, and terrain. However, only a few studies have considered its effects. Hermawan et al. measured pull and lift forces generated by a movable lugged wheel when different inclination angles were encountered [10]. In each configuration, the lug inclination angle was kept constant during wheel rotation. In modeling the lateral force acting on a wheel, Ishigami conducted bulldozing experiments to investigate the relationship between the bulldozing resistance and length of blade sinkage [11]. Based on investigations of soil failure patterns, Harrison et al. modeled lug–soil interaction forces at the start of lug movement by considering three motion parameters: inclination angle, sinkage length, and moving direction angle of the lug [12,13]. These reports indicate that lug trajectories substantially influence the traveling performance of the moving mechanism.

In evaluating the performance of locomotion modules equipped with lugs, an important prediction is the lug–soil interaction. The passive pressure theory is a simple, practical method that has been used successfully to predict lug forces in wet soil [14,15]. However, its main demerit lies in the assumption that the free soil surface must be horizontal, which makes it difficult to deal with situations in which the ground swells continuously. To predict the cutting resistance of the cutting tools, many models have been proposed in three-dimensional conditions [16–19]. Different from the cutting tools, the force characteristics within a transient state from the initial contact of the lug with the soil until its departure from the soil are of importance for the lug–soil interaction prediction. Nakashima et al. proposed the discrete element method (DEM) to estimate the traveling performance of lugged wheels [20]. Its drawback is the need for powerful computers. With the development of planetary exploration technology, many terramechanics models have been proposed to estimate the effects of lugs on robot behavior on sandy terrains [21–24]. However, some factors having strong effects on lug forces have been ignored in previous studies. For example, some studies have only modeled the normal and tangential forces acting on the front surface of the lug, and ignored the effects of the lug-tip surface that significantly contribute to the lug forces observed in our investigation. Overall, no theory pertaining to lug–soil interaction mechanics is well supported.

In our previous research, the advantages of actively adjusting lug sinkage were experimentally analyzed by utilizing an actively actuated lugged wheel [25,26]. When trying to propose a lug trajectory generation strategy to further enhance the traveling performance of the wheel module, we did not find any acceptable model that can reliably predict lug forces. This motivated us to conduct an experimental study to investigate the influence of various motion parameters on lug forces. This paper only reports the lug–soil interaction forces during the translational motion, and the results during the rotational motion will be considered in our future study. The results from the single lug would be useful for modeling lugged wheel–soil interaction forces. The rest of the paper is organized as follows. Section 2 lists the motion parameters whose effects were measured, and presents a force analysis for a single lug. The experimental setup for measuring lug forces is described in Section 3. Measured characteristics of normal and tangential forces are analyzed in Sections 4 and 5, respectively. Conclusions are drawn in Section 6.

2. Motion parameters and lug forces

As a rigid flat lug translates in a world coordinate system defined as shown in Fig. 1, its horizontal and vertical traveling directions are denoted by x and y, respectively. The movement of the lug's tip from T to T' can be represented by incremental displacements along x- and y-axis. Magnitudes of these displacements are Δx and Δy, respectively. The influences of the following five motion parameters were measured in this study.

i. Translational speed v is a resultant speed of the lug without rotational motion.
ii. Horizontal displacement of the lug can be represented by the horizontal displacement Δx of the lug tip.
iii. Sinkage length l_s determines the contact area between the lug and soil below the ground surface.
iv. Moving direction angle β is defined as the angle between the direction of translational velocity and the horizontal axis x. It can be calculated from coordinates of the lug tip as it moves from T to T'.

$$\beta = \text{atan2}(\Delta y, \Delta x) \quad (1)$$

v. Inclination angle α is defined as the angle between the lug and horizontal direction that denotes the ratio of projected areas of the lug on the horizontal plane to the vertical plane.

Normal and tangential directions of the lug are denoted by n and t, respectively, in a local coordinate system fixed

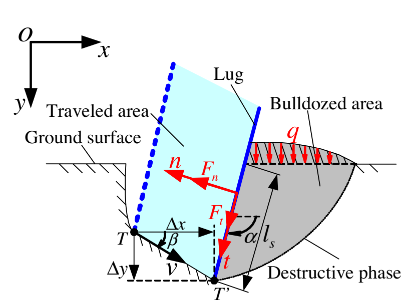

Fig. 1. Motion parameters and force model for a single lug with translational motion.