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PAPER

Granular dampers: does particle shape matter?

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**Abstract**

By means of particle-based numerical simulations using the discrete element method, we address the question of how the performance of granular dampers is affected by the shape of the granular particles. In consistence with previous experiments performed with nearly spherical particles we find that independently of the particles' shape, the granular system is characterized by a gas-like regime for small amplitudes of the container's oscillation and by a collect-and-collide regime for large amplitude forcing. Both regimes are separated by an optimal operation mode—the critical amplitude of the damping oscillation for which the energy dissipation is maximal—which is independent of the particle shape for given conditions of particle mass, material properties and number of particles. However, in the gas-like regime, we find that spherical particles lead to more efficient energy dissipation compared to complex shaped particles of the same mass. In this regime, a dependence on the damper's efficiency on the particle shape is found.

1. Introduction

Granular dampers, that is, containers partially filled with granular material, are widely used as a means for attenuating mechanical vibrations in a broad range of systems [1–14]. Indeed, granular dampers perform particularly well in applications where the acceleration due to gravity can be neglected, because gravity tends to demobilize the granulate (see [15]). This is why much attention has been given to the study of granular dampers in microgravity conditions, in particular to investigate the factors controlling their performance [16–18].

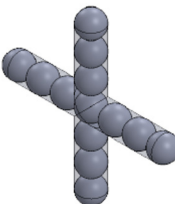
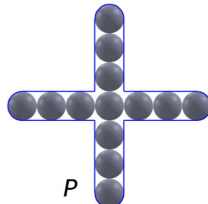
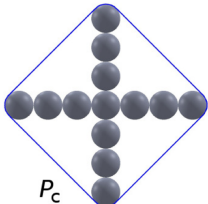
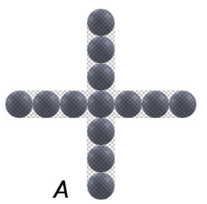
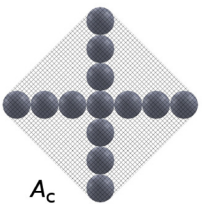
While the influence of the parameters of the driving [15, 19], material properties and particle size [20–23] on the granular dampers' performance has been matter of study by many authors, the rôle of particle *shape* on this performance was paid much less attention. As a matter of fact, the particulate material used in granular dampers is typically composed of spherical particles. However, it is well-known that dissipative properties of granular materials made of complex particle shapes may be very different from the ones of spherical particle ensembles [24, 25]. This different behavior raises the question of whether the particle shape could be used as an adjustable design parameter for the optimal operation mode of a granular damper, depending on the practical application. Moreover, it is relevant to understand to which extent the degree of non-sphericity may affect the performance of the damper.

Particle-based simulations by means of the discrete element method (DEM) provide a powerful means for investigating the dynamics of granular materials [26]. Sánchez *et al* [27] performed the first DEM simulations of granular dampers using different particle shapes. In particular, the authors performed two-dimensional simulations using circles, squares, triangles and hexagons, and found similar values of the frequency response function of the granular system for these particle shapes. Apart from the study by Sánchez *et al* [27], there is no systematic investigation of the rôle of particle shape on the granular dampers' performance. Such an investigation should include a quantitative description of particle shape. Moreover, it should be performed for three-dimensional systems because in practice granular dampers are three-dimensional devices.

Therefore, here we perform this systematic study by investigating a diversity of particle shapes covering a broad range of shape parameter values (specified below). We focus on the relevant quantity characterizing the

Table 1. Particle shapes used in the simulations. The composite particles constructed with the multisphere method are displayed in the first row of the table. The second row shows the symbols associated with each shape as used in figures 2–4. The subsequent rows show the values of shape parameters defined in equations (1)–(4), associated with each particle. For particles #2–#11 (counted from left to right) the shape parameters are calculated with respect to the plane i – j , which is the plane onto which the particle's projected area is maximal (see coordinate system on the bottom right hand corner). The sketches at the bottom of the table show particle #8 with the spherocylinders containing the particle's constituent bead (first sketch from left to right) as well as the definition of P , A , P_c and A_c for this particle.

particle shapes														
symbol														
convexity (C_v)	1.00	1.00	1.00	1.00	0.91	0.76	0.74	0.77	0.69	0.94	1.00	0.89 (C_{v3})	0.95 (C_{v3})	0.97 (C_{v3})
solidity (S)	1.00	1.00	1.00	1.00	0.76	0.76	0.89	0.46	0.80	0.85	1.00	0.44 (S_3)	0.47 (S_3)	0.58 (S_3)
aspect ratio (η)	1.00	0.50	0.25	0.13	1.00	1.00	1.00	1.00	1.00	0.67	0.57	ij plane 0.67	ij plane 1.00	ij plane 1.00
												jk plane 1.00	jk plane 1.00	jk plane 1.00
												ik plane 1.00	ik plane 1.00	ik plane 1.00
circularity (C)	1.00	0.92	0.75	0.58	0.71	0.62	0.65	0.48	0.62	0.77	0.88			

performance and operation mode of granular dampers, that is, the average value of total dissipated energy per oscillation cycle, in response to the vibration amplitude [28, 29].

