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Validation of the Chrono soft-sphere collision model for granular DEM simulations

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Abstract

The soft-sphere DEM model incorporated in Chrono, an open source multi-physics engine, is evaluated for accuracy and physically realistic behavior. A series of validation tests are performed on the Chrono code, ranging from simple simulations with two colliding bodies to more complex systems consisting of tens of thousands of particles. The results of the validation tests are compared against analytical expressions, laboratory experiments, and studies performed by other research teams. Validation testing is carried out with the ultimate goal of introducing Chrono as a reliable tool for research applications related to the exploration of small, regolith-covered bodies.

1. Introduction

Understanding the behavior of granular systems has been a long-time objective in many industries, with agricultural, pharmaceutical, and metallurgical applications. A recent increase in the robotic exploration of planets and small bodies has highlighted the importance of granular research for the space industry as well. Unfortunately, low-gravity environments paired with a general lack of information regarding physical and material properties makes studying the surfaces of asteroids, comets, and small moons even less intuitive than for Earth-based systems. Numerical simulations provide a low-cost solution for expanding our knowledge in this field. Modeling regolith behavior at the grain scale using the discrete element method (DEM) can help us explore theories regarding the formation, morphology, and surface mechanical properties of small bodies. Once validated, such models can even be used to aid with the design and operation of systems that interact with planetary surfaces.

Several existing DEM codes are active among the planetary science community, including PKDGRAV [4], LIGGGHTS, ESyS-Particle [7], and code by Paul Sánchez and Daniel Scheeres [6]. In this work, an alternative code, Chrono, is considered for future granular studies. Chrono is an open source, parallelized, multi-physics DEM software, capable of simulating complex systems by treating particle-particle contacts as either rigid or deformable [8]. A key strength of Chrono is its ability to incorporate full vehicle and robotic systems into simulations such that the dynamic response of the systems can be monitored as they interact with granular surfaces. Extensive work has already been completed by developers to validate the rigid-body collision model in Chrono [5]. However, validation testing of the soft-sphere collision model neglects important particle-to-particle interactions, such as rolling friction, twisting friction and adhesion.

In 2018, in the context of the Mars Moon Explorer Rover mission, CNES funded a study at ISAE-SUPAERO to evaluate Chrono and begin making improvements to the code [3]. This work continues the initial study, with the goal of assessing each element of the Chrono soft-sphere model to verify that simulation outputs match expected results. Code modifications are implemented as required. Once validated, the Chrono soft-sphere DEM code can be used for granular studies related to planetary exploration, such as for analyzing the performance of wheeled rovers on regolith-covered surfaces.

2. DEM validation testing

This work introduces a comprehensive set of ten low-level validation tests to evaluate the implementation of the soft-sphere DEM model in Chrono. In each test, a sphere-to-sphere, sphere-to-wall or wall-to-wall interaction is simulated, with initial conditions dependent on the contact behavior under evaluation. The resulting kinematics and forces on the simulated bodies are measured and compared against theoretical predictions and published studies, such as those described in [1] and [2]. In one test, a box is placed on a plane and provided with an initial horizontal velocity. The distance that the block travels before coming to a rest is compared against an analytical expression. In another test, two spheres are brought together and held under constant adhesion. An external force is applied to one of the bodies, and the reaction of the system is used to assess the implementation of adhesion. In a third test, a series of off-angle impacts are created between a sphere and a wall in order to check tangential damping behavior. The rebound velocity of the sphere and the tangential force profile of the collision offer insight into subtle difference between available force models. Together, the ten validation tests aim to systematically evaluate key aspects of the soft-sphere model in Chrono, including 1) normal and tangential force calculations, 2) normal and tangential damping behavior, 3) the evaluation of the coulomb friction condition, 4) rolling friction, 5) twisting friction, and 6) the inclusion of adhesion. While low-level validation testing may seem simplistic, it is critical for the verification of any DEM code.

Following the completion of the low-level validation tests, a number of more complex studies are completed in order to evaluate Chrono's ability to handle full-scale granular systems. Mid-level validation tests include a "heaping" simulation to verify the angle of repose of different materials, and an "impact" simulation, to measure the response of a projectile when dropped into a bucket of beads. High-complexity tests include simulations of dynamic granular flow in a rotating drum and in a Taylor-Couette shear cell. Simulation results are compared against experimental data.

3. Results

The soft-sphere collision model included in the parallel module of the Chrono 4.0.0 code release accurately calculates the normal and tangential forces resulting from a collision, and correctly evaluates the coulomb friction condition in the absence of adhesion. However, several code modifications are recommended in order to improve model results. Notably, rolling and twisting friction must be implemented, and the placement of the adhesion calculation should be revisited. After making the proposed modifications, Chrono successfully passes all tests. With its efficient parallelization and ability to handle complex wall geometries, Chrono has high potential to aid in the development of future in-situ small body missions.

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