

Damping Characterization of Friction Energy Dissipation for Particle Systems Based on Powder Mechanics and Experimental Verification

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Abstract: We established a friction energy dissipation model for particle damping based on powder mechanics. We investigated the influence of geometric features of the damper on damping characteristics; and the geometric feature studied was the depth and length of the rectangular particle container. The work done by the frictional force between the particle layer and the effect of particle filling rate on the vibration damping characteristics was also explored. We analyzed the friction energy dissipation model, and the relationship between the particle filling rate and the vibration damping. The experimental results show good agreement with the friction energy dissipation model, which verifies the proposed simulation prediction. The results have shown that the particle damping technology can greatly consume the structure kinetic energy, and the vibration reduction effect of particle damping depends mainly on the interaction of the particles near the top. A proper filling rate of particle systems can result in an optimal effect on vibration reduction, which will provide the engineering applications with the theoretical guidance and design criteria. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Particle systems, Powder mechanics, Friction energy dissipation, Experimental verification, Damping characterization.

1. Introduction

Particle damping performs the function of vibration reduction by dissipating kinetic energy between particles through friction and inelastic collisions [1, 2]. Using particle damping technology, vibration energy can be reduced under extreme conditions. The technology has many advantages, such as reduced impact force, reduced effect on structures, and good adaptability to a wide temperature range [3-7]. Particle damping is a

passive damping technique through which a high level of mechanical damping can be achieved [8-10]. These unique features provide for broad application prospects. Its high performance in vibration and noise reduction has led to advances in this technology through research and development [11, 12]. Currently, the research in this field is still at an initial stage. The experimental research is still not perfect, and the theoretical research is also in the exploratory stage. The theoretical methods adopted in the research of the particle damping technology mainly

include the discrete element method [13-16], the collision theory [17, 18], the regression design [19, 20], optimization design [21] etc., and many new theories and methods are constantly introduced into the research of particle damping [22-27].

To further particle damping technology, powder mechanics based on the interaction between particles plays an important role as large quantity of particles is involved [28, 29]. When the excitation level is low and the particle filling rate is fast, most of the particles cluster together. Collisions between particles are weakened, and vibration energy is mainly dissipated through friction between particles and between the particles and the container wall. Powder mechanics theory is effective for describing particle damping characteristics, and requires less computation than other methods.

We began by establishing a model for particle containers of rectangular shapes based on powder mechanics. Second, the corresponding friction energy dissipation of particle damping was calculated, and the effect of the particle filling rate on the vibration reduction characteristics was explored. Third, the friction energy dissipation model was verified, and comparisons of experimental and theoretical results were made. Finally, an analysis method and design criteria were developed for the vibration reduction of particle damping.

2. Effect of Particle Container Geometry on Vibration Reduction

For different applications, the cavity shape of the particle damper can be rectangular, cylindrical, or spherical. For example, the outer surface of the cavity of the particle damper applied in helicopter rotor blades is an irregular curved surface. We explored the effect of geometrical characteristics of a particle container with rectangular cross-section on the particle damping vibration reduction performance.

The discrete element method (DEM) can be used to simulate the response of dampers containing small numbers of particles. A simple, approximate assessment method, such as the consideration of static pressure, is of particular value in the design of dampers where large numbers of particles (well in excess of 5×10^6 particles for the dampers) make the DEM method computationally very demanding. In this paper, a single parameter K is used to describe the way in which the stress field of the particles tends to be redirected perpendicularly to the initial load [22].

If the total height of the particle container is H , the ratio of the length L_1 to the width L_2 is $\alpha = L_1/L_2$, a mechanical model can be established. In Fig. 1, the particle layer of infinitesimal thickness dh is considered. The forces imposed on this particle layer are balanced in the vertical direction by

$$2F_1 + 2F_2 + F_3 = F_4 + G, \quad (1)$$

where F_1 and F_2 are the forces of the side walls of the rectangular container acting on the particle layer under study, and F_3 and F_4 are the forces acting on the particles of the lower part and the upper part of this particle layer.

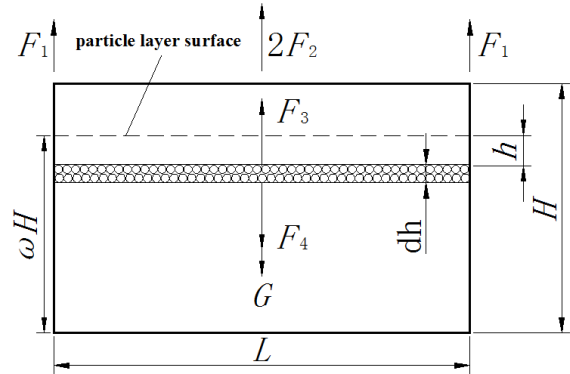


Fig. 1. Stress analysis model for a particle layer with the rectangular damper cross-section.