2. Numerical experiments

We simulate the process using the DEM, that is, simultaneously solving Newton's equations of translational and rotational motion for all particles.

Most DEM models are designed for particulate systems composed of spherical particles, for which contact detection is simple. Geometrically complex particles can be modeled using the multisphere method, where spherical particles are arranged relatively to one another to form composite particles [30–33]. Each composite particle leads to a rigid body, the total force on which is computed by summing up the forces on all constituent spheres. Moreover, the angular momentum of the complex particle is computed from the total torque on all spheres with respect to the body's center of mass [34]. The interactions between spherical particles belonging to distinct composite particles are calculated by considering the contact force model described below.

2.1. Particle shapes

By using the multisphere method, we model different complex particle shapes as shown in table 1. The first of such particle shapes is the rod, which is represented by particles #2–#4 in the first row of table 1. Furthermore, we also model squares, rings, crosses and L -shaped particles, by combining beads of the same size (see particle shapes #5–#10). Moreover, particle #11 is an asymmetric rod that consists of beads of different sizes. It has been inspired by the polar granular rods of [35], which defined rods with a mass gradient along the particle's axis.

In contrast to [35], however, here the particle asymmetry is in the shape and not in the mass. The density of each constituent bead of particle #11 has been chosen such that each bead has the same mass.

For the complex particle shapes #2–#11, all constituent spheres lie on the plane i – j —the coordinate system taken as reference for defining the particle shapes is shown in the bottom right-hand corner of the table. However, particles #12–#14 also contain beads on the plane i – k . Particle #12 can be viewed as a combination of particles #5 and #10, disposed orthogonally to each other on the planes i – j and i – k , respectively. Moreover, particles #13 and #14 consist of two orthogonal rings and squares, respectively. We thus define the particle shapes #2–#11 as *two-dimensional* complex particle shapes, while particles #12–#14 are *three-dimensional* complex particle shapes.

In the following, first we present the parameters used to characterize the two-dimensional particle shapes. Thereafter we show how these parameters are adapted to describe the three-dimensional objects.

The first shape parameter is the *aspect ratio*, that is, the ratio of the Feret's minimum diameter to the Feret's maximum diameter

$$\eta \equiv \frac{D_{\min}^F}{D_{\max}^F}, \quad (1)$$

where the Feret's or caliper diameter gives the length of the object along a specified direction [36, 37]. The second shape parameter is the *circularity* [37]

$$C \equiv \sqrt{\frac{4\pi A}{P^2}}, \quad (2)$$

where A and P denote the area and perimeter of the particle, respectively.

To compute A and P , we consider the projection of each complex particle onto the plane i – j , which is the plane on which the particle's constituent beads lie. However, we do not compute the projection of the single constituent beads, which defines a set of filled circles on the plane i – j . Instead, for simplicity, we approximate the complex multisphere particles by intersecting spherocylindrical shells [38], and we compute A and P from the projection of these shells on the plane i – j . As an example, the perimeter P and the area A obtained from the projection of particle #8 (the cross) is shown on the bottom of table 1. Furthermore, note that each of the rings defining particles #9 and #13 can be obtained by bending a rod to form a closed (circular) loop. The enclosing shell for each ring is obtained by bending the spherocylindrical shell of the associated rod, thereby merging both its dips to form a closed cylindrical shell.

The third shape parameter is the *convexity*,

$$C_x \equiv \frac{P_c}{P}, \quad (3)$$

where P_c is the hull perimeter, that is, the perimeter of the convex hull or smallest convex envelope enclosing the composite particle. This envelope may be visualized as the shape enclosed by a rubber band stretched around the composite particle [37]. For the cross-shaped particle #8, the convex hull from which P_c is computed is shown on the bottom of table 1.

Finally, the fourth particle shape parameter is the *solidity*

$$S \equiv \frac{A}{A_c}, \quad (4)$$

where A_c is the convex hull area. That is, A_c denotes the area inside the convex hull around the two-dimensional particle shape (see example on the bottom of table 1). The solidity gives, thus, the fraction of the area within the convex hull that is filled with particle's material (that is, solid). Correspondingly, the rougher (or less solid) the particle shape becomes, the more the solidity value will approach zero.

We note that, whereas the computation of the particle shape parameters is simplified by using the intersecting spherocylindrical shells as reference geometries, certainly a more precise characterization should incorporate the roughness due to the contours of the single constituent beads along the shell's axis—the roughness due to the shape of the particle without regard to the beads' contours is already incorporated in the solidity. Indeed, the aim of the present analysis is to quantify the main geometric characteristics influencing the particle's rotational behavior, that is the degree of non-sphericity of the multisphere particle shapes, which is why we choose the shape parameters listed above. Moreover, we note that previous DEM simulations using spherocylinders have been presented in [38]. However, here we adopt the multisphere method in the simulations as it leads to an efficient computation of particle–particle contact detection, while with the generated multisphere particles it is possible to capture the main characteristics associated with the rotational behavior of the different modeled shapes.

