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Experimental validation of a differential variational inequality-based approach for handling friction and contact in vehicle/granular-terrain interaction

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Abstract

The observation motivating this contribution was a perceived lack of expeditious deformable terrain models that can match in mobility analysis studies the level of fidelity delivered by today's vehicle models. Typically, the deformable terrain-tire interaction has been modeled using Finite Element Method (FEM), which continues to require prohibitively long analysis times owing to the complexity of soil behavior. Recent attempts to model deformable terrain have resorted to the use of the Discrete Element Method (DEM) to capture the soil's complex interaction with a wheeled vehicle. We assess herein a DEM approach that employs a complementarity condition to enforce non-penetration between colliding rigid bodies that make up the deformable terrain. To this end, we consider three standard terramechanics experiments: direct shear, pressure-sinkage, and single-wheel tests. We report on the validation of the complementarity form of contact dynamics with friction, assess the potential of the DEM-based exploration of fundamental phenomena in terramechanics, and identify numerical solution challenges associated with solving large-scale, quadratic optimization problems with conic constraints.
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Keywords: Terramechanics; Discrete element method; Friction and contact; Differential variational inequality; Validation; Calibration; Direct shear test; Pressure-sinkage test; Single wheel test; Deformable terrain

1. DEM for terramechanics: modeling and numerical solution strategies adopted

This contribution is motivated by an ongoing effort to identify predictive modeling approaches that can characterize dynamics of off-road vehicles. The salient feature of off-road maneuvers is the presence of deformable terrain. Owing to the complex soil behavior, deformable terrain continues to pose significant hurdles that limit the spectrum of scenarios that can be analyzed through computer modeling. The task undertaken is timely, given that it is difficult and expensive to evaluate a vehicle's performance during a majority of off-road maneuvers using physical experiments. Indeed, the range of scenarios that can be considered for physical testing is limited due to time and cost constraints. It is thus desirable to employ computer modeling in a virtual prototyping exercise that, when drawing on physics-based, predictive models, can improve designs, compress the release cycle, and reduce costs.

One off-road scenario of interest is shown in Fig. 1. Therein, the vehicle operates on sand, gravel, or rocky-type soil, which are modeled using DEM. DEM represents

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Fig. 1. A HMMWV traversing a deformable terrain modeled using the discrete element method (DEM).

soil as a multitude of three-dimensional rigid bodies, called elements, where each element is defined by its size, shape, position, velocity, and orientation. By modeling soil using individual elements, DEM allows for significant soil deformation and transport, and the modification of properties such as soil packing structure and non-homogeneity. There are multiple formulations of DEM, classified based on how the contact and impact are handled when two bodies collide. This paper assesses the predictive attribute of the complementarity method, which models contact as a differential inclusion. To that end, it compares results obtained from standard terramechanics experiments to corresponding computer modeling analyses. These experiments include direct shear, pressure-sinkage, and single wheel tests.

1.1. Modeling frictional contact via differential variational inequalities

Consider a three dimensional (3D) system of rigid bodies which may interact through frictional contact. An absolute Cartesian coordinate system will be used to define the equations of motion for the time evolution of such a system (Haug, 1989). Therefore, the generalized positions $\mathbf{q} = \left[\mathbf{r}_1^T, \boldsymbol{\epsilon}_1^T, \ldots, \mathbf{r}_{n_b}^T, \boldsymbol{\epsilon}_{n_b}^T\right]^T$ and their time derivatives $\dot{\mathbf{q}} = \left[\dot{\mathbf{r}}_1^T, \dot{\boldsymbol{\epsilon}}_1^T, \ldots, \dot{\mathbf{r}}_{n_b}^T, \dot{\boldsymbol{\epsilon}}_{n_b}^T\right]^T$ are used to describe the state of the system. Here, $\mathbf{r}_j$ is the absolute position of the center of mass of body j and $\boldsymbol{\epsilon}_j$ is the quaternion used to represent rotation. Note that the angular velocity of body j in local coordinates, $\bar{\boldsymbol{\omega}}_j$, may be used in place of the time derivative of the rotation quaternion. Then, the vector of generalized velocities $\mathbf{v} = \left[\dot{\mathbf{r}}_1^T, \bar{\boldsymbol{\omega}}_1^T, \ldots, \dot{\mathbf{r}}_{n_b}^T, \bar{\boldsymbol{\omega}}_{n_b}^T\right]^T$ can be related to $\dot{\mathbf{q}}$ via a linear mapping given as $\dot{\mathbf{q}} = \boldsymbol{T}(\mathbf{q})\mathbf{v}$ (Haug, 1989).

Due to the rigid body assumption and the choice of centroidal reference frames, the generalized mass matrix $\boldsymbol{M}$ is constant and diagonal. Further, let $\mathbf{f}(t, \mathbf{q}, \mathbf{v})$ be a set of generalized external forces which act on the bodies in the system. Finally, the second-order differential equations which govern the time evolution of the system can be written in the matrix form $\boldsymbol{M}\dot{\mathbf{v}} = \mathbf{f}(t, \mathbf{q}, \mathbf{v})$ (Shabana, 2013).

The rigid body assumption implies that elements that come into contact should not penetrate each other. Such a condition is enforced here through unilateral constraints. To enforce the non-penetration constraint, a gap function, $\Phi(\mathbf{q}, t)$, must be defined for each pair of near-enough bodies. When two bodies are in contact, or $\Phi(\mathbf{q}, t) = 0$, a normal force acts on each of the two bodies at the contact point. When a pair of bodies is not in contact, or $\Phi(\mathbf{q}, t) > 0$, no normal force exists. This captures a complementarity condition, where one of two scenarios must hold. Either the gap is positive and the normal force is exactly zero, or vice versa: the gap is zero, and the normal force is positive.

When a pair of bodies is in contact, friction forces may be introduced into the system through the Coulomb friction model (Anitescu and Potra, 1997). The force associated with contact i can then be decomposed into the normal component, $\mathbf{F}_{i,N} = \hat{\gamma}_{i,n}\mathbf{n}_i$, and the tangential component, $\mathbf{F}_{i,T} = \hat{\gamma}_{i,u}\mathbf{u}_i + \hat{\gamma}_{i,w}\mathbf{w}_i$, where multipliers $\hat{\gamma}_{i,n} > 0, \hat{\gamma}_{i,u}$, and $\hat{\gamma}_{i,w}$ represent the magnitude of the force in each direction, $\mathbf{n}_i$ is the normal direction at the contact point, and $\mathbf{u}_i$ and $\mathbf{w}_i$ are two vectors in the contact plane such that $\mathbf{n}_i, \mathbf{u}_i$, and $\mathbf{w}_i$ are mutually orthonormal. Let the contact points in the local coordinates of each body be expressed as $\bar{\mathbf{s}}_{i,A}$ and $\bar{\mathbf{s}}_{i,B}$ respectively. The governing differential equations are obtained by combining the rigid body dynamics equations with the unilateral constraint equations. Then, the governing differential equations, which assume the form of a