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# PARTICLE DAMPING FOR VIBRATION SUPPRESSION OF A CLAMPED PLATE

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**Key words:** Granular materials, DEM, Vibration suppression, Contact problems.

**Abstract.** In this paper, analytical and experimental studies of the vibration suppression of a square plate with a particle damper are discussed. The primary objective of this paper is to construct an analytical model to simulate the transient impact response of a plate with a particle damper. In the experimental approach, an acrylic resin plate with all sides clamped was used. The transient vibration of the plate caused by the impact of a steel ball was measured with a laser displacement sensor. The effects of the mass ratio, particle material and cavity shape on the damping efficiency were investigated. To capture the behavior of the entire system in detail, an analytical model based on coupling between the finite element method and the discrete element method was constructed. Rayleigh damping was used to approximate the damping behavior of the plate without granular materials. Comparison between the experimental and analytical results showed that accurate estimates of the response of a plate can be obtained.

## 1 INTRODUCTION

Particle damping is a typical cost-effective technique for vibration suppression. It involves the use of small metallic or plastic particles contained in a cavity of a primary mass. The damping effect results from the exchange of momentum during the impact of granular materials against the wall of the cavity. Owing to the simplicity of their construction, particle dampers have been widely used for structural damping applications in boring bars [1], printed circuit boards [2] and double-layered ceilings [3].

Many experimental and analytical studies have demonstrated the effectiveness of particle dampers. In the experimental studies, the effects of the mass ratio, particle size, cavity dimensions and excitation level on the efficiency of the damping system were investigated [4]. In the analytical studies, the discrete element method (DEM) [5, 6] and the direct simulation Monte Carlo approach [7] were used to predict particle damping. Most previous theoretical analyses have focused on single-degree-of-freedom systems with particle dampers. Recently, some researchers have been studying the vibration characteristics of continuous structures with particle dampers [8, 9]. However, these studies were limited to predicting the dynamic responses of a cantilever beam with particle dampers.

In this paper, analytical and experimental studies of the vibration suppression of a square plate with a particle damper are discussed. The primary objective of this work is to construct an analytical model to simulate the transient impact response of a plate with a particle damper. In the experimental approach, an acrylic resin plate with all sides clamped was used. The transient vibration of the plate caused by the impact of a steel ball was measured with a laser displacement sensor. In the theoretical analysis, the simulation was performed by combining the finite element method (FEM) with the DEM. The damping characteristics of the plate without granular materials were approximated by Rayleigh damping.

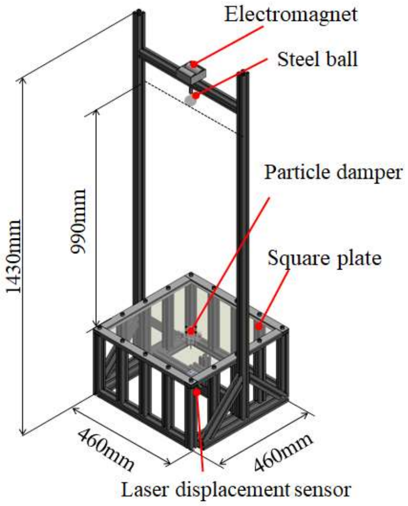


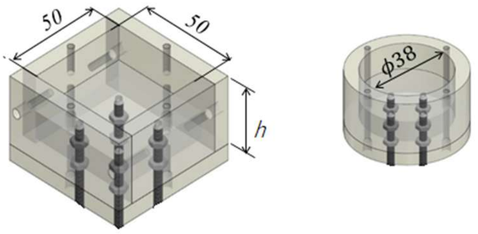
**Figure 1**: Experimental apparatus

## 2 EXPERIMENT

### 2.1 Experimental apparatus

Figure 1 shows the experimental apparatus used in this study. A square plate made of acrylic resin was clamped on all sides. The plate was 400mm wide and 5mm thick. A container enclosing granular materials was attached to the center of the plate as a particle damper. An electromagnet was located above the plate. A steel ball was attached to the electromagnet as an impactor. Upon cutting off the current to the electromagnet, the ball collides with the center of the plate and the plate is allowed to oscillate freely. The motion of the plate was measured with a laser displacement sensor. A ball with a diameter of 12.7mm was dropped from a height of 990mm.