For the three-dimensional particle shapes #12–#14, the convexity and solidity are defined here based on the area and volume associated with the three-dimensional objects, respectively. Specifically, the convexity C_{x3} is

defined as

$$C_{x3} = \frac{A_{c3}}{A_3}, \quad (5)$$

where A_3 is the sum of the total surface area of all spherocylinders enclosing the constituent spheres of the composite particle, while A_{c3} is the area of the three-dimensional convex hull or the smallest three-dimensional envelope enclosing the particle shape. Analogously, the solidity S is defined as

$$S_3 = \frac{V_3}{V_{c3}}, \quad (6)$$

where V_3 is the sum of the volumes of all spherocylinders enclosing the particle's constituent spheres as specified above, while V_{c3} is the volume of the convex hull around the composite particle. Moreover, while the circularity is a measure inherent to two-dimensional objects [37], the aspect ratio of particle shapes #12–#14 can be computed for each one of the planes defined in table 1 and the results are displayed in this table.

Furthermore, the parameters adopted to characterize the particle shape may have different values depending on the particle dimensions. This can be clearly seen from the examples of the rods, that is particles #2–#4 where rods of different lengths—but same *shape*—have different values of aspect ratio and circularity. Moreover, considering a cross (particle #8) with various length values (L) leads to different values of solidity, since $A \sim L$ while $A_c \sim L^2$ due to the definition on the bottom of table 1. Therefore, considering just one single parameter from table 1 is insufficient to describe a given particle morphology. It is rather the set of *all* parameter values (combined) which should be used to characterize a single particle used in the simulation. In other words, it is based on their combined values that the parameters of table 1 are regarded as shape parameters to describe the complex particle shapes in the present work (see also [37]).

We also note that the quantification of the particle shapes can be made in different ways, for instance by performing a Minkowsky tensor shape analysis of the particles [39]. However, the characterization of particle shape presented here can be easily applied in experimental applications, as shown in the experimental works of [37, 40]. As we can see from table 1, for the four particle shape parameters chosen, a broad range of values is obtained for the different particles, thus providing an adequate description of the particle shape diversity considered in the present work.

2.2. Inter-particle force model

The contact forces in DEM simulations can be described through a variety of models, which are suitable for different particle geometry and material behavior [26, 34, 41, 42]. In the simulations of the present manuscript, we consider viscoelastic interaction in the normal direction (see [43]). The normal force corresponding to this model follows the equation

$$\vec{F}_n = \min\left(0, -\rho\xi^{3/2} - \frac{3}{2}A_n\rho\sqrt{\xi}\dot{\xi}\right)\vec{e}_n, \quad (7)$$

where ξ , the compression of the colliding particles, is described by the equation

$$\xi = R_1 + R_2 - |\vec{r}_1 - \vec{r}_2|. \quad (8)$$

In this equation, R_1 and R_2 denote the radii of the particles, which are at positions $\vec{r}_1$ and $\vec{r}_2$. Furthermore, the normal unit vector, denoted by $\vec{e}_n$, is defined as $\vec{e}_n = (\vec{r}_1 - \vec{r}_2)/|\vec{r}_1 - \vec{r}_2|$.

The expression for the normal force encodes, thus, an elastic parameter, ρ , as well as a dissipative parameter, A_n . This dissipative parameter can be obtained from the pre-collisional (impact) velocity, v_{imp} , of the colliding particles and the coefficient of restitution, ε , associated with this collision, as shown in [44–47]. Moreover, the elastic parameter is a function of the Young's modulus (Y), the Poisson's ratio (ν) and the effective radius of the particles, $R_{\text{eff}} \equiv R_1 R_2 / (R_1 + R_2)$. The following expression is used to calculate this parameter

$$\rho \equiv \frac{2Y}{3(1 - \nu^2)}\sqrt{R_{\text{eff}}}. \quad (9)$$

Furthermore, the behavior of many granular systems can be strongly influenced by friction. However, it has been shown in [16] that the dissipative behavior of granular dampers is mainly controlled by dissipation due to *normal* interaction forces. Therefore, although tangential forces play an important role for particle–particle interactions of granular materials, in the present work we build on the results of [16] to discuss the role of particle shape by considering the dissipation model presented above. We anticipate that our simulations showed no significant effect of friction on the conclusions of the present work. However, the detailed investigation of the particles' dynamics in presence of frictional and cohesional forces is still matter of current investigation and will be treated in a future work.

Table 2. Numerical values of the parameters used in the simulations. For particle-wall collisions the Poisson's ratio used was $\nu = 0.37$. The dimensions of the damper (L , W and H , defined with respect to the axes x , y and z , respectively) are as in [28].

