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Damping behaviors of granular particles in a vertically vibrated closed container

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ABSTRACT

Damping behaviors of granular particles in a quasi-two-dimensional (Q-2D) closed container subjected to vertical vibration are simulated by means of Discrete Element Method (DEM). Phase diagram and damping contour of vibrated granular particles in the amplitude-frequency plane of external excitation are obtained, which indicates six different damping phases of vibrated granular particles. Simulation results also reveal that three suspended states of vibrated granular particles (i.e., Leidenfrost effect, Buoyancy convection and Bidirectional Leidenfrost effect) display the higher damping capacity, and especially granular Leidenfrost effect demonstrates the optimal damping effect. Furthermore, the dissipation characteristic of granular Leidenfrost effect is analyzed respectively from the perspective of energy transformation and energy dissipation. The influence of the corresponding parameters (gap clearance, particle diameter and container dimension) on the three high damping suspended phases (HDSPs) of vibrated granular particles is explored. Finally, base on the rheological behavior of vibrated granular particles, a visualization method for evaluating the granular damping effect by DEM simulation is proposed for the first time, which may provide a new idea for designing optimal granular dampers.

1. Introduction

Granular materials subjected to vibration behave as better energy absorbers than continuous materials because of the contact loss between granular particles. The dissipation characteristic of granular materials has been applied as a damping technique, i.e., granular damping to dissipate vibration energy of various engineering structures [1–5]. However, there is not a unified and mature design criterion of granular dampers to date because of the highly nonlinear feature of vibrated granular systems [6–7] and the complex multi-parameter characteristic of granular dampers [8–9], which to some extent hinders the extensive application of granular damping in the engineering fields. How to obtain the optimal damping effect of granular materials has been the common concerned subject of scientists and engineers over the past two decades.

The earlier study of design methodology of granular dampers was reported by Fowler [10] who presented an analytical methodology to design particle damping for dynamic structures based on the particle dynamics method. Xu [11] developed an empirical method for particle damping design based on extensive experiments on three structural objects (steel beam, bond arm and bond head stand). Panossian [12–14] explored the optimal configuration for granular damping treatment through the use of ABAQUS FEM and a genetic optimization algorithm, and then used this method to optimize the design of granular damping for composite honeycomb structures. Sánchez [15–16] revealed by discrete element simulation the corresponding relationship between dynamic effective mass and dynamic effective damping of a single degree of freedom system treated with a granular damper, and further indicated the universal response of the optimal granular damping devices. All of above investigations about the optimal issue of granular damping are conducted in the presence of gravity and play good roles in promoting the development of this field. However, there still exist some problems in the optimal design of granular damping. On the one hand, regardless of the change of the motion state of damping particles within granular dampers, most previous researchers prefer to measure the power dissipation or estimate the damping performance of granular dampers through trial and error in specific initial conditions. The lack of essentially understanding the change of granular damping effect results in the higher design cost and longer design period of granular dampers. On the other hand, as far as we know, there is not to date a simple constitutive relation that can apply to all motion states of vibrated granular materials in the presence of gravity, which poses an obstacle to establishing a global dynamical model for aiding the optimal design of granular dampers quantitatively. Therefore, the existing methods for designing granular dampers, essentially phenomenological, are difficult to extrapolate beyond their respective experimental conditions.

In recent years, the energy dissipation characteristic of driven granular materials in the absence of gravity was also investigated by the Institute for Multiscale Simulation led by Prof. Thorsten Pöschel [17–19], which reported quantitatively that the most efficient damping effect of vibrated granular materials can be obtained in the phase transition from "collect-

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and-collide" regime to "gas-like" regime. Their studies reveal essentially the optimal damping mechanism of granular matter in the absence of gravity and have great application value in the optimal design of granular damping in the zero-gravity environment. However, granular materials submitted to vertical shaking in the presence of gravity can exhibit richer and more complex dynamical behaviors [20], such as formation of heaps [21,22], undulations and other wave patterns [23–25], arching [26], bouncing bed [27], convection [28,29], granular Leidenfrost effect [30, 31], and granular gas [32]. A granular damper looks like a vibrating closed container which is partially filled with a host of damping particles. In the presence of gravity, damping particles in a granular damper can also show different motion states as well as granular particles in a vibrated granular bed. The damping performance of granular dampers varies with the motion state of damping particles because that damping particles in different motion states demonstrate different damping effect [33–35]. What's the optimal phase of damping particles which can bring the optimal damping performance of granular dampers in the presence of gravity? It's very significant to explore the optimal damping phase of vibrated granular materials for aiding the optimal design of granular dampers in more engineering practices.