Figures 2(a) and 2(b) show the shapes of the containers of the particle damper. To investigate the effect of the shape on the damping performance, cubic and cylindrical containers were used. Also, the effects of the mass ratio λ and particle material on the damping performance were investigated.



(a) Cubic container (b) Cylindrical container

**Figure 2**: Shapes of containers of the particle damper

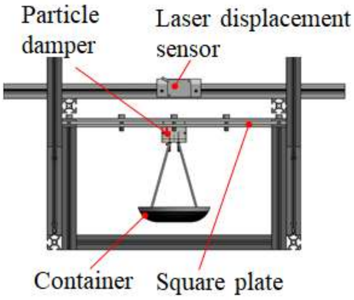


**Figure 3**: Measurement of the spring constant

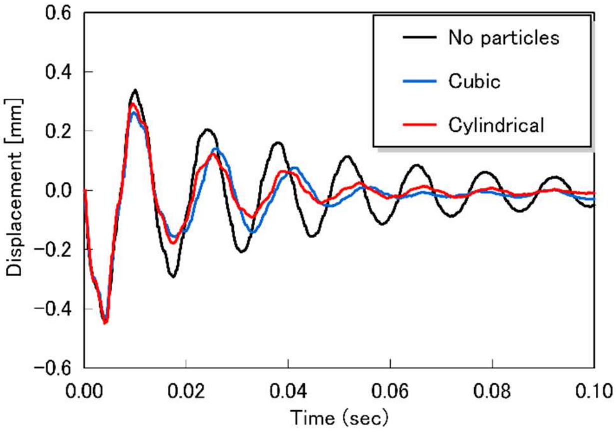


**Figure 4**: Effect of the shape of the container
($h$=8.0mm, $\lambda$ =14.6%, $\phi$ 6.35mm, copper particles)

Here, the mass ratio $\lambda$ is the total mass of the granular materials divided by the equivalent mass of the first mode of the plate. The equivalent mass was obtained as follows. A container was hung from the plate and a predetermined mass was placed on the container. The displacement of the center part of the plate was measured with the laser displacement sensor, which was installed as shown in Figure 3. Because the weight is proportional to the displacement, the spring constant $k_1$ was determined from the proportionality constant. Then, the equivalent mass is given by

$$m_1 = k_1/(2\pi f_{n1})^2, \tag{1}$$

where $f_{n1}$ is the fundamental frequency of the plate.