The following formulas are used to calculate the relevant forces involved:

$$F_1 = \mu_s K \sigma_p L_1 dh, \quad (2)$$

$$F_2 = \mu_s K \sigma_p L_2 dh, \quad (3)$$

$$F_3 = (\sigma_p + d\sigma_p) L_1 L_2, \quad (4)$$

$$F_4 = \sigma_p L_1 L_2, \quad (5)$$

$$G = \rho g L_1 L_2 dh, \quad (6)$$

where G is the gravitational force of the particle layer, μ_s is the friction coefficient between the particle and the inner wall of the damper, K is the Janssen coefficient, σ_p is the static stress in the vertical direction of the particle layer, ρ is the bulk density of the particle material.

If Eqs. (2)–(6) are substituted for F_1 – F_4 as well as G in Eq. (1), the integration gives:

$$\sigma_p \exp\left[\frac{2\mu_s K(L_1 + L_2)h}{L_1 L_2}\right] = \frac{\rho g L_1 L_2}{2\mu_s K(L_1 + L_2)} \exp\left[\frac{2\mu_s K(L_1 + L_2)h}{L_1 L_2}\right] + C \quad (7)$$

where C is the integration constant determined from initial conditions. When the initial pressure of the upper surface of the particles is 0, that is, $h=0$, $\sigma_{p0}=0$, Eq. (7) is reduced to

$$\sigma_p = \frac{\rho g L_1 L_2}{2\mu_s K(L_1 + L_2)} [1 - \exp(-\frac{2\mu_s K(L_1 + L_2)h}{L_1 L_2})], \quad (8)$$

3. Analysis of Frictional Energy Dissipation

When the system is subjected to a harmonic excitation, and reaches the equilibrium state, with low vibration amplitude and a filling rate of more than 80 %, the distribution of overall particles in the container is in the recurrent state: going from thin to thick and then back to thin again.

3.1. Slippage between Particle Layers

From a microscopic point of view, particle movements will keep reciprocating. Because the relative velocity among the particles is relatively small (as the amplitude of excitation force is less than 1/5 of system gravity), the collisional energy

consumption among the particles can be neglected, and the frictional energy dissipation among particles is dominant for particle damping. It can be assumed that slippage from the thinnest to the thickest (or from the thickest to the thinnest) for an arrangement of particles can be documented every cycle, as shown in Fig. 2.

When the arrangement is the thinnest, the distance between the upper two particles on the same layer is $2r$. As shown in Fig. 2, when the arrangement is the thickest, this distance becomes $4\sqrt{3}r/3$ [8], leading to a change in distance between two adjacent particles on the same layer.

$$\Delta l = \left(\frac{4\sqrt{3}}{3} - 2\right)r, \quad (9)$$

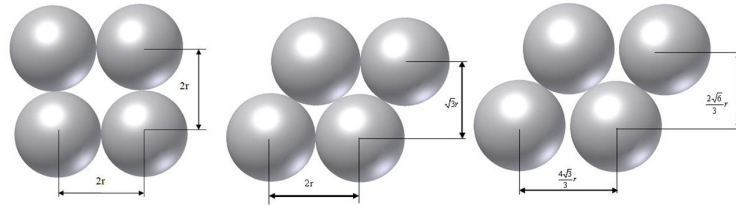


Fig. 2. The thinnest and thickest arrangements between the upper and lower particle layers.

3.2. Model of Frictional Energy Dissipation

During the relative slippage process, the frictional force does work, and dissipates the energy between particle layers. It can be concluded, based on energy conservation law, that the kinetic energy between layers will decrease, and the vibration of the system will be weakened, so the purpose of vibration and noise reduction can be achieved.

The work done by the frictional force between the i^{th} particle layer and the $(i+1)^{\text{th}}$ particle layer due to the relative slippage is

$$W_i = f_{h_i} \Delta l_i = \sigma_{p_i} \mu_{p_i} S \Delta l_i, \quad (10)$$

where W_i is the work done by the frictional force f_{h_i} between the adjacent particle layers when the particle layer depth is h_i , Δl_i is the relative displacement of the particle layer i with respect to layer $(i+1)$, σ_{p_i} is the vertical stress for particle layer i , μ_{p_i} is the friction coefficient between particles, and S is the area for rectangular cross-section of the particle container, $S=L_1L_2$.

