

Induced Particle Sloshing in a Rotating Container

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Abstract

Vibration absorbers are employed for both structural safety and comfort reasons. This paper explores a novel absorber which uses the sloshing of granular particles to dissipate energy in a rolling container. Some of the parameters which affect energy dissipation have been experimentally studied. Detailed description of one experiment is given. Further work involves numerical exploration.

Introduction

Sloshing refers to the low frequency oscillation of the free surface of a liquid in a partially full container. Intentionally induced sloshing is employed in tuned sloshing absorbers which can provide benefits similar to that of a tuned vibration absorber for structural vibration control.

Liquid sloshing absorbers are low maintenance components. They have found use in flexible structures, such as towers and suspension bridges under wind and earthquake loading. One of the challenges in the design of sloshing absorbers is to provide fast energy dissipation, once a strong interaction is established between the sloshing liquid and the structure to be controlled. This paper details an experimental investigation in which granulated solids are used, instead of liquid, in a sloshing absorber.

Dampers using granular materials exist in the literature in the form of impact dampers. Impact dampers are mass dampers which use plastic collisions and momentum transfer between the damper, a loose mass, and its boundaries which are attached to a primary vibrating system to be controlled [6]. Because significant impact forces are employed in absorbing vibrations, rapid deterioration of materials may occur. Papalou and Masri [6] propose the use of a damper with multiple particles, to reduce such maintenance problems. The concept of particle damping involves the use of powders or particles of small diameter inside enclosures that are part of a vibrating structure [9]. The dissipative forces in such a configuration are a combination of collision, friction and shear damping [4, 5].

Granular materials flow, like a liquid, when their container experiences an excitation. To the best of the authors' knowledge, no other research exists in the literature which utilises a sloshing absorber using granular materials in place of a liquid. The preliminary investigations show clearly that with a damper which uses sloshing particles in a container, it is possible to achieve effective energy dissipation. In the following, experimental details are discussed first. Subsequently, the experimental observations together with their interpretation are presented.

Experiments

Experiments consisted of freely allowing a cylindrical container to roll down a ramp from a known height onto a surface. The enclosure contained different amounts of particles for each experimental run. The effect of various parameters has been explored on the effectiveness of energy dissipation, namely con-

tainer dimensions, particle dimensions, particle roughness (coefficient of friction), enforcement of perfect roll on the ramp, ramp height and ramp inclination.

Experiments consist of dissipating a known potential energy given to a cylindrical container through induced relative motion of granular solids in a container. Releasing a container from a pre-determined height ensures consistent starting incident potential energy, whereas the distance the container stops away from the release point is an indication of effective energy dissipation. The most effective dissipater stops the container motion over the shortest distance from release. This setup is described in Figure 1 in which the rolling surface (1), angle between surface and ramp (2), ramp (3), container (4) and bump stop (5) are shown. Parameter X represents the distance travelled. The dissipation of energy is the result of the "flow" of granules, frictional dissipation due to the relative motion of granules, and collisions between particles and enclosures walls. Although dissipation is frictional in nature, it may also be considered as "viscous dissipation" in equivalent sense.

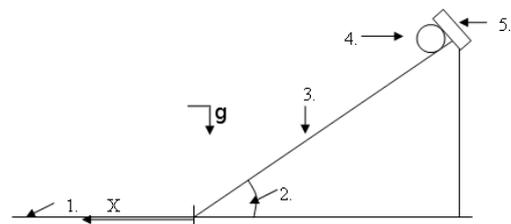


Figure 1: Schematic of experimental setup, showing (1) surface, (2) angle between ramp and surface, (3) ramp surface, (4) container and (5) bump stop.

The motion of the container started from a complete rest at the point of release. As it lost altitude, it gained kinetic energy down the inclined ramp, both translating and rolling about its own centre. The bottom of the ramp represented the point where all the starting potential energy has been converted to kinetic energy. The rolling of the container continued some distance away from this location until its energy is dissipated by the flow of the granular material inside the container. At this point, the container came to a complete stop.

