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Comparative evaluation of normal viscoelastic contact force models in low velocity impact situations

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ABSTRACT

The issue of the dissipative normal nonlinear Hertz type contact, extensively explored in the discrete element simulations, is addressed. As several viscoelastic normal contact force models equally coexist, selected viscous damping models for spherical contacts (Lee and Hermann, 1999; Tsuji et al., 1992; Kuwabara and Kono, 1987; Hu et al., 2011) are investigated, and a comparative evaluation of these models in single particle and granular chain impact situations is presented. It is shown that these models can be characterised by different values of the inter-particle displacement (overlap) exponent equal to 0, 0.25, 0.5 and 1.5, respectively. A benchmarking is performed in terms of non-dimensional variables, where a variation of the damping ratio and the contact force for a wide range of coefficient of restitutions is studied. The main purpose of this study is to demonstrate the contribution of models to the propagation of force in a chain of contacting particles. Numerical results and their validation against an available experiments are given. The sensitivity of models to the impact velocity is also illustrated. Finally, based on the investigation's results, conclusions and recommendations for DEM simulations are given.

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1. Introduction

The Discrete Element Method (DEM) introduced by Cundall and Strack [1] has been widely recognised as the most suitable numerical technique for simulating the behaviour of granular materials on both microscopic and macroscopic scales. As the dynamic state of a particles system on the macroscale is governed by the evolution of single contacts during (in the simplest case) binary collisions on the microscale, a simplified but still realistic description of the contact between interacting particles represents the most essential task in a DEM simulation. Generally, the contact problem of particles during binary collisions can be resolved in the framework of contact mechanics on the continuum level. The fundamentals of the contact phenomena, as well as the description of interaction laws and numerous applications may be found in Johnson [2], Wriggers [3], Matuttis and Chen [4]. Comprehensive reviews of theoretical models for various contact forces extensively used in the DEM are presented in the DEM-related works by Schäfer et al. [5], Džiugys and Peters [6], Zhang et al. [7], Lu et al. [8], and the references therein.

It is worth mentioning that, regardless of the actual particle shape, forces (torques) and displacements (rotations) in the particle contact point are usually considered by two perpendicular components normal and tangential to the contact surface. Note that our study is limited to normal contact analysis. However, it's worth to mention that there are cases when major part of energy losses could be caused by the contact force in tangential direction due to the tangential damping or friction force. This case occurs when particles velocity is relatively low and density of particles occupied volume is high.

The most important aspect attributed to DEM contact force models is the physical nature of the contact. The elastic (reversible and non-dissipative) behaviour is well understood. A collision is elastic when the contact displacement is independent of the displacement rate and any consolidation time. The elastic contact of a spherical particle in the approach and repulsion phase is described by Hertz theory [2]. A particular focus on normal contacts and extensive reviews may be found in Stevens and Hrenya [9] and Kruggel-Emden et al. [10], who studied binary collisions based on experimental data involving different material combinations and contact mechanisms.

In contrast to elastic contact behaviour, the interpretation of the dissipative behaviour in non-elastic contacts is more complicated. Usually, two dissipation mechanisms, i.e. elastic–plastic and viscoelastic, dominate in a normal contact. A plastic collision

leaves the involved particle permanently deformed, but the deformation of a body in this case is independent of the displacement rate (cf. [4,11]).

In the case of a viscoelastic contact, the contact deformation of particles is reversible, but the displacement itself shows a dependence on the displacement rate and possible consolidation time. In most of the earlier DEM studies, the viscoelastic contact is treated using a linear interaction model consisting of a linear spring and linear dashpot (LSD), where the dissipative behaviour is characterised by a single constant. In spite of computational simplicity, the linear model possesses physical inconsistencies such as the jump of the contact force at the beginning of the collision or the occurrence of artificial attraction and a constant impact velocity independent duration of contact (see [6,12]). To overcome some of the limitations such as the non-zero force towards the end of a contact, linear spring dashpot (LSD) models were sometime being assumed to cease when the contact force assumed a value of zero instead of the overlap being zero (cf. [13]). However, such model modifications fix only some of the problems related to LSD models [10].

Extending (LSD) models combinations of the Hertzian spring with dashpots are classified as non-linear, or Hertzian (HSD), models. Since nonlinear dashpots are constructed based on different assumptions, various viscous damping models of different complexity were elaborated theoretically and applied in DEM simulations.

