F. Biondani, R. Zhang, M. Morandini, G.L. Ghiringhelli, P. Masarati
Particle Damper Simulation Tools
in: 26th Conference of the Italian Association of Aeronautics and Astronautics (AIDAA 2021),
2021, p. 1-7 [26th Conference of the Italian Association of Aeronautics and Astronautics
(AIDAA 2021), Online Event, 31 Aug.-3 Sept. 2021]

The project leading to this application has received funding from the Clean Sky 2 Joint Undertaking (JU) under grant agreement No 687023. The JU receives support from the European Union's Horizon 2020 research and innovation programme and the Clean Sky 2 JU members other than the Union

Italian Association of Aeronautics and
Astronautics
XXVI International Congress
31st August – 3rd September 2021
On-line event hosted by the Tuscany AIDAA Section in Pisa

PARTICLE DAMPER SIMULATION TOOLS

Fabio Biondani[1], Runsen Zhang[1,2*], Marco Morandini[1], G. L. Ghiringhelli[1], Pierangelo Masarati[1]

[1]Politecnico di Milano, Dip. di Scienze e Tecnologie Aerospaziali, via La Masa 34, 20156 Milano

[2]School of Aeronautic Science and Engineering, Beihang University, Beijing 100 083, China

*runsen.zhang@polimi.it

ABSTRACT

The simulation of particle dampers can require significant computational resources and time, even when the massive parallelism offered by modern GPUs is leveraged. Furthermore, the particle damper often needs to interact with multibody or FEM deformable models; this coupling can further increase the required computational time. Three discrete particle simulation codes are coupled with the multibody solver MBDyn and compared. The solvers are used to simulate experiments from the literature, and gain insight into how the discrete element method can be used to design particle dampers.

Keywords: particle damper, multibody, discrete element method

1 INTRODUCTION

Particle dampers are passive damping devices, consisting of one or more enclosures, partially filled with particles and attached to vibrating structures that needs damping. These devices can achieve high energy dissipation rates by means of inelastic collisions and friction between particles.

Among their numerous advantages, particle dampers can operate in harsh conditions, can work in multiple directions and at a wide range of frequencies. Their use in aerospace applications is being considered [11].

However, the behavior of these devices is highly non-linear: their damping performance largely depends on the input's amplitude [10], and they can also exhibit chaotic response [19]. Furthermore, the particles rheological behavior plays an important role in the amount of dissipation obtainable by particle dampers, and many motion regimes were experimentally proven [23].

Simple models, such as the one particle equivalent model, have been used to model particle dampers, as reported in the literature; however, these models are usually limited to specific cases or motion regimes, and are not valid outside those boundaries. For these reasons, numerical analyses of particle dampers usually rely on implementations of the discrete element method (DEM) [11], despite the large computational cost of simulations.

Different techniques can be used to implement DEM solvers and to couple them to multibody software; however the authors found no references in the literature to work pertaining the comparison of the results of analyses of particle dampers with different discrete element models. Nevertheless, the authors believe that such a comparison could give insights into how to use the DEM in operative design enviroments, which require fast analyses and iterations without giving up too much accuracy.

In this paper, three discrete particle simulation codes, coupled to the general-purpose multibody solver MBDyn [15], are compared by their characteristics and used to reproduce an experimental test case from the literature.

2 SIMULATION CODES

This section summarizes the main characteristics of the three considered solvers. The descriptions are focused on the characteristics and architecture of the employed discrete element methods, as well as the co-simulation schemes used to couple the codes to MBDyn.

2.1 Chrono::NSC with tight coupling

Non-smooth contact dynamics (NSCD) is an effective simulation tool for rigid bodies with friction, contacts and impacts [17]. It has been widely used in the simulation of non-smooth rigid bodies with complex geometry [6], and in particle dampers [24]. In this work, the NSCD is also choosen as an alternative tool for simulating particle dampers.