Due to the exploratory nature of the experiments, many combinations of the identified variables were attempted in order to determine those which directly influence the outcome. For brevity, only typical cases are presented here, with the remainder published in an internal report [3].

During the experiments, two ramps were used, in three different configurations. The ramp properties are listed in Table 1. The first series of experiments was designed to determine the effect of container dimensions on the results, which are given in Table 2. Particles are added to container 1 with increments of 10 to 50

Ramp	Angle °	Height (m)
1	35	0.2
2	15	0.15
3	41	0.23

Table 1: Length measurements have an error margin of ± 0.5 mm. Consequently, angles determined have a margin of error of $\pm 0.5^\circ$.

particles. For each increment, the container is released from the ramp's bump stop, and allowed to roll until it comes to a complete stop. The same procedure is repeated for four combinations of two variables, the ramp and container. Four repetitions are used and the average of four reported in the next section. In the second series of experiments, the effect of the particle size, density and particle surface friction have been partially explored. Four particle have been used during experiments whose relevant parameters are listed in Table 3.

In the third series of experiments, controlled perfect sliding motion and (almost perfect) rolling motion are compared to determine their suitability as an energy sink. Perfect sliding was approximated by attaching container 3 to a carriage, with a mass of 0.012 kg. Ramp 2 was specifically designed to accommodate for the ground clearance constraints imposed by the vehicle. As the height of the ramp was different to the other experimental runs, the results for this experiment are shown through incident potential energy mgh , where m is the total mass, g is gravitational acceleration and h is the height of release. Perfect rolling motion was investigated through the addition of a rubber mat to ramp 3 to approximate no-slip condition. Both experiments use particle 2.

Results

In Figure 2, observations are presented to explore the effect of different container dimensions. Observations with identical ramp, particles and surfaces are compared for containers 1 (—●—), 2 (—▲—) and 3 (—■—). It is worth mentioning here that the variation in the volume of different containers is more than 100%, as given in Table 2. In this figure, the vertical axis represents X , the distance travelled by the container on the flat surface from the bottom of the ramp until it came to a complete rest, whereas the fraction of the container being filled with particles (volume fraction) is given on the horizontal axis. Up to a 15% volume fraction, the distance decreases with increasing number of particles. A relatively flat section follows the initial decreasing trend, until about 60%. A rapid increase follows the flat section, up to the point where the container is completely full. A simple observation from the trends in Figure 2 is that the distance X is dependent on the volume fraction alone, regardless of the container size. By using "Volume Fraction" on the horizontal axis, the data points of different experiments with different numbers of particles collapse onto one line.

In Figure 3 the effect of varying particle size (Table 3) is shown. —◆— represents 1; —■— represents 2 (repeated from Figure 2); and —▲— represents 3. The axes are the same as in Figure 2. An approximately flat section is observed until the container is 50% full, after which a drastic increase in distance travelled occurs. The smallest particles (1, —◆—) have the shortest stopping distance while the vessel is less than 50% full. Meanwhile, larger particles give smaller X for a greater range of volume fractions. One anomaly observed during this experiment has been the container sliding on the ramp, prior to, or in tandem with, the rolling motion. This observation and its influence on the results led to the investigation between the perfect roll and perfect slide. The sliding and rolling motion on the

container has been observed mainly at higher energy levels (or larger volume fractions).

In Figure 4 the results of the comparison between the perfect slide (—◆—) and the (almost) perfect roll (—▲—) are shown, utilising the same axes as in the previous graphs. The perfect slide case shows no clear change in distance travelled based on the amount of particles in the container. Furthermore, the distance travelled is quite significant when compared to the perfect roll case. Perfect sliding did not create sloshing of particles and did not dissipate energy in an efficient fashion, which caused all further experiments in this direction to be ceased. In contrast, perfect roll is an efficient energy dissipater whose level of energy dissipation may depend strongly on the volume fraction.