Parameter	Symbol	Value
Particle material density	ρ_p	7800 kg m ⁻³
Particle diameter	d	4 mm
Young's modulus	Y	10 ⁸ Pa
Poisson's ratio	ν	0.3
Box length	L	100 mm
Box width	W	50 mm
Box height	H	50 mm
timestep	Δt	10 ⁻⁶ s

2.3. Simulation of the granular damper

The equations used for computing the interactions between the particles and the walls of the damper are the same used to calculate the inter-particle interaction forces, with one of the contact partners being of infinite mass and radius [33, 48, 49].

In accordance with the experiments of [28], in each numerical experiment we consider a total of 473 complex (multisphere) particles, each with mass equal to the mass of a steel sphere diameter 4 mm—the size of the steel beads used in the experiments [28]. The diameters of the constituent spheres of each particle are thus chosen such as to reproduce the specified mass. Initially the particles are deposited under the action of gravity on the bottom of the granular damper, whereupon the damper starts to oscillate with frequency ω and amplitude A_{damp} . While the deposition of the particles with the damper at rest is performed using Earth gravity, the shaking of the damper occurs under conditions of weightlessness [18, 28].

2.4. Model parameters and numerical integration

The values of the model parameters are listed in table 2. The integration was performed using the DEM library of [50], which has been extended here to incorporate the analytical model of [47] for obtaining the viscoelastic constant A_n . In order to compute this constant, we assume a coefficient of restitution $\varepsilon_{pp} \approx 0.75$ and $\varepsilon_{pw} \approx 0.76$, for particle–particle and particle–wall collisions, respectively, associated with a pre-collisional velocity $v_{\text{imp}} \approx 1.0 \text{ m s}^{-1}$. Using these values of restitution coefficient and a different numerical tool based on event-driven DEM simulations, [16] reproduced well the dynamics of center of mass position of the granular system investigated here.

We note that, while we have chosen parameters based on the material properties of steel, the coefficient of restitution chosen here is rather low. Following a previous particle-based model for granular dampers [16], this choice is made because part of the collisional dissipation is due to frictional forces, which are not considered in the simulations. The value of 0.75 was obtained in [16] by comparing simulation results using frictionless particles to the experimental results obtained with steel particles. In this reference, excellent agreement was found between the trajectory of the center-of-mass position of the particles relative to the box center, thus indicating that simulations with normal dissipation (using this value of coefficient of restitution) can well describe the dissipative behavior of the particles due to collisions with the side walls.

The integration time step Δt must be small enough to accurately solve Newton's equations for the particle interaction. For undamped collisions, the duration T_{col} of the collision can be estimated using the equation [41]

$$T_{\text{col}} \approx 3.21 \left(\frac{M_{\text{eff}}}{\rho} \right)^{2/5} v_{\text{imp}}^{-1/5}, \quad \text{where} \quad M_{\text{eff}} \equiv \frac{m_1 m_2}{m_1 + m_2} \quad (10)$$

with m_1 and m_2 standing for the masses of the interacting particles. Typically a timestep much smaller than T_{col} is recommended [51]. We thus calculate the collision time of two spheres with diameter equal to $\approx 1 \text{ mm}$, which is the smallest diameter value of all beads adopted to model the different particle shapes in table 1. Since the time T_{col} for such a collision computed using equation (10) with the material properties specified above is about 20 μs , we use here $\Delta t = 10^{-6} \text{ s}$. Moreover, we have found that using smaller timestep values does not change our results.

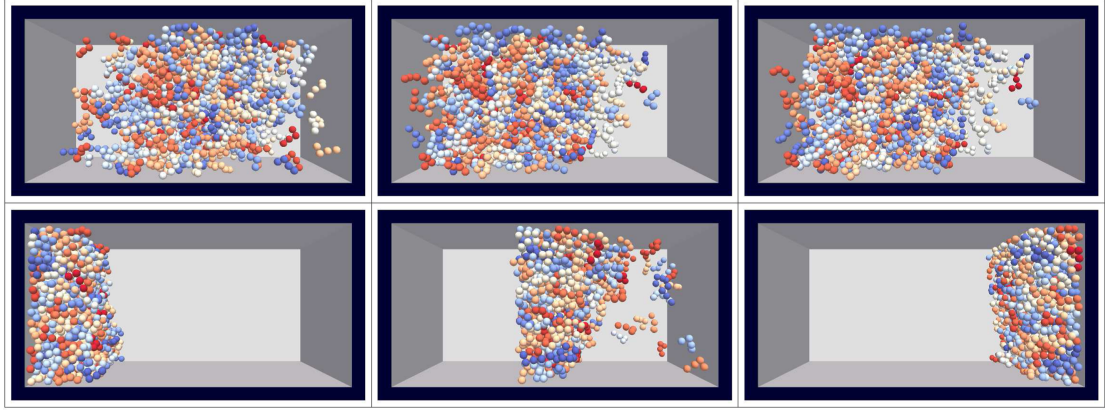


Figure 1. Snapshots of the damper simulations using L -shaped particles (10th particle shape from left to right in figure 1) at oscillation amplitudes $A_{\text{damp}} = 10$ mm (top; gas-like regime) and $A_{\text{damp}} = 80$ mm (bottom; collect-and-collide regime). For both amplitudes, the displayed snapshots correspond to the oscillation phases $\pi/2$, π and $3\pi/2$ (from left to right), whereas the damper's horizontal position evolves in time according to the equation $x(t) = A_{\text{damp}} \sin(2\pi\nu t)$ (where $\nu = 4$ Hz is the oscillation frequency [28]).