The code of the NSCD is provided by a large open-source multiphysics c++ library, Project Chrono [21], in detail, by the module Chrono::Engine (ChSystemNSC) and the module Chrono::Multicore (ChSystemMulticoreNSC) through a multi-thread simulation, which are collectively referred as Chrono::NSC in this work. Using the NSCD, non-smooth interactions among bodies are modelled as frictional unilateral constraints, where the three-parameter impact law based on the Newton impact law and Coulomb dry friction law is used [3]. An event-capturing time-stepping scheme based on the semi-implicit Euler scheme is implemented in Chrono for the integration of the non-smooth equations, by which non-smooth events are captured automatically, and a larger time step size can be used in the simulation [20]. In each step, non-smooth interactions are translated into cone complementarity problems (CCPs) to be solved by optimization methods [20].

For the coupled problems between rigid/flexible multibody systems with particle dampers, a co-simulation platform between MBDyn and Chrono::NSC module is established, where a tight co-simulation scheme, also called implicit or iterative co-simulation scheme [24], is implemented, as shown in figure 1. From the figure, it can be concluded that the tight co-simulation scheme performs a prediction-correction procedure per step, where MBDyn predicts motions for the multibody models at the first iteration, and then an iterative process that requires the restart of Chrono is carried out. The iterative process can also be omitted, resulting in a loose co-simulation scheme [24]. Compared to the loose co-simulation scheme, the tight one takes more computation costs because of the iterative process, but it shows better co-simulation stability [24].

2.2 Chrono::GPU with loose coupling

Chrono::GPU is a module of the open-source multiphysics simulation engine Project Chrono, that provides a simulation tool for granular dynamics running on the GPU through CUDA.

Chrono::GPU simulates systems of monodisperse spheres interacting with both analytical boundary conditions and triangle meshes. Contacts are modelled using a penalty-based method and the full-history of each contact is memorized so that models like the Mindlin-Deresiewicz model [5], or even more complex phenomenological models [7] can be used with multistep incremental evolution of the contacts [8].

One of the main characteristics of this program is the ability to process problems with hundreds of millions particles thanks to adimensionalization and the use of heterogeneous data types to reduce memory usage and increase arithmetic intensity [13]

Chrono::GPU was coupled to MBDyn using the loose co-simulation scheme shown in figure 2. This scheme lacks the iterative procedure shown in figure 1 for a tight co-simulation scheme.

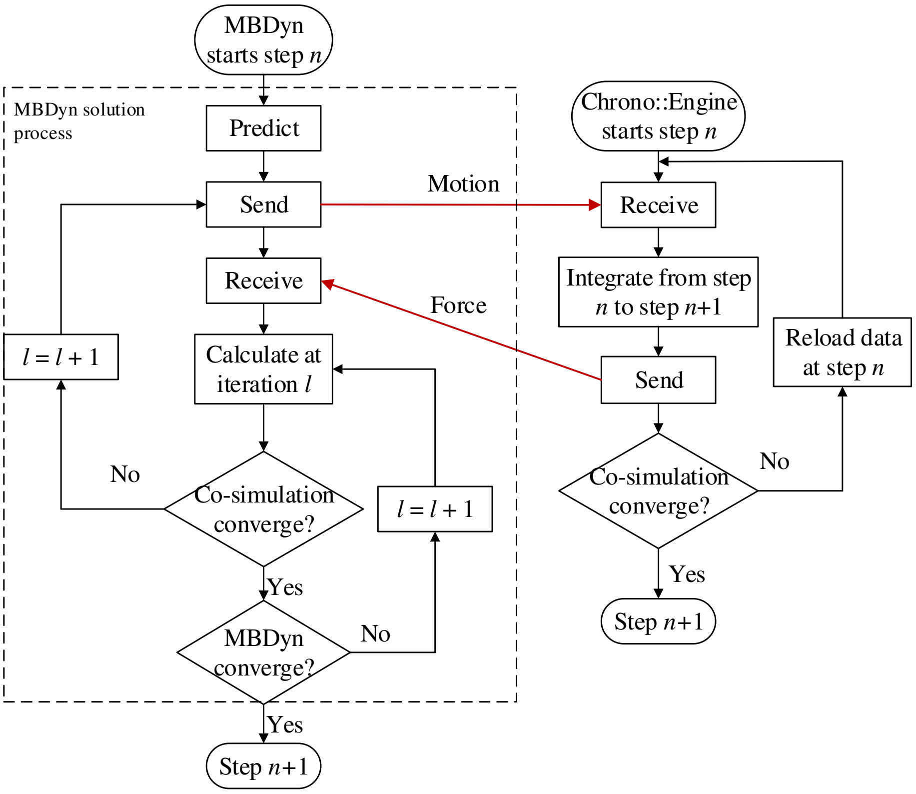


Figure 1: Tight coupling strategies between multibody and particle damper codes [24]