In Figure 5 the performance of particles 1 (—■—), 2 (—▲—) and 4 (—●—, —■—) is compared. All experiments are run using the same container, and with (almost perfect) rolling. The smaller and denser particle 4 is clearly a better energy dissipater at small volume fractions. However, as the volume fraction increases, the larger particles (2) seem to produce better results. In Figure 6 the same data is represented as Figure 5, however the incident potential energy in the system is shown along the horizontal axis. The data points for particle 4, are shifted right, while those of particles 1 and 2 maintain their relative positions, indicating that particle 4 can dissipate more incident energy over the same distance travelled by the container. Due to the promising results, further investigation, which included video recordings of the experiments, was conducted.

In summary, the most effective energy dissipation occurs when particles freely move inside the container and collide with other particles and walls. Furthermore, the breaking of the secondary waves provides effective dissipation, for a range of volume fractions between 0.15 and 0.35. However, as the incident potential energy increases so does the container velocity, causing particles to remain in contact with the surface of the container, which seems to inhibit the dissipation of energy.

Conclusions

As mentioned previously, vibration absorbers are used in flexible structures for both safety and comfort reasons. Liquid sloshing absorbers provide the added benefit of low maintenance to other absorber systems. The ideas discussed in this research proposes replacing the liquid component with a granular solid which also flows when its container receives external excitation. Currently, a model using a fixed ramp and a container partially filled with particles has been used to determine the proposed ideas are viable as an energy absorber. Some parameters which affect efficiency have been identified with others still under investigation.

Using Volume Fraction as the horizontal scale, the data points of containers of different sizes (using the same particle) collapse onto a single line. Further, the distance travelled by the partially filled container is directly dependent on the number of particles inside. Additional experiments have shown that encouraging rolling motion of the container, rather than sliding motion, makes for a good energy dissipater.

While experiments have been run in order to determine if particle size affects energy dissipation, they can only conclusively show that our smallest particle was the best dissipater. Further experiments are necessary to determine the relationship between the particle size and the efficiency of energy dissipation.

Further research in the area is required to determine the means of improving the efficiency of such an absorber, as well as defining the requirements for an absorber which can be used for

structural control. Currently, the next stage involves the use of Discrete Element Method for numerically validating our experimental results [1, 2, 8]. Further away, predictions derived from this codebase will help guide the design process for such an absorber.

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Container	Volume (l)	Height (m)	Diameter (m)	Mass (kg)
1	1.1	0.095	0.13	0.05
2	0.5	0.1	0.06	0.002
3	0.625	0.17	0.065	0.027

Table 2: Container properties.

Particle	Freely Settled Bulk Density (kg/l)	Height	Width	Length
		(Average) (mm)		
1 (lentil)	0.8	2 - 3.5 (2.7)	5 - 6 (5.6)	5 - 6 (5.6)
2 (soy bean)	0.8	4.5 - 6.5 (6)	7.5 - 9 (8.2)	12 - 17 (16)
3 (broad bean)	0.8	5.5 - 7.5 (6.4)	12 - 15 (13.6)	18 - 23 (22.5)
4 (sand)	1.7	0.3 - 0.5 (0.4)	0.3 - 0.6 (0.4)	0.3 - 0.6 (0.4)

Table 3: Particle properties given as ranges and averages of 16 particles. Values for particle 4, sand, are approximations based on high resolution pictures of the particles used. All other particle measurements have error margins of ± 0.5 mm.