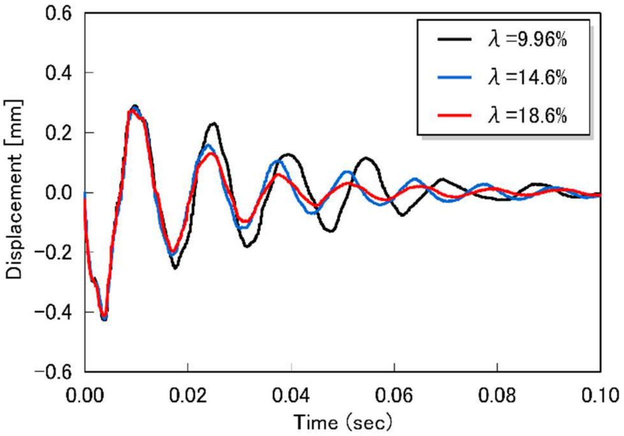


**Figure 5**: Effect of the mass ratio
(cubic container, *h*=8.0mm, ϕ 4.0mm, steel particles)

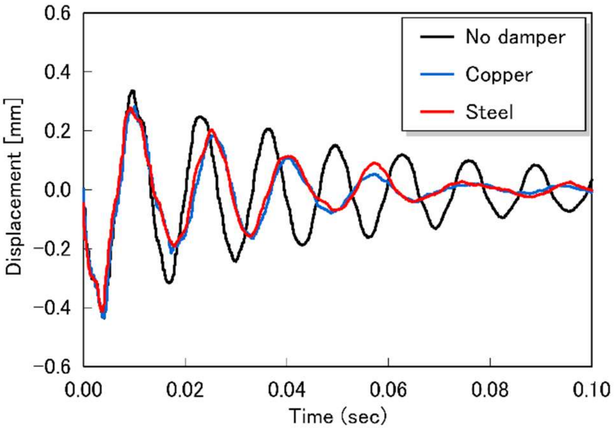


**Figure 6**: Effect of the particle material
(cubic container, *h*=8.0mm, λ =14.6%, ϕ 6.35mm)

## 2.2 Experimental results

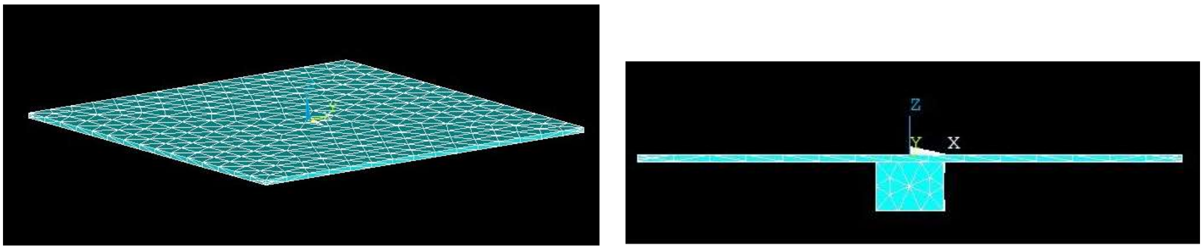
Figure 4 shows the effect of the shape of the container on the damping performance. This figure also shows a plot of the displacement of the center of the plate versus time. It is clear that damping is efficient in the presence of granular materials. There is little difference in the time history between the cubic and cylindrical containers. Therefore, it is shown that the shape of the container does not affect the damping performance.

Figure 5 shows the effect of the mass ratio λ on the damping performance. It is shown that the damping performance increases with the mass ratio. This appears to be because more momentum transfer occurs as the mass ratio increases.

Figure 6 shows the effect of the particle material on the damping performance under the same mass ratio. Although the same mass ratios were used for the steel and copper particles, the number of steel particles was different from the number of copper particles owing to the density difference. It is clear that the damping performance is independent of the particle material.

## 3 NUMERICAL METHOD

To capture the behavior of the entire system in detail, the equations of motion for the plate and each particle should be solved. In this paper, physical interpretations of the damping behavior of the plate with the particle damper are given with the help of coupled FEM-DEM simulations. In this study, the simulation code was developed using C++ language.



(a) Single view drawing (b) Side view

**Figure 7**: FEM mesh representing the plate

### 3.1 Model of the vibration system

Figure 7 shows the FEM mesh representing the plate with the particle damper used in this numerical analysis. The plate was modeled with tetrahedral elements. The equation of motion for the plate is given by

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = \{f\}, \tag{2}$$

where $\{u\}$ is the displacement of each node and $[M]$, $[C]$ and $[K]$ are the mass, damping and stiffness matrices, respectively. The dots denote time derivatives and $\{f\}$ is the external force vector. Rayleigh damping was used to approximate the damping behavior of the plate without granular materials.

The equation of motion for particle $i$ is given by

$$\begin{aligned} m\ddot{\boldsymbol{p}}_i &= \boldsymbol{F}_i - m\boldsymbol{g} \\ I\ddot{\theta}_i &= \boldsymbol{T}_i \end{aligned}, \tag{3}$$

where $m$ is the particle mass, $I$ is the moment of inertia of the particle, $\boldsymbol{p}$ is the position vector of the center of gravity of the particle, $\theta$ is the angular displacement vector, $\boldsymbol{F}_i$ is the sum of the contact forces acting on the particles and $\boldsymbol{T}_i$ is the sum of the torque generated by the contact forces.