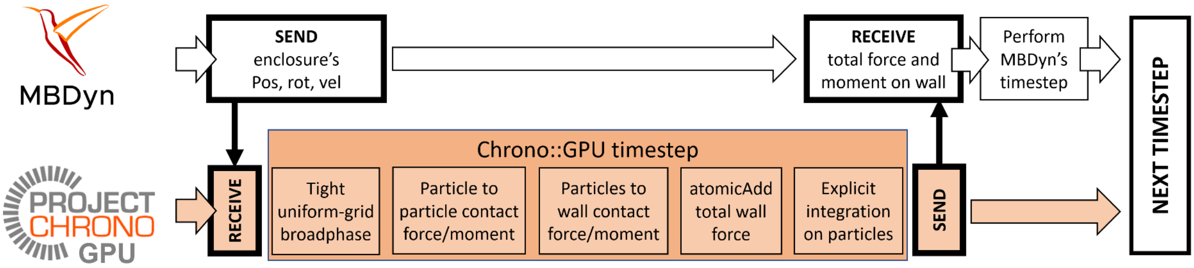


Figure 2: Loose co-simulation timestep scheme used to couple Chrono::GPU and MBDyn

2.3 PMB with interleaved loose coupling

PMB is an explicit integration GPU discrete element solver [2], based on a CUDA sample named "particles" [12]. At the moment, PMB can analyse monodisperse spherical particles enclosed in cavities with analytical geometries.

Simplicity and execution times are key elements of PMB's implementation, as the authors wanted to contain as much as possible the computational cost of the discrete element method, even giving up some complexity of the models in the process.

The broadphase particle-to-particle contact detection is performed with a loose uniform grid spatial subdivision and sorting [12, 1]: as there is no need to implement more complex and costly broadphase algorithms.

The normal force between two particles (or between a particle and a wall) is computed with a linear spring-dashpot (LSD) model. The value of the spring is usually determined by experience or guesses, so that desiderable values of overlap between particles are obtained [4], or computed from the material properties [22].

The tangential force between two particles is computed with a simplified and computationally

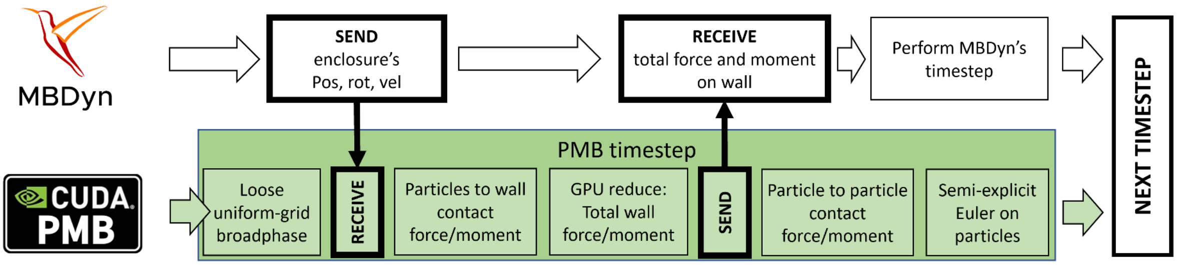


Figure 3: Interleaved loose co-simulation timestep scheme used to couple PMB and MBDyn

cheap directional Coulomb's law widely used in particle dampers' literature [18]. This model is deemed as insufficient by Matuttis and Chen [16], since it is unphysical and not even able to reproduce the simplest problems for static friction, nevertheless Fleissner [9] suggested that, in highly dynamic systems, slipping friction is dominant and it is often legitimate to neglect sticking friction.

In order to efficiently compute the total contact force and moment acting on the enclosure's walls, GPU parallel transform and reduction operations from the library Thrust are used.

PMB was coupled to MBDyn using the loose co-simulation scheme shown in figure 3. The scheme was designed to interleave the two solvers as much as possible, hence maximising the work performed in parallel and minimizing the waiting time in the communications. This approach led to significant time savings in case of few particles in the enclosure, or in case of very complex multibody models.