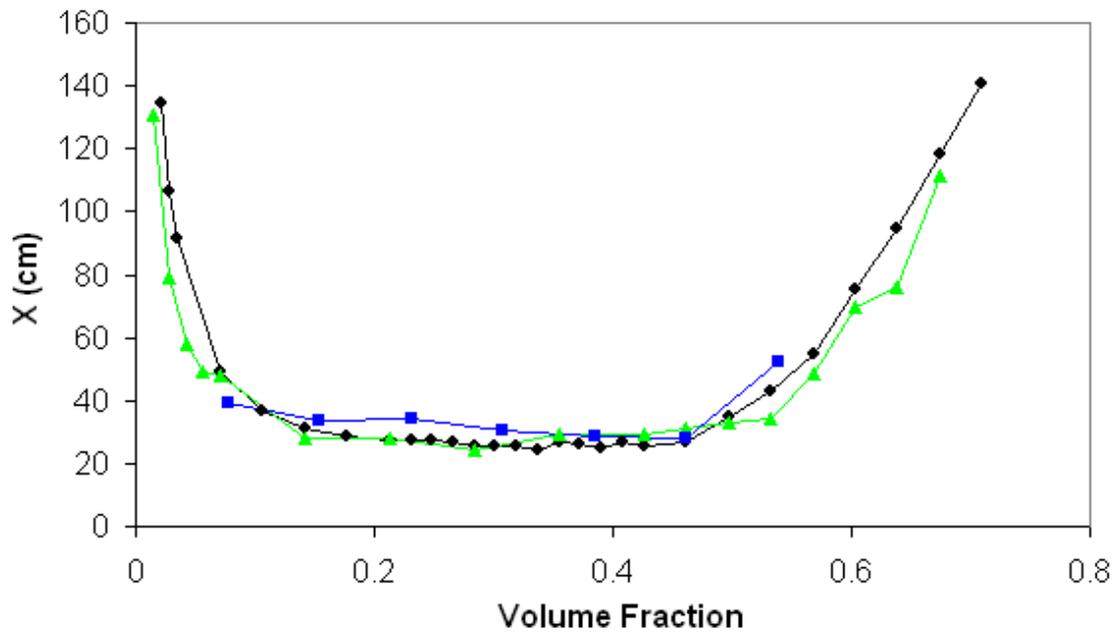


Figure 2: Variation of X with volume fraction with container 1 (—●—), 2 (—▲—) and 3 (—■—). All experiments with ramp 1, particle 2 on glass surface.

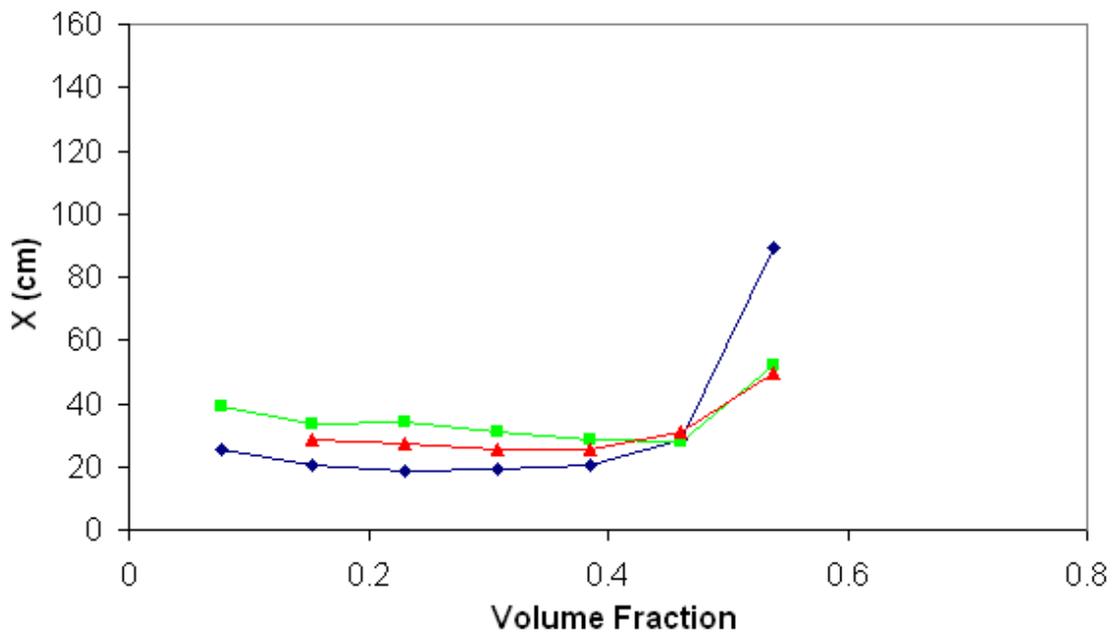


Figure 3: Effect of particle size and shape: 1 (◆), 2 (■) and 3 (▲). All experiments with ramp 1 and container 2. The axes are the same as in Figure 2.