3. Results and discussion

Figure 1 shows snapshots of the simulations of the damper oscillation using the L -shaped particles in the 10th column from left to right in table 1. The snapshots in the upper and lower rows refer to amplitude of oscillation of 10 mm and 80 mm, respectively. As we can see from this figure, for an amplitude of 10 mm, the granular system is in a gas-like regime, in which only a few particles interact with the oscillating walls during one oscillation period [28]. In this regime, particle-wall collisions are just sufficient to balance the energy loss resulting from the particle–particle collisions in the bulk of the material. By contrast, for the amplitude of 80 mm, the system is in the collect-and-collide regime [28]. That is, during the inward stroke all the material is *collected* and accumulates as a packed layer at the wall of the container. Once the container has passed the phase of maximal velocity, it decelerates and the granular particles move away from the wall collectively. When the bulk of particles impacts onto the opposite wall of the container, a large fraction of the system's kinetic energy is dissipated due to inelastic collisions.

Moreover, the gas-like and collect-and-collide regimes are separated by an optimal operation mode—the critical amplitude of the damper's oscillation for which the energy dissipation is maximal. Similar behavior was found for all particle shapes considered.

In order to quantify our results we calculate the energy dissipated per cycle of the damper's oscillation as a function of the oscillation amplitude A_{damp} . To do so, we integrate the product of the measured force $F(t)$ —that is, the total force exerted by the particles on the side walls of the damper (parallel to the direction of motion)—and velocity $\dot{x}(t)$ over one period, $T = 2\pi/\omega$, of the sinusoidal driving $x = A_{\text{damp}} \sin(\omega t)$, that is

$$E_{\text{diss}} = \int_T \dot{x}(t) F(t) dt. \quad (11)$$

Moreover, the maximum energy, E_{max} , that can be dissipated in one oscillation cycle can be estimated by considering all particles colliding inelastically with the wall at the maximal relative velocity, $v_{\text{max}} = 2A_{\text{damp}}\omega$ [28]. At the collision with one wall (half cycle), the maximal energy that can be dissipated is equal to $mv_{\text{max}}^2/2$, while the corresponding value for one entire cycle is twice as large, or $E_{\text{max}} = mv_{\text{max}}^2$. Therefore, E_{max} , the maximal energy which can be dissipated in one period of oscillation in the stationary state [28], follows the equation

$$E_{\text{max}} = 4mA_{\text{damp}}^2\omega^2, \quad (12)$$

where m is the total mass of *all* particles in the system [28].

The damping efficiency associated with a given particle shape can be characterized by computing the relative energy dissipated per cycle, $E_{\text{diss}}/E_{\text{max}}$. Figure 2 shows the damping efficiency defined in this manner as a function of the oscillation amplitude for all particle shapes investigated. As we can see in this figure, for all particle shapes, the value of damping efficiency (that is, $E_{\text{diss}}/E_{\text{max}}$) increases linearly with the amplitude A_{damp} in the gas-like regime, for $0 < A_{\text{damp}} \lesssim 20$ mm. The damping efficiency displays a fast increase with A_{damp} as the oscillation amplitude increases beyond 20 mm, whereas for $A_{\text{damp}} \approx 30$ mm a maximal value for $E_{\text{diss}}/E_{\text{max}}$ is reached. The system enters the collect-and-collide regime as the amplitude becomes larger than 30 mm. In [28], it was shown that the critical amplitude separating the gas-like regime from the collect-and-collide regime

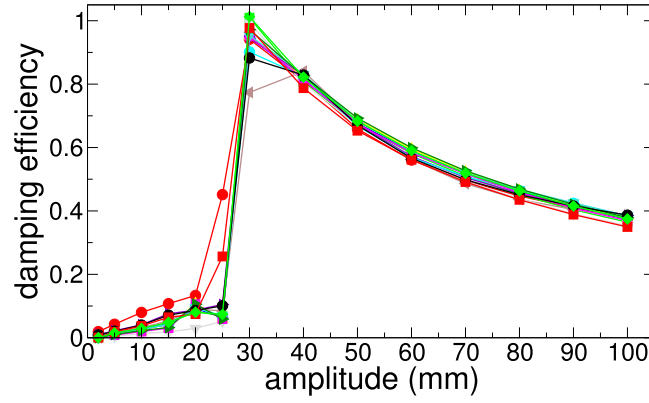


Figure 2. Damping efficiency, $E_{\text{diss}}/E_{\text{max}}$, as a function of the oscillation amplitude. The symbols denote different particles as defined in the first and second rows of table 1.

can be estimated using the equation

$$A_{\text{crit}} \approx \frac{L_g}{\pi}, \quad (13)$$

where L_g is the clearance of the granular material in the damper. This clearance is the difference between the length (L) of the container and the thickness of the granular layer associated with all particles deposited on the container's bottom wall. It can be obtained by calculating the volume occupied by all particles in rcp on the bottom of the damper at rest. Using the reference value $L_g = 89.4$ mm of the clearance associated with the spherical particles of diameter $d = 4$ mm [28]—and thus with the same volume as each of the particles considered in our simulations—we obtain $A_{\text{crit}} \approx 28.5$ mm, which is indeed very close to the amplitude value at which the damping efficiency obtained in our numerical experiments is maximal (see figure 2).