2.4 Solvers comparison

This sub-section shows a direct comparison of the main characteristics of the three solvers considered, as well as preliminary considerations related to performance. The comparison is summarised in table 1.

The table shows that Chrono::NSC is the most versatile and complex of the considered codes, since it can consider colliding bodies of any shape, with a BVH broadphase and optimization techniques to solve Differential Variational Inequalities (DVI) equations applied to NSCD. Chrono::GPU and PMB are both penalty-based discrete element solvers; the particles positions and velocities are computed with an explicit integration scheme to solve Ordinary Differential Equations (ODE); their performance is accelerated using GPU computing based on CUDA.

PMB is the simplest of the considered codes, its simplicity was obtained at the cost of less physical contact models and limitations regarding the shape and size of the colliding bodies, as it can simulate only monodisperse particle beds. Preliminary analyses on a simple oscillating cylindrical particle damper showed that PMB can be 3 times as fast as Chrono::GPU for particles number varying from hundreds to millions. Depending on the timestep employed in the non smooth analyses, Chrono::NSC simulation speed can be comparable to Chrono::GPU for few hundreds of particles, however, for increasing number of particles, the relative difference in execution times increases considerably.

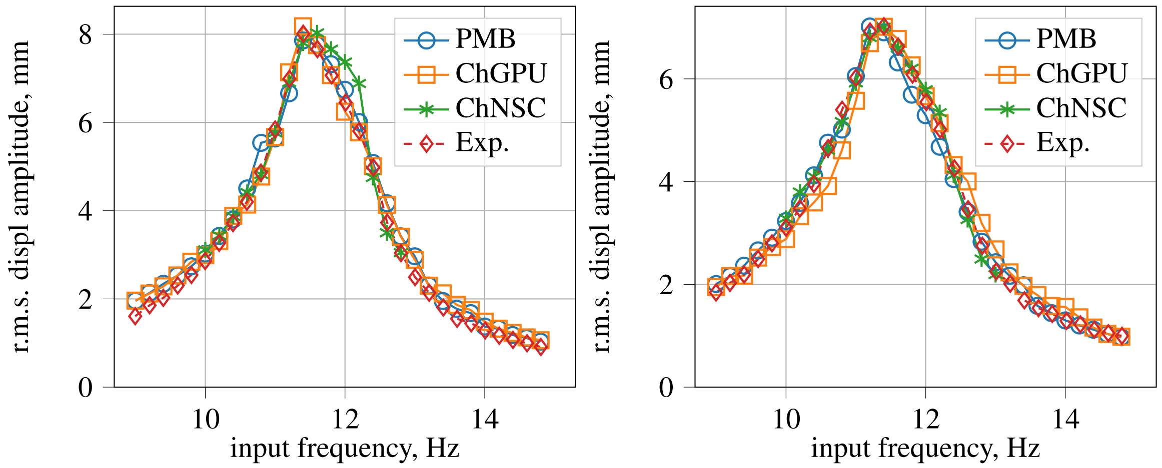
Nevertheless, Chrono::NSC was coupled to MBDyn using a tight co-simulation scheme with iterations which greatly improved algorithmic stability compared to loose co-simulation schemes, as shown by Zhang [24].

3 CASE STUDY SIMULATION RESULTS

The considered coupled codes were used to simulate Saeki's horizontal particle damping experiment [18]. Saeki's experiments consisted in measuring the transfer function of a one degree of freedom mass-spring-damper system with a cuboid particle damper forced via stepped sines in the horizontal direction. The experiments were reproduced using the DEM and numerical trade studies were executed to study the influence of different parameters. Given the clarity in the description of how the results were obtained,

	Chrono::NSC	Chrono::GPU	PMB
Bodies shapes	Complex	Monodisperse spheres	Monodisperse spheres
Normal contact model	Non-smooth	Hertzian	Linear dashpot
Tangential contact model	Coulomb's law	Mindlin-Deresiewicz	Directional friction
Equations	DVI	ODE	ODE
DEM integration	CCP optimization	explicit	explicit
Co-simulation scheme	tight	loose	interleaved loose
Broadphase	BVH	tight uniform-grid	loose uniform-grid
Architecture	multicore CPU	GPU	GPU
Simulation speed	fast for a few particles	faste even with many particles	2-3 times Chrono::GPU
Timestep selection	based on contact durations	based on contact stiffness	based on contact stiffness

Table 1: Comparison of the characteristics of the considered discrete element solvers applied on particle dampers



(a) 200 particles

(b) 250 particles

Figure 4: Comparison between Saeki's experimental results, and the simulation results with the considered solvers.

