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A Comparative Study of Penalty and Complementarity Methods for Handling Frictional Contact in Large Multibody Dynamics Problems

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Two competing approaches have emerged as viable solutions for large computational dynamics problems that contain millions of bodies interacting through frictional contact. Mature and widely adopted, the so-called Penalty (P) method is a regularization, or smoothing, approach that relies on a relaxation of the rigid-body assumption. Using various constitutive relations, normal and tangential forces are calculated based on the local body deformation which is defined, in a somewhat ad-hoc fashion, as the penetration (overlap) of the two otherwise rigid bodies. Once the frictional contact forces are known, the time evolution of each body in the system is obtained by integrating the Newton-Euler equations of motion. Due to large contact stiffness, the P method is limited to very small integration step-sizes, which leads to very long simulation times. Typically known as the Discrete Element Method, the P method has been adopted by all leading multibody dynamics and discrete element commercial packages.

A different and relatively more recent method is based on a Lagrangian approach to the frictional contact problem. The non-penetration constraints are written as complementarity conditions which, in conjunction with a Coulomb friction law, lead to a Differential Variational Inequality (DVI) form of the equations of motion. Unlike the P method, which is hindered by numerical integration stability constraints, DVI-based approaches allow large integration time steps, one to two orders of magnitude larger than those associated with the P method. However, this comes at the cost of a more complex solution sequence since DVI approaches lead upon discretization to large mathematical programs with complementarity and equality constraints. Various relaxation techniques result in tractable linear complementarity (LCP) or cone complementarity (CCP) problems that are solved at each time step to yield the normal and friction forces for all the contacts present in the system.

The goal of this work is to produce a systematic comparison of the P and DVI methods in terms of accuracy, robustness, efficiency, and scalability. We also report on the ability of the two methods to incorporate additional interface phenomena beyond dry-friction such as cohesion, plasticity, etc. Within the context of an open source parallel simulation framework, the two methods are compared in conjunction with models that contain millions of bodies that interact through tens of millions of contacts to represent, for instance, the physics associated with granular flow or ground vehicle mobility.

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