The normal component of the contact force acting on a particle is given by [10]

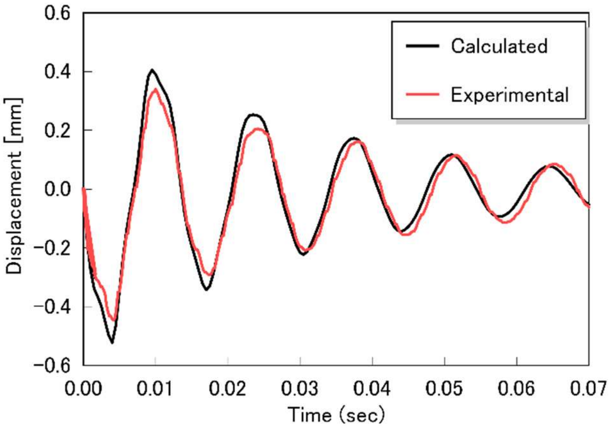
$$f_N = k_N {\delta_N}^{3/2} + \eta_N \dot{\delta}_N, \tag{4}$$

$$\eta_N = \alpha\sqrt{mk_N}\delta_N^{1/4}, \tag{5}$$

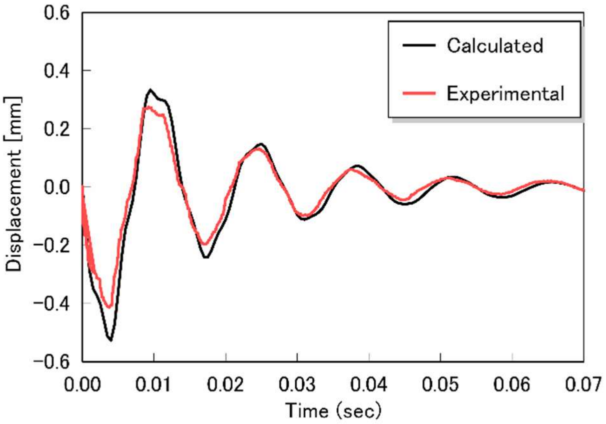
where $\delta_N$ and $\dot{\delta}_N$ are the normal displacement and velocity of particle $i$ relative to particle $j$, respectively. The value of $\alpha$ is determined by the coefficient of restitution.

The tangential component $f_T$ of the contact force is given as follows if there is no slipping [10]:

$$f_T = k_T {\delta_T}^{1/2} \delta_T + c_T \dot{\delta}_T, \tag{6}$$



(a) Cubic container without granular materials



(b) Cubic container with granular materials
(*h*=8.5mm, $\lambda$=18.8%, $\phi$ 4.0mm, steel particles)
**Figure 8**: Experimental and analytical results

where $\delta_T$ and $\dot{\delta}_T$ are the tangential displacement and velocity, respectively.

In the case of slipping, the following equation is satisfied:

$$f_T > \mu_s |f_N|, \tag{7}$$

where $\mu_s$ is the coefficient of static friction.

When Eq. (7) is satisfied, the tangential component $f_T$ of the contact force is expressed as

$$f_T = -\mu_k f_N \dot{\delta}_{T/} |\dot{\delta}_T|, \tag{8}$$

where $\mu_k$ is the coefficient of kinetic friction. The contact force acting on the impactor was also calculated using Eqs. (3)–(8).

The procedure for the calculation is as follows. First, collision detection is performed and the contact force is calculated. This force is used to analyze the vibration of the plate by the FEM. Then the particle motion is analyzed using Eq. (3). The same procedure is repeated for all the particles.

### 3.2 Analytical results

Figures 8(a) and 8(b) show experimental and analytical results in the same plane as in Figure 4. For the cases in Figures 8(a) and 8(b), the cubic containers without and with granular materials, respectively, were used. As shown in Figures 8(a) and 8(b), it was found that the calculated results agree with the experimental results. Therefore, the analytical approach in this study is very effective for estimating the damping effect in the dynamics of a plate with granular materials.

## 4 CONCLUSIONS

The dynamics of a square plate with a particle damper was investigated both experimentally and analytically. The combination of the finite element method with the discrete element method yielded an analytical solution for estimating the transient impact response of a plate with a particle damper. From the experimental results, it was shown that the shape of the container does not affect the damping performance. It was also shown that the mass ratio affects the damping performance whereas the particle material does not affect the damping performance. An analytical approach using the coupled FEM-DEM is very effective for estimating the transient vibration of a plate with a particle damper.

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