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EXPERIMENTAL AND NUMERICAL STUDIES ON THE EFFICIENCY OF DAMPING UPON HORIZONTAL STIRRING OF GRANULAR MATERIALS

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Abstract. In this study, the damping torque exerted on a horizontally rotating blade in granular materials under gravity was investigated. To capture the stirring behaviour of the granular materials in detail, a mechanical stirring apparatus was fabricated. The rotating blade was driven sinusoidally by a shaker through a ball screw mechanism. It was found that energy dissipation depends on various parameters such as particle material and particle size. Energy dissipation was also calculated using the EDEM® software based on the discrete element method. To verify the validity of the numerical simulation model, numerical simulation results were compared with experimental results.

Keywords: Granular Materials, DEM, Mechanical Stirring, Dissipated Energy.

1 INTRODUCTION

Damping devices using granular materials are often used to suppress vibrations occurring in mechanical units. Since, unlike oil dampers, they use particles only, their damping performance with appropriate materials is independent of temperature. Particle dampers are typical damping devices [1], in which granular materials are placed inside a container that is attached to a vibrating structure. When the primary mass vibrates, the granular materials inside the container also start to move and collide with the container walls. As a result, the vibration of the primary mass is attenuated through momentum transfer [2]. To move the granular materials in the container, the inertial force acting on the granular materials should be greater than the frictional forces between the granular materials and the container's floor. Therefore, particle dampers do not work at a low acceleration. In such situations, particle tuned mass dampers have been used [3]. Since such dampers consist of a tuned mass damper with granular materials, a frequent maintenance of the tuned mass damper is required. Shimoji et al. investigated the damping torque exerted on a rotating blade in granular materials [4]. They showed that the damping torque can occur at a low acceleration. However, in their study, they focused on the damping torque exerted on the rotating blade around the vertical axis.

The objective of our study is to investigate the energy dissipated by stirring granular materials in a horizontal container using a mechanical stirring apparatus with a flat blade. The blade was rotated sinusoidally by a shaker through a ball screw mechanism. It was found that energy dissipation depends on various parameters such as particle material, packing ratio and particle size. To examine the behaviour of the entire system in detail, dissipated energy was calculated using the EDEM® software based on the discrete element method. We calculated the damping torque exerted on the rotating blade, whose results were compared with the experimental results to verify the validity of the simulation.

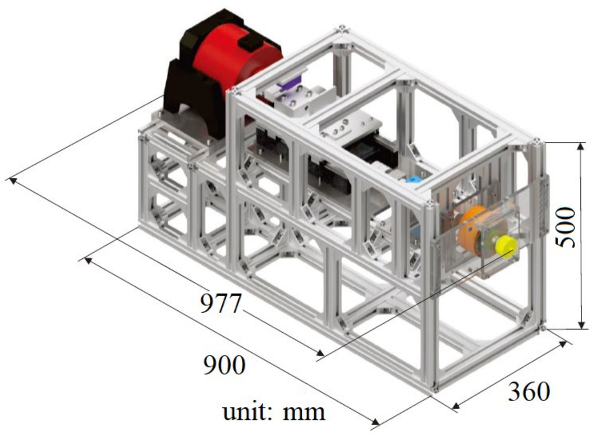


Figure 1: Mechanical stirring apparatus

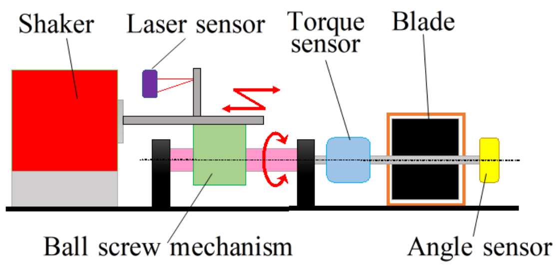


Figure 2: Device configuration and sensors

2 EXPERIMENT

2.1 Mechanical stirring apparatus

Figure 1 shows the mechanical stirring apparatus used in this study. The device configuration and sensors are shown in Figure 2. The rotating blade was driven sinusoidally by a shaker through a ball screw mechanism. The displacement of the shaker and the rotation angle of the blade were measured using a laser displacement sensor and an angle sensor, respectively. The stirring torque exerted on the blade was measured using a torque sensor. The relationship between the displacement x of the shaker and the rotating angle θ of the stirring is given by

$$\theta = 2\pi \frac{x}{l} \tag{1}$$

where l is the lead of the ball screw.