We note that the results from experiments with oscillation frequency ν in the range $1 \leq \nu/\text{Hz} \leq 5$ suggested independence of the critical amplitude on the frequency (for this range of ν). This behavior is consistent with equation (13), which predicts independence of A_{crit} on ν . In consistence with previous experiments [28], we thus perform simulations with an oscillation frequency of $\nu = 4$ Hz, that is within the aforementioned range, for all particle shapes investigated.

As can be seen from figure 2, the critical amplitude A_{crit} is nearly independent of the particle shape. Indeed, a theoretical model for explaining this critical amplitude has been proposed by [28]. According to this model, desynchronization of the collective particle motion occurs if the particle bulk arrives at the opposite wall at a time where this wall is accelerating away from it, which means that the granular system will not get collected by the wall but mainly scattered. This criterion for the transition is indeed independent of the particle shape, as is the value of A_{crit} obtained from our simulations.

Moreover, we see in figure 2 that the results for the different particle shapes collapse well for amplitudes larger than A_{crit} , the collect-and-collide regime. In this regime, the behavior of the system can be described by means of a one-particle model, as shown by [16]. That is, the granular system behaves like a single quasi-particle cycling between the walls of the container in the direction of the oscillation. Once the particles collectively hit one of the walls, the quasi-particle associated with the bulk loses all its relative velocity with respect to the wall, which means that the collision is characterized by a vanishing coefficient of restitution. Reference [29] tested this theory against systematic experiments in microgravity conditions thereby finding quantitative agreement between measured and predicted values of the average dissipated energy per cycle as a function of the amplitude in the collect-and-collide regime (see figure 8 of [29]). Our results show that this model proves applicable not only for spherical particles but also for complex particle shapes.

For amplitudes in the gas-like regime (in particular when $A_{\text{damp}} \ll A_{\text{crit}}$), we observe an interesting behavior in figure 2, that is the curves do not collapse as well as they do in collect-and-collide regime ($A_{\text{damp}} > A_{\text{crit}}$). In the gas-like regime, we expect the dissipative behavior of the system to be related with the granular temperature [25, 26], or equivalently the spread of the granular system, since in this regime the bulk of particles is located around the center of the damper (thus far from the driving walls). This means that the dissipated energy is due to collisions of only a few particles with driving walls, which are far away from the bulk.

The simplest quantity which we can compute to investigate this behavior is the standard deviation of the positions of the particles along the oscillation axis relative to the particles' center-of-mass position. We thus investigate the time-averaged standard deviation of the particles' positions $x_i(t)$ relative to the center-of-mass position $x_{\text{cm}}(t)$ of the granular material, $\sigma_x = \langle \sum_{i=1}^N (x_i(t) - x_{\text{cm}}(t))^2 / N \rangle_t^{1/2}$ (with $N = 473$ particles), for an

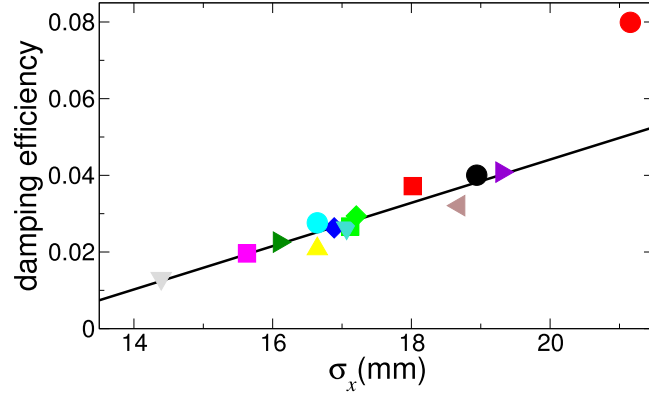


Figure 3. Damping efficiency, $E_{\text{diss}}/E_{\text{max}}$, as a function of the time-averaged standard deviation of the particles' positions along the oscillation axis (x) relative to the center-of-mass position of the granular system, for an amplitude of oscillation $A_{\text{damp}} = 10$ mm (gas-like regime). The symbols denote different particle shapes as defined in table 1, while the continuous line represents the fit to the simulation data associated with the complex particle shapes using equation (14).