Assuming $h_i = \omega H$, the maximum frictional energy dissipation of particle damping is

$$W = \sum_{i=1}^N \sigma_{p_i} \mu_{p_i} S \Delta l_i, \quad (11)$$

where N is the number of particle layers in the container, $N = \omega H/d$, and d is the particle diameter, $d = 2r$.

As slippage from the thinnest to the thickest for the arrangement of particles can be completed every cycle and Δl is the maximum slippage between layers, the maximum frictional energy dissipation of particle damping is

$$W = \frac{2\sqrt{3}-3}{6} \sum_{i=1}^N \frac{\mu_p \rho g L_1^2 L_2^2 d}{\mu_s K (L_1 + L_2)} \left\{ 1 - \exp \left[\frac{-2\mu_s K (L_1 + L_2) h_i}{L_1 L_2} \right] \right\} \quad (12)$$

4. Experimental Verification and Discussion of Results

4.1. Dependence of Stress in the Particle Layer

The parameters are assumed to be $\mu_s=0.55$ (steel to aluminum oxide), $K=0.7$, $\mu_p=0.3$ (aluminum oxide), $\rho=1.8\text{g/cm}^3$, and $\sigma_{p0}=0$ (particles are in equilibrium under their own weight).

We analyzed the variation of the stress of the particle layer σ_p in the vertical direction with the depth h of the particle layer. Rectangular particle containers with H of 0.25, 0.5, 1, and 1.5 m were used to examine the effect of the surface depth h of the particle layer on the applied stress σ_p in the vertical direction.

As shown in Fig. 3, the stress in the particle layer increases as the depth of the particle layer increases. The only difference is that when H is small, the rate of change of the stress of the particle layer is large, and the maximum stress is low. When H is 1.5 m, the maximum value of the stress of the particle layer is approximately 4,868 Pa. When H increases, the stress of the particle layer approaches a maximum value. As the surface depth exceeds a certain value, the motion capacity of the particle layer becomes weak, but the particles at this depth can maintain the rigidity of the whole system.

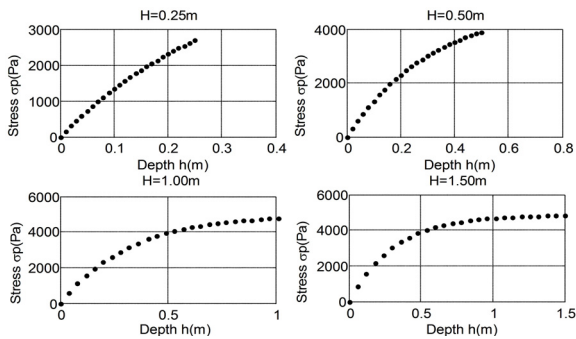


Fig. 3. Effect of h on the stress σ_p of the particle layer for various H .

The relationship between the particle layer depth h and the ratio of length to width of the particle container α and the stress σ_p is shown in Fig. 4. With increasing α , the pressure saturation occurs preferentially at the surface of the deeper particle layer. For a given excitation force, the stress σ_p varies with the shape differences, which result from the cross-section and ratio of length to width of particle container changes.

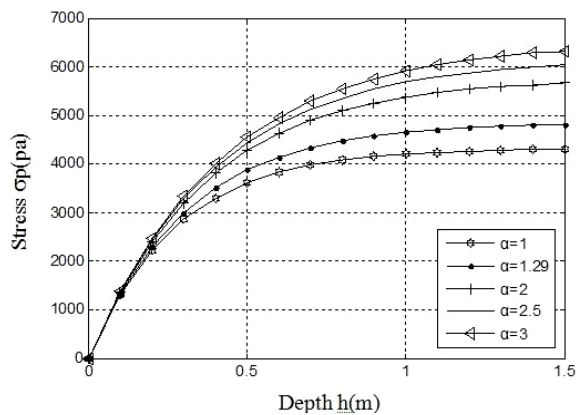


Fig. 4. The effect of particle layer depth h and α of the particle container on the static stress distribution.

The effects of h and filling rate ω on the stress σ_p of the particle layer in the vertical direction were investigated, as shown in Fig. 5. With the increase in the filling rate, the stress of the particle layer at the same position increases. However, an increase in the filling rate also results in an increase in the total quantity of the particles participating in movement and collisions in the container, therefore enhancing the vibration damping effect.