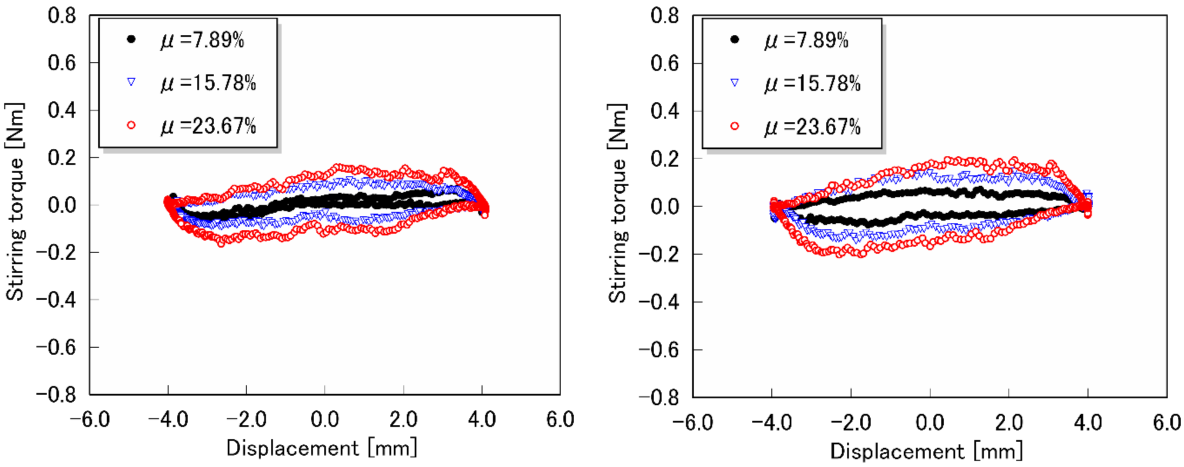
The amplitude of the shaker was 4mm and the frequency was set arbitrarily. The lead of the ball screw was 25mm. The granular materials consisted of spherical particles with the same radius, and three different materials were used as source of the particles: steel, glass and PMMA balls. The stirring container was made of PMMA and had a cylinder-like shape with an internal radius of 40mm and a height of 50mm. The measured data was retrieved after 40s of shaking.

The average torque for 30 cycles was used for temporal variation.

2.2 Effect of packing ratio μ

The effect of packing ratio μ on stirring torque can be seen in Figures 3(a) and (b). The packing ratio is defined as the ratio of the total volume of granular materials to the internal volume of the cylindrical container. In these figures, the area of the loop equals the dissipated energy during one cycle. As shown in these figures, the area of the loop is larger at 3.0Hz than at 2.0Hz.

In Figure 4, the variation of the dissipated energy is given for different shaker frequencies. As shown in this figure, the dissipated energy increases with the frequency. Moreover, the rate of increase in dissipated energy increases with the packing ratio.



(a) 2.0Hz (b) 3.0Hz

Figure 3: Effect of packing ratio on the stirring torque (Glass particles, ϕ4mm)

