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Bouncing behavior and dissipative characterization of a chain-filled granular damper

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ABSTRACT

We have experimentally investigated the bouncing behavior and damping performance of a container partially filled with granular chains, namely a chain-filled damper. The motion of the chain-filled damper, recorded by a particle tracing technology, demonstrates that the granular chains can efficiently absorb the collisional energy of the damper. We extract both the restitution coefficient of the first collision and the total flight time to characterize the dissipation ability of the damper. Two containers and three types of granular chains, different in size, stiffness and restitution coefficient, are used to examine the experimental results. We find that the restitution coefficient of the first collision of a single-chain-filled damper can linearly tend to vanish with increasing the chain length and obtain a minimum filling mass required to cease the container at the first collision (no rebound). When the strong impact occurs, the collisional absorption efficiency of a chain-filled damper is superior to a monodisperse-particle-filled damper. Furthermore, the longer the chains are, the better the dissipative effect is.

1. Introduction

In the field of civil engineering, machinery manufacturing, and aerospace industry, mechanical vibration often results in deterioration and even failure of equipment performance [1]. To address this issue, a vibration damper has been introduced to minimize the irritating vibration in a wide variety of applications, including vibration attenuation of metal cutting machines [2], turbine blade oscillation [3], vibrating antennae [4], sports equipment [5], medical tools [6], etc. In contrast with a conventional damper, a granular damper constitutes a promising technology for designing a next-generation damper, because it is efficient over a range of driven-frequencies, low-cost, long lifetime, easy maintenance and insensitive to external temperature [7–9]. The granular damper is a container partly filled with granular particles, which is attached to or embedded in a vibrating structure to weaken the external vibration. During the vibration, the energy or momentum from the vibrating structure is transferred to filling particles. Then the transferred energy is rapidly dissipated through the inter-particle friction and inelastic inter-particle and particle-wall collisions in finite time. As a result, the vibration is considerably attenuated or even eliminated.

The dissipation efficiency or performance of a granular damper relies on many system parameters, such as the geometry of the container, material properties of filling particles, and external vibrations. For example, the damping performance between a piston-type and a box-type granular damper was compared by a numerical simulation [10]. It was found that for the box-type damper, a uniform energy dissipation occurred because almost all particles contributed equally to the energy transfer. In contrast, for the piston-type damper, only local particles directly under the piston were involved in the energy transfer. In general, the box-type damper is more dissipation efficient than the piston-type damper only due to the geometry. As stated before, both the friction and collision contribute to the energy dissipation during a damping process. The collisional intensity and frequency of inter-particle collisions significantly depend on the fluidization extent of granular particles. Thus, collision contributes more to energy dissipation at low volume fraction; friction contributes more at low vibration frequency [11]. Furthermore, the relative significance between the friction and collision also depends strongly on the particle size [12]. The friction often plays a more important role in damping than the collision for small particles, but the collision becomes dominant as the particle size increases. These examples above show that for various situations an appropriate damper ought to be carefully chosen to achieve the optimal dissipation. It is therefore necessary to study the dissipation performance of a variety of granular dampers at different conditions, which may be potentially helpful for the engineering.

Almost most of previous efforts, if not all, focus on the granular damper filled with monodisperse particles. It is very attractive to compare the performance of energy dissipation between monodisperse particle-filled

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dampers and other dampers with different filling materials, which is potentially useful to design new granular damping systems. Compared with the monodisperse particle, the granular chain, mainly acting as an experimental analogy with molecular chains in most cases [13–15], is a promising candidate to provide competitive dissipation performance. Although considerable researches involving granular chains have been performed, the mechanical behavior of granular chains in many aspects did not receive enough attention yet [16]. The investigation on the chain-filled damper appears to be absent. The connection between the dissipation efficiency and the material properties of the damper needs to be explored in details.

In the manuscript, we experimentally study the dynamics of a chain-filled damper which bounces on a flat plate. Two kinds of chain-filled dampers, namely the single-chain-filled and multiple-chains-filled damper, are used to measure the restitution coefficient of the first impact ε_1 and total flight time τ under different conditions. The relationships between the measured quantities and the external parameters such as filling mass, chain length, and clearance length are presented. On the basis of the measurement, we qualitatively compare the dissipation efficiency of a chain-filled damper with a monodisperse-particle-filled damper. In addition, we rescale the ε_1 for a single-chain-filled damper, and find that these curves collapse together in a linear fashion in which the underlying physics can be explained by using a momentum exchange model.