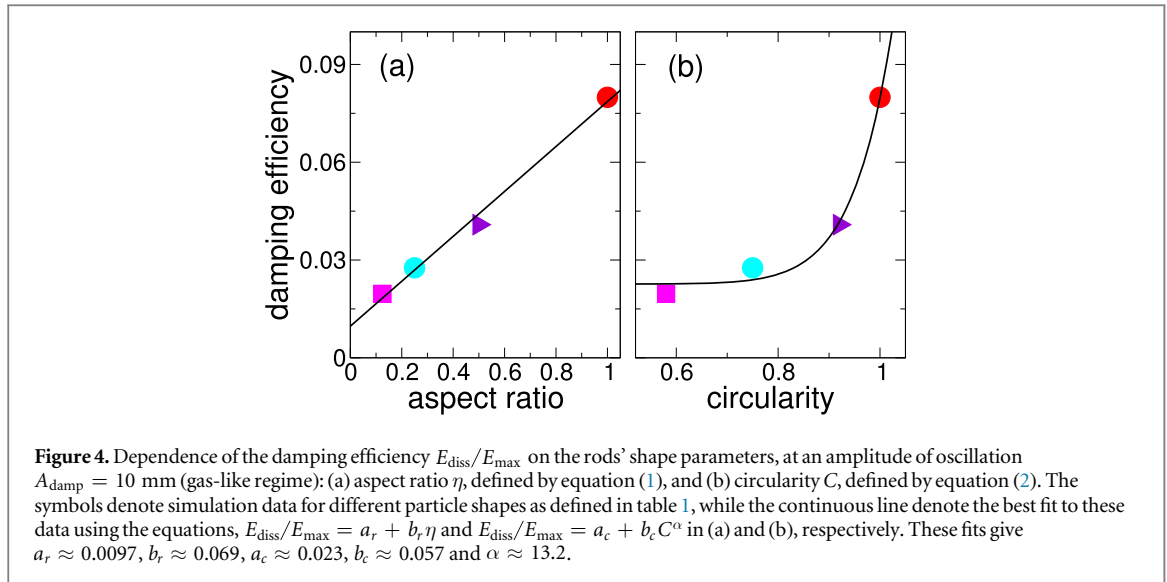
amplitude $A_{\text{damp}} = 10$ mm, which is well within the range of amplitudes characterizing the gas-like regime. Figure 3 shows the damping efficiency as a function of σ_x for all particle shapes investigated. The symbols denote the corresponding particle shapes as specified in table 1 (see first and second rows). As we can see, by considering all complex particles shapes investigated, a linear increase of the damping efficiency with σ_x is observed, whereas this behavior is found for all amplitudes below 15 mm, that is when the system is well within the gas-like regime. The best fit to the simulation data associated with the complex particle shapes using the equation

$$\frac{E_{\text{diss}}}{E_{\text{max}}} = a + b\sigma_x \quad (14)$$

gives $a \approx -0.0688$ and $b \approx 0.00565 \text{ mm}^{-1}$, with correlation coefficient 0.95. This best fit is denoted by the continuous line in figure 3.

As we can see from figure 3, equation (14) describes well the behavior of the damping efficiency as a function of σ_x for all complex particle shapes. However, the fit to the data from the complex particles does not capture the point associated with the spherical particles (red circle). The observed value of $E_{\text{diss}}/E_{\text{max}}$ for the spherical particles is much larger than the value predicted from the fit to the complex particles data using equation (14). It is interesting to discuss this behavior in the light of the experimental results of [25], who investigated the dynamics of rods in a stationary box with sidewalls vibrating in antiphase under microgravity conditions. These authors found much smaller mean free path values for the rod particles compared to the spherical particles, meaning that for the complex shaped particles, grain–grain collisions dominate over grain–wall collisions. We note that lower mean free path means less dissipation due to particle–wall collisions due to lower dispersion of the particles from the center-of-mass position—or, equivalently, lower σ_x . Indeed, the more compact the particles are distributed around the center-of-mass position the lower the mean free path and σ_x . Qualitatively our findings are, thus, consistent with this experimental result since less dissipation (due to collisions with the driving walls) is observed for the complex particle shapes in the damper (see figure 3). However, we note that since the experiments of [25] differ from the granular damper dynamics it is difficult to make a comparison of the granular dynamics between both systems—for example of the distribution of the particles in the container. Nevertheless, our simulations suggest that the spherical particle shape is the optimal shape to be used in granular dampers with regard to energy dissipation in the gas-like regime.