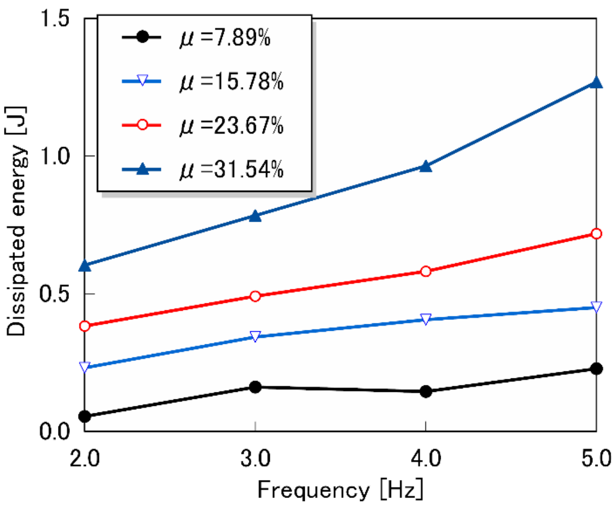
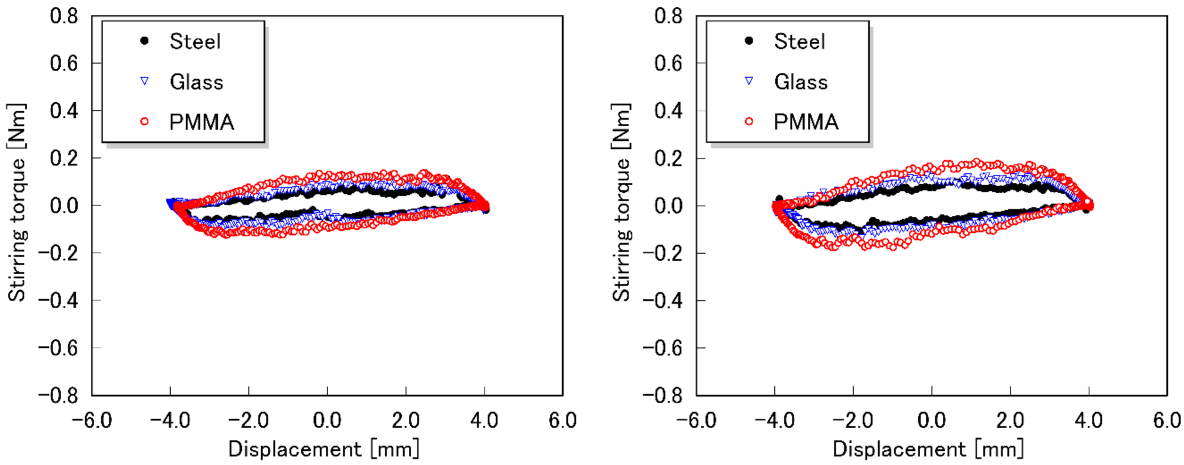


Figure 4: Variation of the dissipated energy for different frequencies (Glass particles, ϕ4mm)

2.3 Effect of particle material

In Figure 5, the effect of particle material on stirring torque can be seen at the same total mass of granular materials. The packing ratios μ for glass, PMMA and steel particles were 15.78%, 33.50% and 5.06%, respectively. The order of increasing dissipated energy is steel, glass and PMMA particles.

In Figure 6, the variation of the dissipated energy is given for various particle materials. As shown in this figure, the dissipated energy is always higher for PMMA particles than for the other materials. It is also shown that the rate of increase in dissipated energy increases for PMMA particles than for the other materials.



(a) 2.0Hz (b) 3.0Hz

Figure 5: Effect of particle material on the stirring torque (ϕ4mm, total mass =100g)

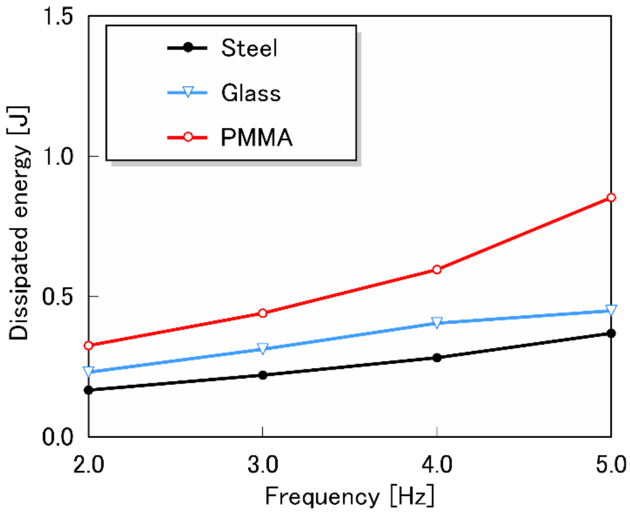


Figure 6: Variation of the dissipated energy is given for various particle materials (ϕ4mm, total mass =100g)

3 NUMERICAL SIMULATION

3.1 Discrete element method

In this study, the mixing behaviour of particles in the horizontal stirring container was calculated using the EDEM® software based on the discrete element method. Table 1 and 2 show the parameter values and the contact conditions, respectively.