Fig. 6 shows the frictional energy dissipation of particle damping calculated according to Eq. (12) under various particle filling rate. It shows that the particle filling rate has a significant influence on the frictional energy dissipation. When the actual filling rate reaches 100 %, there is no friction displacement space for individual particles, and the friction between particles is weakened, resulting in the decrease of the friction energy dissipation amount. It can be seen from this plot that the frictional energy dissipation would increase when the particle size increases at the same particle filling rate.

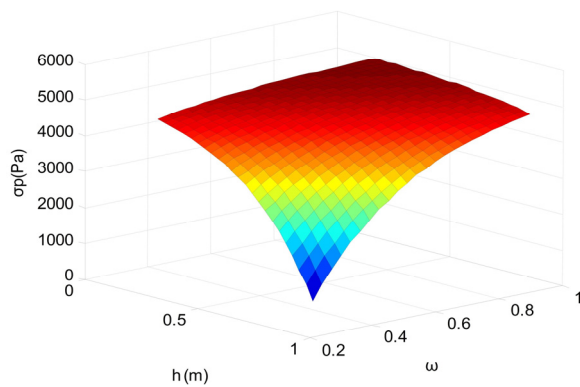


Fig. 5. Variations of σ_p with h and ω .

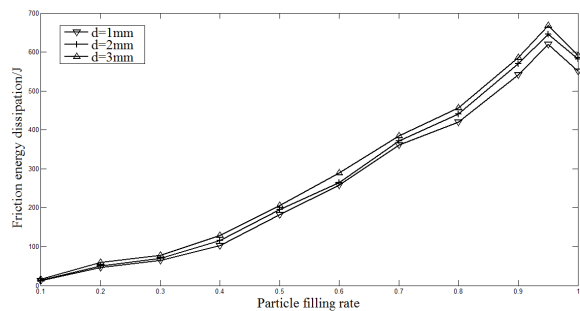
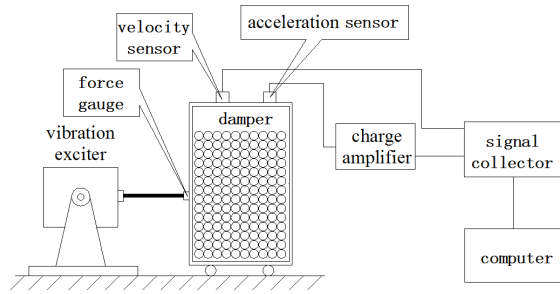


Fig. 6. The calculated friction energy dissipation of the particle damping vs. the particle filling rate.

4.2. Experimental Verification

We performed particle vibration reduction experiments to investigate the effect of the filling rate on the vibration reduction performance of particle damping. The schematic diagram and photographic picture of the particle vibration experiment system is shown in Fig. 7.

The experimental setup mainly includes four parties – experimental components, excitation equipment, sensing equipment and analysis equipment. The test material is aluminum oxide particles with a diameter of 1 mm. As the excitation source, the exciter was installed on the particle damper to generate the excitation signal. The acceleration and speed were measured at various positions in the experimental box through acceleration sensors and speed sensors, and the signals were acquired by a data collection instrument via a power amplifier, and transferred to a dynamic analysis system for processing.



(a) Schematic diagram



(b) Photographic picture

Fig. 7. Schematic diagram of the experiment system.

The friction energy dissipation of the particle damping in experiment is given by

$$W_{exp} = W_{exc} - E_{kin} \quad (13)$$

where W_{exp} is the friction energy dissipation in experiment, W_{exc} is the work done by excitation which can be measured through the force gauge, and E_{kin} is the kinetic energy measured through the velocity sensor and acceleration sensor.

When the amplitude of the excitation force is less than 1/5 of system gravity, the particle system is mainly in a static friction state and a sliding friction state and the frictional energy dissipation among particles is dominant for particle damping. Fig. 8 compares theoretical and experimental results of the relationship of damper frictional energy dissipation vs. filling rate of the aluminum oxide particles. The

vibration damping effect is enhanced with increasing the filling rate, but at approximately 95 %, the effect falls off. The theoretical results and experimental results are in good agreement. This proves the rationality of particle frictional energy dissipation theory model.

It would appear from the data presented in Fig. 8 that the theoretical results are slightly less than experimental results. And the reason for such deviation is that in the theoretical computation, the dissipation model only contained the frictional energy, however, in the experiment many mechanisms of energy dissipation such as the friction, the collision, the noise and the adhesion force were contained.