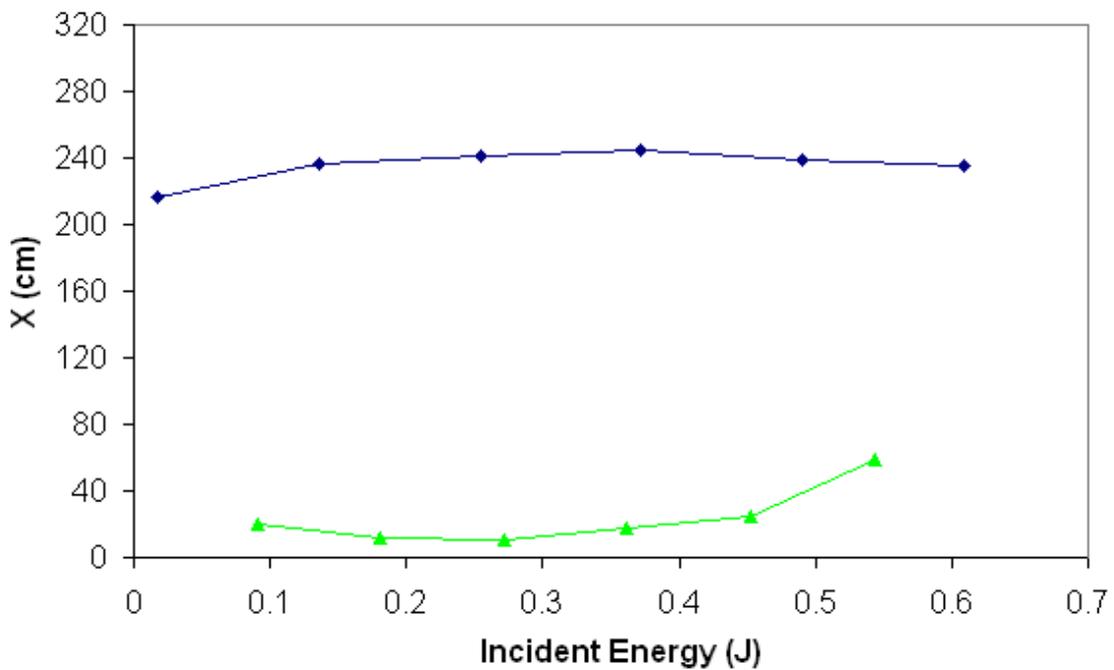


Figure 4: Comparison between perfect roll (▲) and perfect slide (◆). The axes are the same as in the Figures 2 and 3.