The total torque acting on the blade is given by

$$T = \sum (F_y p_x - F_x p_y) \tag{2}$$

where F_x and F_y are the x and y components of the contact force exerted on the stirring blade, and p_x and p_y are the x and y components of the contact position, respectively.

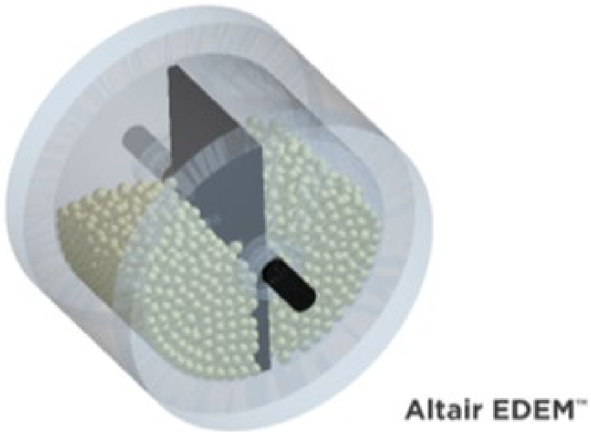


Figure 7: Packing behavior of glass particles in the stirring container ($\mu = 32.78\%, \phi$4mm)

Figure 7 shows the packing behavior of glass particles in the stirring container obtained using the EDEM ® software.

Table 1: Parameter values

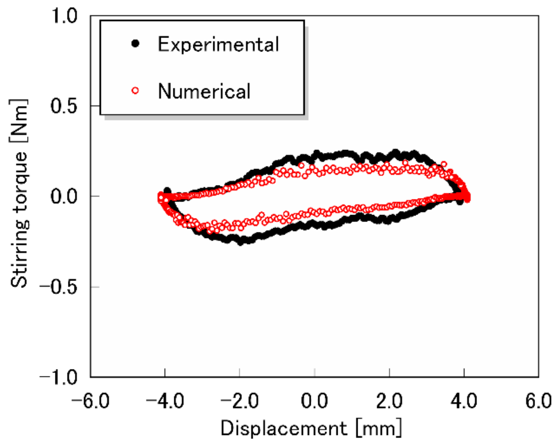
	Young's modulus [GPa]	Poisson's ratio	Density $[\mathrm{kg/m^3}]$
Glass	71.3	0.22	2527
PMMA	3.0	0.35	1180

Table 2: Contact conditions

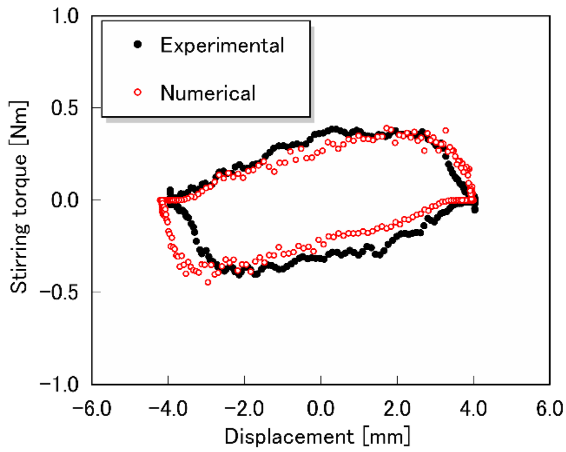
	Coefficient of restitution	Coefficient of friction
Particle-particle	0.923	0.25
Particle-wall	0.938	0.40

3.2 Experimental and numerical simulation results

Figures 8(a) and (b) show the comparison of the experimental results with the numerical