Saeki's paper was identified by Lu [14] as a reference to follow to validate DEM particle dampers programs.

In all the simulations, MBDyn was tasked with the simulation of the mass-spring-damper system, while the discrete element solvers were tasked with the simulation of the cuboid particle damper. Module HFelem in MBDyn was used to obtain the response of the dynamical system at convergence for each stepped sine.

Two specific cases from Saeki's paper were selected to be reproduced with the considered coupled codes, the first with a particle damper containing 200 particles, the second containing 250 particles; the experimental results of those cases are reported in figure 5b of Saeki's paper [18].

Figure 4 shows the frequency response obtained from the simulations with the three considered codes compared to Saeki's experimental results. Good correspondence to the experimental results was obtained for all the considered solvers.

4 CONCLUDING REMARKS

Three very different discrete element solvers to simulate particle dampers, coupled to MBDyn with different techniques, were compared and used to simulate a case study from the literature.

The results from the simulations showed that all the solvers were capable to reproduce the experimental results, despite the differences in contact models and complexity.

These results seem to suggest that the analysis of particle dampers with discrete element solvers, for design purposes, should be carried with the fastest code among those considered, since additional model complexity did not provide more accuracy in reproducing the experimental results.

However, only two case studies from the same paper were considered for this comparison; therefore, the above inference cannot be considered conclusive, but these results show that there is a need for a more extensive framework of experimental results able to uncover the limitations of the discrete element solvers used to model particle dampers and provide a base for code calibration.

ACKNOWLEDGMENTS

Part of the work was funded by the European Community's Horizon 2020 Programme (H2020-EU.3.4.5.5. – ITD Engines) under grant agreement N. 687023 (EMS UHPE - Engine Mount System for Ultra High Pass Engine).

The second author acknowledges the financial support by the China Scholarship Council and the Academic Excellence Foundation of BUAA for PhD Students. The second author is supported by the National Natural Science Foundation of China (11772021).

REFERENCES

[1] Davide Barbieri, Valeria Cardellini, and Salvatore Filippone. "Fast Uniform Grid Construction on GPGPUs Using Atomic Operations". *Parallel Computing: Accelerating Computational Science and Engineering (CSE)*, pp. 295–304 (2014).

[2] Fabio Biondani, Marco Morandini, Gian Luca Ghiringhelli, Mauro Terraneo, and Potito Cordisco. A Simple Discrete Element Code for Particle Dampers in "Proceedings of *International Design Engineering Technical Conferences & Computers and Information in Engineering Conference IDETC-CIE 2021*", **(**Aug. 2021**)**.

[3] Bernard Brogliato, AA Ten Dam, Laetitia Paoli, Frank Ge
not, and Michel Abadie. "Numerical simulation of finite dimensional multibody nonsmooth mechanical systems". *Appl. Mech. Rev.* **55**.**2**, pp. 107–150 (2002).

[4] Paul W Cleary and Mark L Sawley. "DEM modelling of industrial granular flows: 3D case studies and the effect of particle shape on hopper discharge". *Applied Mathematical Modelling* **26**.**2**, pp. 89–111 (Feb. 1, 2002).

[5] Herbert Deresiewicz and Raymond D Mindlin. *Elastic spheres in contact under varying oblique forces*. OCLC: 504883595. 1952.

[6] Nicolas Docquier, Olivier Lantsoght, Frédéric Dubois, and Olivier Brüls. "Modelling and simulation of coupled multibody systems and granular media using the non-smooth contact dynamics approach". *Multibody System Dynamics*, pp. 1–22 (2020).

[7] Luning Fang and Dan Negrut. "Producing 3D friction loads by tracking the motion of the contact point on bodies in mutual contact". *Computational Particle Mechanics*, (Jan. 2, 2021).

