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A high-fidelity approach for vehicle mobility simulation: Nonlinear finite element tires operating on granular material ☆

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Abstract

Assessing the mobility of off-road vehicles is a complex task that most often falls back on semi-empirical approaches to quantifying the vehicle–terrain interaction. Herein, we concentrate on physics-based methodologies for wheeled vehicle mobility that factor in both tire flexibility and terrain deformation within a fully three-dimensional multibody system approach. We represent the tire based on the absolute nodal coordinate formulation (ANCF), a nonlinear finite element approach that captures multi-layered, orthotropic shell elements constrained to the wheel rim. The soil is modeled as a collection of discrete elements that interact through contact, friction, and cohesive forces. The resulting vehicle/tire/terrain interaction problem has several millions of degrees of freedom and is solved in an explicit co-simulation framework, built upon and now available in the open-source multi-physics package Chrono. The co-simulation infrastructure is developed using a Message Passing Interface (MPI) layer for inter-system communication and synchronization, with additional parallelism leveraged through a shared-memory paradigm. The formulation and software framework presented in this investigation are proposed for the analysis of the dynamics of off-road wheeled vehicle mobility. Its application is demonstrated by numerical sensitivity studies on available drawbar pull, terrain resistance, and sinkage with respect to parameters such as tire inflation pressure and soil cohesion. The influence of a rigid tire assumption on mobility is also discussed.

Keywords: Mobility; Off-road vehicle dynamics; Nonlinear finite element; ANCF; Discrete element method; Chrono; Co-simulation; High-performance computing

1. Introduction: Computational approaches to wheeled vehicle mobility analysis

Traditional approaches for the modeling and simulation of vehicle dynamics on deformable soil rely on semi-empirical methods. A great of deal of these studies have shed light on vehicle–tire–terrain interaction phenomena, including the analysis of available drawbar pull, tire inflation pressure, and soil characteristics, among many others. Some crucial references in this field are due to Wong and Reece (1967a,b, 2001). In relation to the importance of tire deformation, Wong postulated that tire mobility depends on the tire's mode of operation: *rigid regime* if the sum of the inflation and carcass pressure is larger than the maximum pressure that the terrain can support, and *elastic regime* otherwise. Semi-empirical approaches have also been the basis for computational, systematic analysis of

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vehicle mobility. Senatore and Sandu (2011) developed a computational tool for predicting mobility in vehicle dynamics simulation with a focus on multi-pass effects, which included a wheel model that incorporated tire size, construction, and inflation in the form of an experimentally-obtained parameter. Along these lines, soft soil contact models were proposed in the literature to integrate semi-empirical approaches in multibody simulations in a computationally efficient manner (Krenn and Gibbesch, 2011).

Experiments on pneumatic tire–deformable soil interaction have demonstrated the effects of parameter variation on mobility metrics for a single tire: normalized drawbar pull coefficient increases with terrain compaction, but decreases for larger tire inflation pressure or larger normal loads (Naranjo et al., 2014). Experimental results and simulations on granular terrain have also shown that the normalized drawbar pull coefficient peaks at a larger longitudinal slip compared to tires traveling on rigid ground (Johnson et al., 2015). These complex interaction effects between tires and soil may be studied from a higher-fidelity perspective, which usually involve the use of finite element models for tires and continuum-based or discrete approaches for soil modeling.

Even though qualitative classification of the modes of operation of vehicles and soil empirical models have greatly contributed to gaining insight into ground-vehicle mobility characteristics, high-fidelity models aim at capturing the physics of vehicle–terrain interaction by minimizing the assumptions involved in the problem setup and instead relying on the use of physically meaningful parameters. Recently, there have been efforts to validate high-fidelity soil models based on discrete elements (Smith et al., 2014) and Lagrangian solid finite elements (Yamashita et al., 2016). Detailed finite element models of tires have been developed for mobility purposes (Shoop, 2001). Additionally, small deformation formulations for the simulation of finite element tires in vehicle dynamics have been developed by Kazemi et al. (2015). Other multibody approaches involving finite strain shell elements have recently been proposed in the literature, including those based on the absolute nodal coordinate formulation (ANCF) (Yamashita et al., 2016) and on geometrically exact formulations (Roller et al., 2015). Likewise, monolithic single tire–soil models involving finite elements have been presented in the literature (Recuero et al., 2016; Bekakos et al., 2016). These higher-fidelity approaches to vehicle mobility simulation represent the backbone of the new proposals for the development of the next-generation NATO reference mobility models (NG–NRMM), see McCullough et al. (2016).

The push for general, higher-fidelity vehicle mobility simulations seems to have been limited to a single tire and a deeper level of detail involving the tire or the soil, but not both of them. This work presents a novel computational approach that integrates multi-layered, orthotropic nonlinear finite element models of tires with granular soil, which is modeled using the penalty discrete element method (DEM). A tire rig mechanism with a single tire and, in addition, an off-road vehicle are numerically integrated by using co-simulation strategies in the multi-physics, open-source software Chrono (Tasora et al., 2016). While Chrono has been used in the past for studies of ground vehicle mobility, all previous numerical experiments were limited to either flexible tires over rigid (flat) terrain, or to rigid tires over granular terrain. With the numerical framework introduced in this work, we are in a position, for the first time, to analyze vehicle-terrain interaction problems with high-fidelity models at all levels: flexible tires modeled with nonlinear ANCF and deformable DEM-based terrain. This proposed approach includes a new implementation of large deformation, detailed tire models which are integrated in a framework where they can operate as a part of a full vehicle on multi-million degree-of-freedom soil models and for extracting mobility measures of practical use, such as sinkage, drawbar pull, terrain resistance, and tractive force. These mobility measures can be naturally retrieved as reaction forces at mechanical joints or as the sum of contact forces between the three-dimensional deformable finite element meshes and soil particles. The framework used in this paper makes use of parallel computing techniques on various levels: several Message Passing Interface (MPI) nodes coordinate the communication between tires, soil, and vehicle. Intensive computations on the terrain and tire nodes, which include particle collision detection and nonlinear material internal force calculations, are accelerated using multi-core, shared-memory parallelization with OpenMP directives. Finally, single instruction multiple data (SIMD) architecture is leveraged in low-level matrix operations using advanced vector extensions (AVX). The entire framework is intended to provide a software solution to the problem of high-fidelity wheeled-vehicle mobility simulations. Despite the entire framework not being validated against test data, its constituents formulations have been validated against experimental or analytical references, which are provided in the text.

This paper is structured as follows. The dynamic formulations used for modeling the tire, the soil, and the vehicle are described in Section 2. Section 3 focuses on the explicit co-simulation framework devised for the numerical experiments, in the tire test rig and the off-road vehicle. Key mobility measures are obtained in Section 4 using the high-fidelity simulations, with a special focus on the influence of crucial parameters, such as tire inflation pressure and soil cohesion, one mobility performance. Section 5 demonstrates the proposed approach for a full vehicle with four ANCF tires running on granular terrain and negotiating a large obstacle. Finally, conclusions and future research directions are outlined in Section 6.

2. Vehicle–terrain system models

This section outlines the main features of the dynamic formulations used to model the tire, granular terrain, and vehicle.