By considering one type of particle shape (the rods), we can see a dependence of the damping efficiency on some of the shape parameters. We see in figure 4(a) that the damping efficiency increases linearly with the aspect ratio η of the rods, whereas the best fit to the data using the equation $E_{\text{diss}}/E_{\text{max}} = a_r + b_r\eta$ gives $a_r \approx 0.0097$ and $b_r \approx 0.069$ with correlation coefficient 0.997. Moreover, in figure 4(b) we see that the damping efficiency increases nonlinearly with circularity (C) of the rods. The best fit using the equation $E_{\text{diss}}/E_{\text{max}} = a_c + b_c C^\alpha$ gives $a_c \approx 0.023$, $b_c \approx 0.057$ and $\alpha \approx 13.2$ with correlation coefficient 0.994. We note that both fits include the data point associated with the spherical particles ($\eta = C = 1$). It is interesting to note that the value of σ_x is smaller the more elongated the rod, that is, the more the particle deviates from the spherical shape (see figure 3). Therefore, a relationship between σ_x and the shape parameters mentioned above is found in our simulations. Moreover, the relationship between the granular temperature (which is related to σ_x) of the system and the rod's aspect ratio has been shown in [25]. However, we note that the fits presented in figure 4 do not capture the simulation data for the other particle shapes. We conclude that the dependence of the damping efficiency on the



shape parameters should be sensitive to the rotational characteristics of the different types of particle geometries, which remains to be investigated.

Indeed, it is interesting to note that the linear fit equation for the damping efficiency as a function of σ_x (figure 3) describes well the behavior of *both* two-dimensional and three-dimensional complex shapes. This interesting behavior remains to be investigated in future work. In particular, we note that friction largely influences the rotational behavior of the particles and we thus expect different dissipative behavior of the various particle shapes in presence of friction. Future work should thus focus on the effect of friction on the result of figure 3.

Moreover, while in figure 4 we show a dependence of the dissipative behavior on aspect ratio and circularity of the rods, we remark that other shape parameters should be important for the dissipative behavior of the granular damper. However, based on the available simulation data, we could not find any dependence of the dissipated energy on the solidity or convexity (such as we found for the aspect ratio and circularity in figure 4). The reason for this result remains to be clarified in future work.

While the present manuscript focuses on the damping efficiency based on the conditions of the experiments of [16, 18, 28], the physics of the granular system in the gas-like regime should be investigated more systematically considering different particle numbers and system sizes. Moreover, it would be interesting to investigate the dissipative behavior of the different particle shapes in more detail, especially close to the critical amplitude where dissipation is maximal (see figure 2).

4. Conclusions

We have performed particle-based (DEM) simulations of granular dampers in the absence of gravity using a broad range of particle shapes. The results of our simulations indicate that the critical amplitude A_{crit} of the damper's oscillation for which the efficiency is maximal does not depend on the shape of the particles, provided the material properties as well as the particle mass and number of particles are the same. For intense forcing, $A_{\text{damp}} > A_{\text{crit}}$, the system is found in the collect-and-collide regime, in which the granulate's center of mass moves synchronously with the driven container. For weak forcing, $A_{\text{damp}} < A_{\text{crit}}$, the particulate system exhibits gas-like behavior. In this gas-like regime, we found that the damping efficiency is smaller for complex particle shapes than for spherical particles. Moreover, a dependence of the damper's efficiency on the aspect ratio and circularity of rod-shaped particles was found.

We note that in previous experiments by Marhadi and Kinra [21] the average kinetic energy converted into heat per cycle of the damper oscillation was measured for spherical particles as well as for irregularly shaped particles (including quartz sand grains) of different materials. However, as pointed out by the authors of this study, it was not possible to conclude on the rôle of particle shape based on the experimental data since the samples were associated with different particle size and mass values. Here we have performed a systematic study of the rôle of particle shape by considering the same number of particles in all numerical experiments, and by using the same particle mass for all particles, independently of the particle shape.

We note that the behavior of the granular system also depends on the parameters of the driving and also on the elastic and dissipative properties of the particles, as discussed in previous works [20–23]. However, here these

characteristics have been considered the same in all simulations since the present work is focused on the effect of particle shape. Moreover, we have also performed simulations by including tangential forces as in previous works [26, 33, 48, 49] and found that the conclusions of the present manuscript do not change when friction is taken into account. That is, the same dissipative behavior of the granular damper is observed if friction is included, which means roughly shape-independent values of dissipated energy in the collect-and-collide regime and larger dissipation for spherical particles in the gas-like regime compared to complex particle shapes. Moreover, we also found that the value of the critical amplitude also changes negligibly with friction. Notwithstanding these preliminary findings, we remark that the dissipative properties of granular systems constituted of frictional particles is still poorly understood and matter of active research [52–54]. Granular dampers in microgravity provide an excellent laboratory for investigating these properties, and the present work should be thus continued to investigate in more detail the effect of friction on the characteristics of the inter-particle interactions for the different particle shapes—in the particular in the gas-like regime.

It should be further remarked here that our results were obtained for particulate ensembles in the regime where attractive particle interaction forces can be neglected. Indeed, cohesive forces may largely influence the dynamic behavior of the granular system, in particular leading to the emergence of clustering and the formation of particle agglomerates [48, 55]. Since it is known that the packing behavior and dynamic properties of cohesive granular materials may display strong dependence on the particle shape (see e.g. [56]), the present study should be extended in the future in order to account for cohesive forces between the granular particles. Therefore, our contribution should be now continued by investigating to which extent the answer to the question of the present manuscript's title is affected by the consideration of attractive particle interaction forces.

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