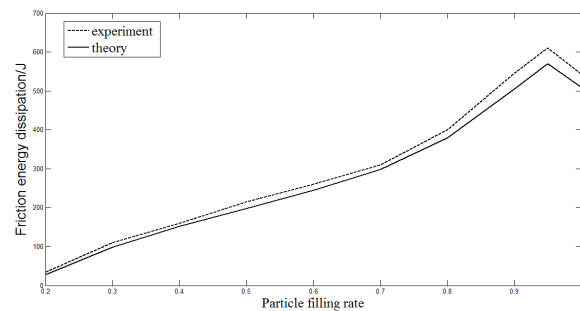


Fig. 8. Comparison of the experimental and theoretical results.

The effect of the filling rate on the particle vibration reduction in time-domain experiment is shown in Fig. 9, which the excitation force is steady sine wave. The particle filling rates were 0 %, 50 %, 95 %, 100 % respectively for these tests. When the particle filling rate decreases, the vibration reduction effect is reduced because there is only collision between particles and the collision probability is low. When the particle filling rate is more than 95 %, the quantity of the particles occurring collision reduces and the vibration damping effect also decreases. So, when the vibration reduction effect is optimal, there shall be an optimal particle filling rate, which will provide the engineering applications with the theoretical guidance and design criteria.

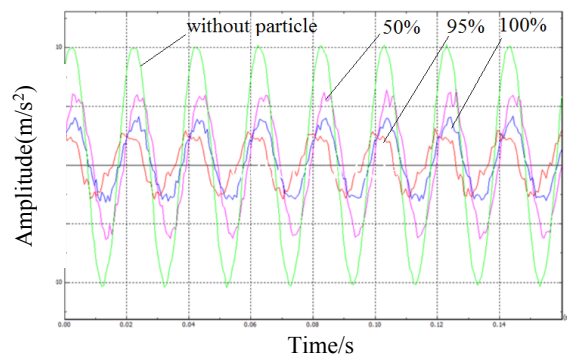


Fig. 9. Time-domain acceleration curve of the damper at various filling rates.

The experimental results of the acceleration transfer function at various filling rates are shown in Fig. 10. The particle filling rates were 0 %, 50 %, 95 %, 100 % respectively for these tests. The vibration damping effect increases with the increase in the particle filling rate, but after the particle filling rate reaches a certain value, the vibration damping effect reduces. The transfer functions of the filling rate on the particle vibration reduction are similar to the time-domain trend. It is interesting to note that the FRF curves move to the low frequency with the increase of particle filling rate. For the filling rate of 95 %, the FRF curve is relatively flat and no obvious resonance peak appears, with the best effect of vibration reduction.

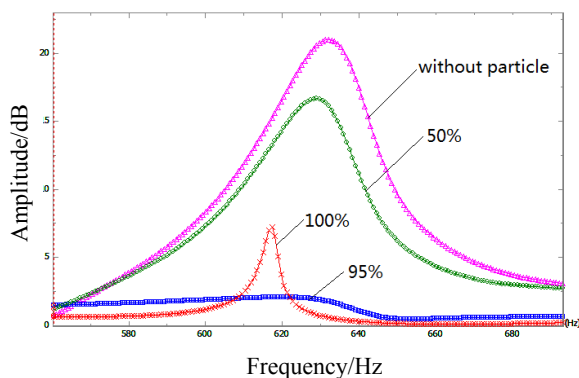


Fig. 10. Results of the acceleration transfer functions at various filling rates.

5. Conclusions

Based on the theories of powder mechanics, the effect of the geometric characteristics of the particle container on the vibration reduction performance were theoretically deduced, simulated, and experimentally analyzed. The factors and rules affecting stress of the particle layer were studied, and the following conclusions were drawn:

1) The vibration reduction effect of particle damping depends mainly on the interaction of the particles near the top. As the surface depth exceeds a certain value, the motion capacity of the particle layer becomes weak, but the particles at this depth can maintain the rigidity of the whole system.

2) At the same depth, the stress of the particle layer increases with increasing α , and makes the liquid-like motion of particles more difficult.

3) With an increase in filling rate, the stress of the particle layer at the same position increases. However, an increase in filling rate also increases the total quantity of particles participating in collisions and frictional contact in the container. This means that a proper filling rate can result in an optimal effect on vibration reduction, which will provide the engineering applications with the theoretical guidance and design criteria.

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