In our previous work [35], the rheology behaviors and optimal damping effect of granular particles in a 3D granular damper were investigated by cantilever system experiments and vibration table tests, where we observed that when the granular damper displayed the optimal damping performance granular Leidenfrost effect occurred in the granular damper. But, to our knowledge, both the damping performance of granular dampers and the motion state of damping particles are susceptible to the design parameters of granular dampers (such as geometry of the container, size of damping particles and packing configuration of damping particles, etc.) and the excitation situation. Thus, the motion state of the optimal damping particles in granular dampers should be further verified by varying the corresponding design parameters of granular dampers and external excitation condition. The current work is the follow-up study of the previous work, with the primary purpose of determining the motion state of the optimal damping particles in a Q-2D closed granular system subjected to vertical vibration by DEM simulation. Combined with the previous research results, the universality of the optimal damping capacity of granular Leidenfrost effect is further verified and three HDSPs of vibrated granular particles are revealed. Finally, based on the influence of the corresponding parameters on the three HDSPs, a visualization method for obtaining the optimal damping effect of vibrated granular materials by DEM simulation is first put forward.

2. Modeling

Our simulations are performed by the commercial software, EDEM, based on the Discrete Element Method (DEM) which is first developed by Cundall and Strack more than thirty years ago [36]. As an effective numerical method used to calculate the mechanical behaviors of granular materials, DEM has been applied extensively for the studies of various aspects of granular system [37–38]. Here, a brief description of the method is given for completeness. The details of this method can be found in Ref. [39].

2.1. Principles of DEM

In the DEM implementation, all particles are assumed to be rigid spheres and the particle displacement and contact area are assumed to be small relative to the particle sizes. As the external input energy causes container to oscillate, each particle may collide with many other particle as well as the walls of the container. Over small-step iterative computation cycles, all of these collisions will dissipate energy due to the loss of contacts and formation of new contacts, thus providing a damping effect on the container. The contact forces resulting from each contact of a pair of bodies are calculated based on a contact force model.

The contact force model used in this work is the Hertz-Mindlin (no slip) model, where the normal force model is based on Hertzian contact theory [40], the tangential force model is based on Mindlin-Deresiewicz work [41]. Both normal and tangential forces have damping components where the damping coefficient is related to the coefficient of restitution as described in Ref. [42]. The tangential friction force follows the Coulomb law of friction model [43], the rolling friction is implemented as the contact independent directional constant torque model [44]. Please see Refs. [39,45] for the details.

The displacement in the force-displacement contact model can be obtained by Newton's second law. The equations of motion for the ith particle are given as

$$\begin{cases} m_i\ddot{u}_i = \sum F \\ I_i\ddot{\theta}_i = \sum M \end{cases} \tag{1}$$

where $\ddot{u}_i$ is the acceleration of the ith particle, $\ddot{\theta}_i$ the angular acceleration of the ith particle, m_i the mass of the ith particle, I_i the inertia moment of the ith particle, F the resultant external force of the mass center of the ith particle, M the resultant external moment of the mass center of the ith particle. The dot above the variables represents the derivatives of the variables with respect to time. Given the resultant forces and moments, the position of the particle in one time step, Δt, is updated based on the equation:

$$\begin{cases} (u_i)_{t+1} = (u_i)_t + (\dot{u}_i)_{t+\frac{1}{2}}\Delta t \\ (\theta_i)_{t+1} = (\theta_i)_t + \left(\dot{\theta}_i\right)_{t+\frac{1}{2}}\Delta t \end{cases} \tag{2}$$

where the mid-interval quantities are computed based on a centered finite difference scheme of the velocities:

$$\begin{cases} (\dot{u}_i)_{t+\frac{1}{2}} = (\dot{u}_i)_{t-\frac{1}{2}} + \left[\sum F/m_i\right]_t\Delta t \\ \left(\dot{\theta}_i\right)_{t+\frac{1}{2}} = \left(\dot{\theta}_i\right)_{t-\frac{1}{2}} + \left[\sum M/I_i\right]_t\Delta t \end{cases} \tag{3}$$

As a result, in each time step new contacts are generated and some of the existing contacts are broken. The cycle of contact calculation is repeated for the next time step to track the movement of each particle at any time.

2.2. DEM model of granular system

In this work, we first focus our attentions to a Q-2D Perspex container ($L_x \times L_y \times L_z = 100\ \text{mm} \times 6\ \text{mm} \times 50\ \text{mm}$) which is closed and partially filled with granular particles and shaken vertically. The granular particles consist of 2000 spherical beads with diameter $d_p = 2$ mm and density $\rho_p = 7800\ \text{kg/m}^3$. The DEM model of granular system is shown in Fig. 1.

Under the random packing condition and with the entire system at rest in simulations, the Q-2D granular system is estimated to contain about 14 layers of granular particles. A series of sinusoidal excitations are applied to the container along the Z axis, and the displacement of container bottom from its initial position is described by $A\sin(\omega t)$ where A is the amplitude of the oscillatory motion, $\omega = 2\pi f$ the vibration angular frequency, f the vibrating frequency. The two control parameters in simulations are A and f. By altering A(0.5–5 mm) and f(15–150 Hz) respectively, a wider range of excitation intensity than that used in the previous experimental studies [35] can be covered.

The coefficient of restitution and coefficient of friction used in the simulations are set to 0.92 and 0.3 respectively, which is based on the previous experimental data [46] where the authors conduct a series of mechanics tests to acquire the approximate values of the two parameters of different granular matarials. In this work, 100 sets of simulations