[8] Jonathan Fleischmann, Radu Serban, Dan Negrut, and Paramsothy Jayakumar. "On the Importance of Displacement History in Soft-Body Contact Models". *Journal of Computational and Nonlinear Dynamics* **11**.**44502**, (Nov. 13, 2015).

[9] Florian Fleissner, Timo Gaugele, and Peter Eberhard. "Applications of the discrete element method in mechanical engineering". *Multibody System Dynamics* **18**.**1**, p. 81 (June 1, 2007).

[10] R.D. Friend and V.K. Kinra. "Particle impact damping". *Journal of Sound and Vibration* **233**.**1**, pp. 93–118 (2000).

[11] Louis Gagnon, Marco Morandini, and Gian Luca Ghiringhelli. “A review of particle damping modeling and testing”. *Journal of Sound and Vibration* **459**, p. 114865 (Oct. 27, 2019).

[12] Simon Green. *Particle Simulation using CUDA*. NVIDIA. 2013, p. 12.

[13] Conlain Kelly, Nicholas Olsen, and Dan Negrut. “Billion degree of freedom granular dynamics simulation on commodity hardware via heterogeneous data-type representation”. *Multibody System Dynamics* **50**.**4**, pp. 355–379 (Dec. 1, 2020).

[14] Zheng Lu, Sami F. Masri, and Xilin Lu. *Particle Damping Technology Based Structural Control*. Springer Tracts in Civil Engineering. Springer Singapore, 2020. ISBN: 9789811534980. DOI: `10.1007/978-981-15-3499-7`. URL: `https://www.springer.com/gp/book/9789811534980` (visited on 07/03/2020).

[15] Pierangelo Masarati, Marco Morandini, and Paolo Mantegazza. “An Efficient Formulation for General-Purpose Multibody/Multiphysics Analysis”. *Journal of Computational and Nonlinear Dynamics* **9**.**41001**, (July 11, 2014).

[16] Hans-Georg Matuttis and Jian Chen. *Understanding the Discrete Element Method: Simulation of Non-Spherical Particles for Granular and Multi-body Systems*. Google-Books-ID: SssOBAAAQBAJ. John Wiley & Sons, May 12, 2014. 827 pp. ISBN: 978-1-118-56728-9.

[17] Jean J Moreau. “Unilateral contact and dry friction in finite freedom dynamics”. In: *Nonsmooth mechanics and Applications*. Springer, 1988, pp. 1–82.

[18] M. Saeki. “Impact damping with granular materials in a horizontally vibrating system”. *Journal of Sound and Vibration* **251**.**1**, pp. 153–161 (2002).

[19] Martín Sánchez and C. Manuel Carlevaro. “Nonlinear dynamic analysis of an optimal particle damper”. *Journal of Sound and Vibration* **332**.**8**, pp. 2070–2080 (Apr. 2013).

[20] Alessandro Tasora and Mihai Anitescu. “A matrix-free cone complementarity approach for solving large-scale, nonsmooth, rigid body dynamics”. *Computer Methods in Applied Mechanics and Engineering* **200**.**5-8**, pp. 439–453 (2011).

[21] Alessandro Tasora, Radu Serban, Hammad Mazhar, Arman Pazouki, Daniel Melanz, Jonathan Fleischmann, Michael Taylor, Hiroyuki Sugiyama, and Dan Negrut. Chrono: An Open Source Multi-physics Dynamics Engine in “Proceedings of *HPCSE*”, (2015).

[22] Carl Wassgren, *Discrete Element Method (DEM) Course Module*, (2008), DOI: `https://pharmahub.org/resources/113`.

[23] Kai Zhang, Tianning Chen, Xiaopeng Wang, and Jianglong Fang. “Rheology behavior and optimal damping effect of granular particles in a non-obstructive particle damper”. *Journal of Sound and Vibration* **364**, pp. 30–43 (Mar. 3, 2016).

[24] Runsen Zhang, Huimin Zhang, Andrea Zanoni, Qi Wang, and Pierangelo Masarati. “A tight coupling scheme for smooth/non-smooth multibody co-simulation of a particle damper”. *Mechanism and Machine Theory* **161**, p. 104181 (2021).