(a) 2.0Hz



(b) 3.0Hz

Figure 8: Comparison of the experimental results with the numerical ones for the variation of the stirring torque (Glass particles, $\mu = 32.78\%, \phi 4\text{mm}$)

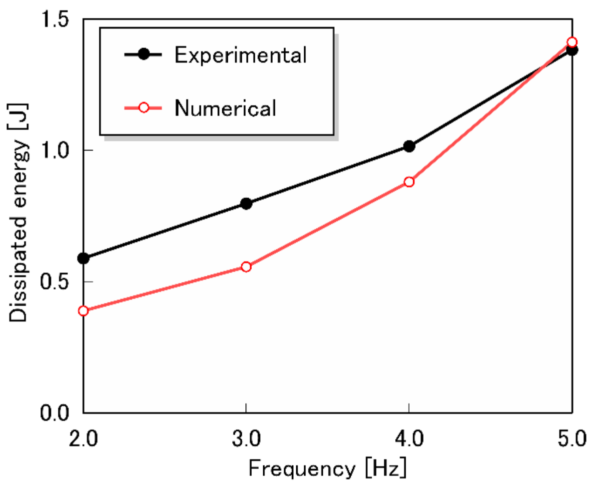


Figure 9: Comparison of the experimental and numerical results for the variation of the dissipated energy (Glass particles, $\mu = 32.78\%, \phi 4\text{mm}$)

ones for the variation of the stirring torque versus the displacement of the shaker. Although the maximum stirring torque obtained from the numerical results is different from that obtained from the experimental ones, the numerical results are qualitatively consistent with the experimental ones.

Figure 9 shows the comparison of the experimental and numerical results for the variation of the dissipated energy versus the shaker frequency. Although the dissipated energy measured in the experiment is higher than that calculated at frequencies 2–4Hz, the trend of numerical results follows that of experimental results. Therefore, the numerical approach of this study is effective for estimating the efficiency of damping the damping torque exerted on the horizontally rotating blade in granular materials.

Figure 10 shows the variations of the dissipated energy at different shaker frequencies in the horizontal and vertical containers. These results were obtained from the simulation. The shape of the vertical container was the same as that shown in Figure 7 and the rotation axis of the blade was parallel to the direction of gravity. As shown in Figure 10, there is little difference in the variation of the energy dissipated by stirring granular materials in the horizontal and vertical containers.

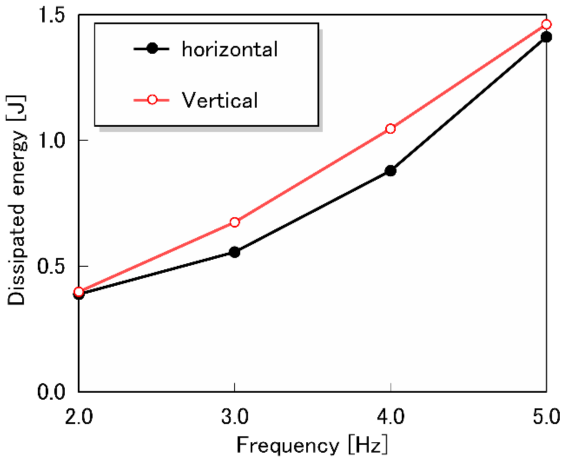


Figure 10: Variation of the dissipated energy for different frequencies in horizontal and vertical containers (Glass particles, $\mu = 32.78\%, \phi 4\text{mm}$)

4 CONCLUSIONS

The damping torque exerted on a horizontally rotating blade in granular materials was experimentally and numerically investigated. A mechanical stirring apparatus was fabricated. The blade was rotated sinusoidally by a shaker through a ball screw mechanism. It was found that the dissipated energy increases with the shaker frequency. It was also found that the order of increasing dissipated energy is steel, glass and PMMA particles. Energy dissipation was calculated using the EDEM® software based on the discrete element method. Although the dissipated energy measured in the experiment was higher than that calculated at frequencies 2–4Hz, the dissipated energy calculated was in qualitative agreement with that measured in the experiment. Therefore, the numerical approach of this study is effective for estimating the efficiency of damping exerted on the horizontally rotating blade in granular materials.

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