It is worth noting that parameters involved into the dashpot model do not always possess clear physical meanings. The model, combining the nonlinear Hertzian spring with a linear dashpot characterised by zero exponent, which was proposed by Lee and Herrmann [14], may be also classified to the category of non-linear models. This model [14] produces several physical inconsistencies as the linear LSD models, but offers a varying collision time [10]. A refined nonlinear damping model based on the theory of viscous-elastic continuum materials was proposed by Kuwabara and Kono [15], while an analogous formulation was later discussed by Brilliantov et al. [16]. This model is applicable to the collision of viscoelastic spheres. Tsuji et al. [17] heuristically derived a damping model, where the coefficient of restitution is independent of the initial contact velocity. It is worth noting that the HSD type Tsuji model also produces some physical inconsistencies that were observed for linear models; the collision time is however impact velocity dependent and for zero overlap the contact force is zero as expected [10]. Still, all 3 (HSD) models [14,15,17] suffer from an un-physical attractive force during the evolution of the contact. An attempt to avoid the physically incorrect attraction force has been made by Hu et al. [18], where a modification of the Tsuji model exhibiting a hysteresis without attraction was suggested. Matuttis [19] also made a suggestion to overcome the attractive force within normal force models. It was applied successfully for contacts of polygonal particles. However, the proposed model extension results in a non-continuous evolution of the contact force. The briefly discussed (HSD) models excluding the modification by Matuttis [19] are considered hereafter, and they are denoted by the abbreviations LH, KK, TS and HU, respectively.

Since direct evaluation of the physically adjustable macroscopic dissipative constants of the material is extremely difficult, the concept of the coefficient of restitution (COR) [20,21] has been extensively explored. The COR is a parameter whose value is relatively easy accessible during an impact experiment. In order to adjust the coefficients of the dissipative models, experimental data are required. Various aspects of damping in binary and to a limited extent in multiple contacts have been investigated by several authors, e.g. Luding et al. [22], Matuttis [19], Rosas et al. [23], Antypov and Elliott [24], Malone and Xu [25], Gharib and Hurmuzlu [26], Ray et al. [27]. The focus in [19,23–25] was set on evaluating

the mechanisms of energy dissipation and analysing the analogies between linear and non-linear models to derive adequate parameters. It can be summarised that evaluation of damping during binary interaction is an important aspect but not the final issue as the question remains how damping affects the different coexisting force models and to answer the admittedly difficult question of which force model/models to favour from the coexisting ones in this context.

Damping plays an important role in a variety of applied problems. It should be noted that the dissipation of impact energy in a multi-particle damper [28,29] or the propagation of dynamic force waves in powder mixtures [30], soils [31,32] and silo quakes [33] can be mentioned as representative illustrations. The dissipative nature of a granular system is essentially the summed process of multiple inelastic collisions on the particle level. Therefore, a demonstration of the contribution of the damping and, more definitely of particular damping models, would be beneficial from both theoretical and practical points of view.

Note that the dissipation of energy in multi-particle systems differs, however, from what is observed in simple binary normal interactions, because in multi-particle systems energy dissipates through different mechanisms (e.g. shear, torsion, rolling). Therefore, recovery of the contribution of normal damping is not a simple task. Nonetheless, the normal contribution is usually still the strongest, especially in dynamic behaviour of particle systems [34].

Against this background, the role and essential features of viscoelastic damping during multiple normal contacts may be best illustrated by the behaviour of one-dimensional systems. Particle impact and the propagation of compression waves in granular chains of spherical particles are therefore subjects which have been studied from many points of view. Extensive work has been conducted over the past three decades to observe and analyse the wave propagation in granular media. Methodologically, most of these studies have been focused on the comparison and validation of numerical developments with the experimental results [35–38] and in enriching fundamental knowledge. Theoretical studies were aimed towards examining various aspects of the force propagation in granular media that differ considerably from the wave propagation in continuum matter. The different kinds of granular columns [22,39] and chains, such as the tapered and stepped chains [35,37,40–42] as well as disordered chains [43] are investigated apart of mono-sized chains.

The paper presents a comparative analysis of the adequacy of selected nonlinear viscous damping models. This motivates us to perform further studies on the contribution of these damping models on the particle behaviour during the single contact and extend it to a multi-particle system. The initial contribution of this research was given in conference paper [44].

Since the dynamic behaviour of contacting particles is very sensitive to many factors, the proper choice of damping models, or systematic evaluation of available model is the issue to be known before starting simulations. Here the aim, however, is to evaluate and demonstrate the contribution of different models observed in a single contact and chain impact situations. Based on these investigations, recommendations for the selection of non-linear viscoelastic models for DEM applications are given.

The paper is organised as follows. The simulation methodology and description of collision process comprising viscoelastic damping models under consideration is described in Section 2. The non-dimensional formulation with the focus on finding model specific damping ratios is presented in Section 3. Numerical results for particle impact containing comparative analysis contact force and contribution of impact velocity are demonstrated in Section 4. Simulation results for the granular chain impact are shown and discussed in Section 5.