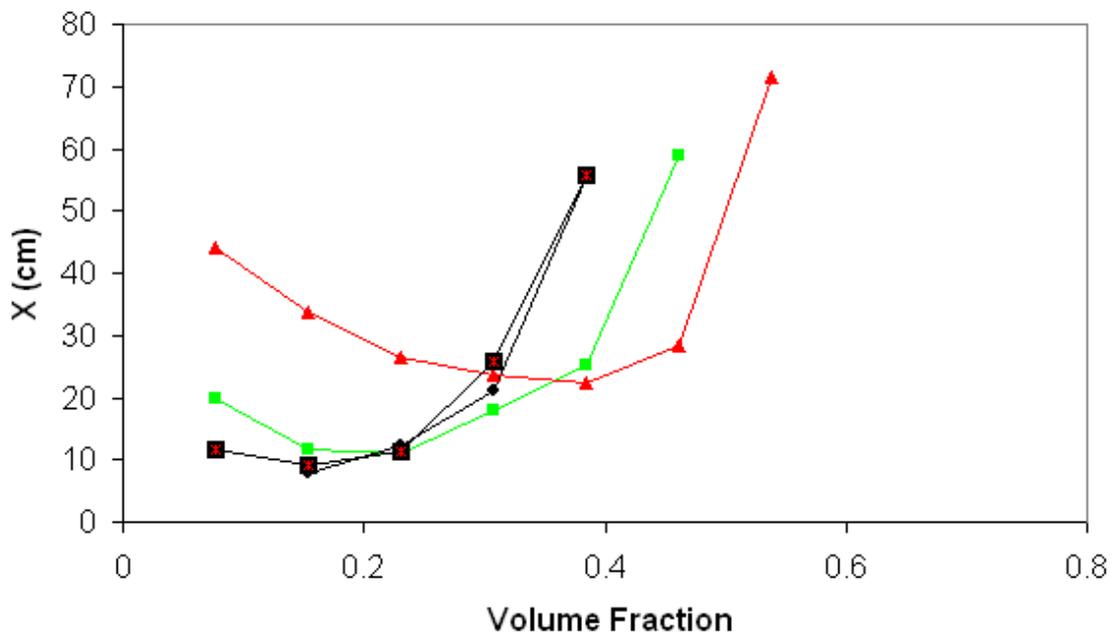


Figure 5: Comparison between particles 1 (■); 2(▲) and 4(◆, ◆) for perfect roll. Axes are the same as in previous figures.

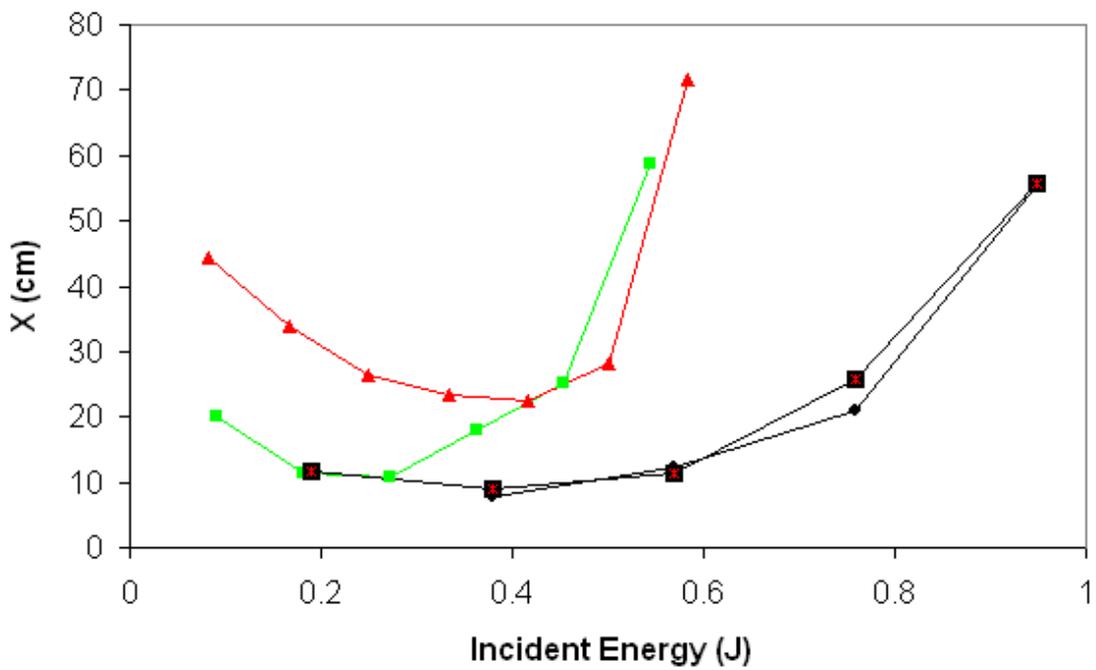


Figure 6: Same as Figure 5 but for incident energy rather than Volume Fraction.