2. Experimental setup

The experimental setup is demonstrated in Fig. 1. The damper consists of a cylindrical, empty container and granular chains filled into the container. The inner diameter of the container is 30 mm, and the outer diameter is 40 mm. The low end of the container is closed with a rounded acrylic cap. The upper end is sealed by a baffle so that the clearance length of the container, L, can be changed by adjusting the position of the baffle. The case $L = \infty$ corresponds to the absence of the baffle. The semi-rigid chains inside the container are composed of hollow, steel balls and steel rods, which are similar with those used in previous work [14,17]. The rod, as a link connecting balls, is not fixed, but rather retractile. In order to verify the generality and robustness of the measurement results, different containers and granular chains are employed in the experiment. The initial status of the granular chains inside the container is always set to be random packing to minimize the effect from different initial packing status. The stationary container is released from a given height, and bounces after it collides with a massive steel base below. To ensure the rebound stability of the bouncing container, a glass tube with a slightly larger diameter is used to align the container vertically, and a heavy base with smooth, flat surface is placed on a cushion. With using a free-fall experiment to examine the air drag on the motion of the damper, it is found that the air drag appears to be negligible. A high-speed camcorder (Phantom V7.3) tracks the trajectories of the bouncing container in real time, and thus a wealth of information such as restitution coefficient can be accurately extracted by an imaging algorithm. To confirm the generality of the experiment results, two different containers A1 and A2 (the geometries of two containers A1 and A2 are same), and three types of chains C1, C2 and C3 are used (see details in Table 1 for their material properties). Unless otherwise noted, each measurement was repeated 5 times.

3. Results and discussion

3.1. Single-chain-filled damper

In this section only one single chain is placed into the container, and the filling mass M_{fill} is proportional to the chain length N, $M_{fill} = Nm_\rho$, where m_ρ is the mass per unit length of a chain. Unless specified otherwise, the upper end of a container is always free, namely $L = \infty$. Fig. 2(a) shows that the vertical position h of the geometric center of a container is plotted as a function of time for different filling masses, or chain lengths. The first rebound height decreases as the chain length (the filling mass) increases. The restitution coefficient $\varepsilon = -{}^{V_a}/_{V_b}$ is displayed in Fig. 2(b) for the first five impacts, numbered by n_b, where V_a and V_b are the velocities of the container after and before the impact, respectively. For the first impact, the restitution coefficient ε_1 drops with the increase of the chain length, namely the filling mass. For the damper

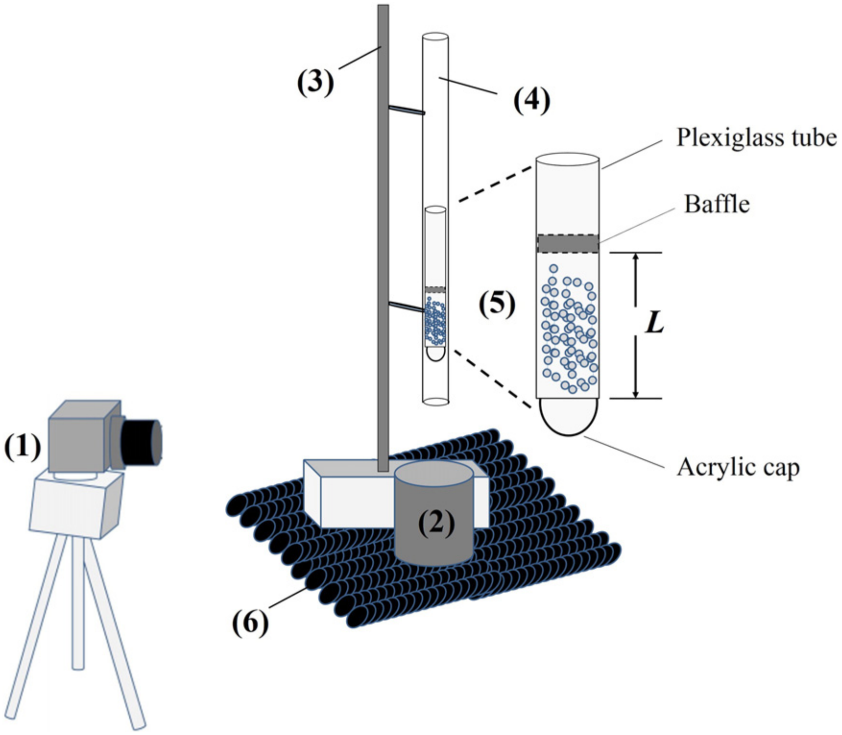

Fig. 1. Schematic of the experimental setup, not to scale. (1) High-speed camcorder (2) steel base, (3) mounting bracket, (4) glass tube, (5) plexiglass container, (6) cushion. The enlarged portion of the plexiglass container shows the basic structure, the description of which is detailed in the text.