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How universal is the vibration-velocity controlled granular convection?

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Abstract. Recently, a number of articles have reported that granular convection induced by continuous vibration is controlled by vibration velocity, in contrast with some previous studies. We have reported such an example for the Brazil nut effect when the vibration is given discontinuously, using a one-layer granular bed in a cell with down-facing side walls. Here, we report the effect of vibration phase and wall friction using the same experimental system, to confirm rising motion of an intruder induced by granular convection is again governed by vibration velocity. We compare two different cases of vibration phase for giving intermittent vibration cycles, and found one, in which granular packing is well established before grains start to lose contacts due to vibration, provides distinctly high reproducibility. We further control the side wall friction using a microfabrication technique, and found that significantly high reproducibility is attained in a cell with vertical side walls when a millimeter texture is introduced on the side walls. Our results indicate that the granular convection is universally controlled by vibration velocity. The present study opens a way to conduct highly reproducible experiments on granular dynamics, which is indispensable for deep physical understanding of granular flow and segregation.

1 Introduction

Recently, a number of articles have reported that granular convection induced by continuous vibration is controlled by vibration velocity [1–3]. We have reported such an example for the Brazil nut effect when the vibration is given discontinuously [4], using a one-layer granular bed in a cell with down-facing side walls.

The Brazil nuts (BN) problem is a size segregation of grains by shaking: when a cell that contains mixture of grains of large and small sizes are vibrated, large ones tend to rise up in the cell. This problem was introduced in the field of physics in 1987 by a simulation study [5], which was followed by pioneering experimental studies [6–8]. Since then many studies have been performed and various mechanisms have been proposed, which include void filling [9], convection [7], and arching effect [8]. However, physical understanding of the phenomenon remains to be a current issue.

In 1996 and 1997, the convection-driven rising motion was shown to be characterized by the acceleration and frequency of the vibration [10, 11]. However, in 2012, it was shown that the convection-driven rising motion was clearly characterized, in terms of vibration parameters, solely by the vibration velocity [1]. In 2014, the convection velocity in a different granular system was also characterized by the vibration velocity [2]: when the convection velocity obtained at different accelerations and frequencies of vibration is plotted as a function of vibration velocity, all the data collapsed onto a master curve.

Since these results for the velocity-controlled granular convection do not seem to be consistent with classic studies [10, 11], we need to examine how universal is the velocity-controlled granular convection. This problem has been answered in our recent studies [3, 4] to some extent, as described above.

In this study, we further examine how universal is the velocity-controlled convection using the same experimental setup. For this purpose, we focus on the case of discontinuous vibration, in which one cycle of sinusoidal wave is given with a regular interval. We examine whether the rising dynamics is unchanged when we modify the selection of the initial phase of each cycle of wave and the friction on the side walls.

In the previous study [4], we selected the initial phase of each cycle so that the cell is first moved downwards before a upward motion. This "down-up" case is compared with the opposite "up-down" case in the present study. As a result, we find that the latter case leads to a remarkably high reproducibility.

We further examine the effect of friction on the side walls. In the previous study [4], we used down-facing side walls, which introduces some ambiguity in defining cell width, although it was necessary to obtain a stable motion. In the present study, we instead use vertical side walls but with a millimeter texture created by virtue of a microfabrication technique. As a result, we find that such textures also contribute to high reproducibility of the experiment.

These examinations of the effects of vibration phase and wall friction allow us to open a way to perform experiments of the Brazil nut effect with a significantly high

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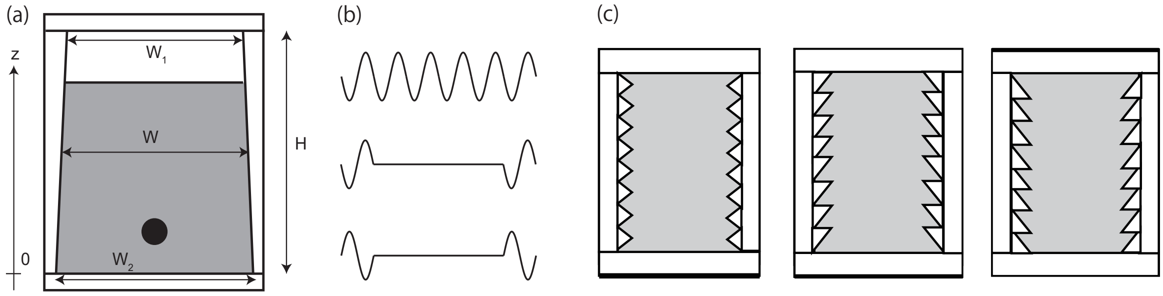

Figure 1. (a) Experimental setup. (b) Continuous vibration vs. two types of discontinuous vibration: down-up and up-down cycles. (c) triangular texture, and upward and downward sawtooth.

precision. As a result, we find that the rising motion is again governed solely by the vibration velocity.

2 Experiment

In our previous study, we used a cell with side-walls facing down as shown in Fig. 1 (a), where $W_1 = 90$ mm, $W_2 = 110$ mm, and $H = 280$ mm. We used a transparent acrylic plate (thickness 3 mm) and copper plate (thickness 2 mm) for the front and back plates of the cell, in order to reduce static electricity. These walls were separated with spacers of thickness $D = 1.3$ mm. The cell contained a disk-shaped intruder (diameter 18 mm and thickness 1 mm) and one layer of small balls of aluminum oxide with an average diameter $d = 1$ mm (AL-9, AS ONE Corp.). The balls, sieved with a mesh of size 1.13 mm, filled the cell with the intruder to a depth $H = 170$ mm. The slight difference between W_1 and W_2 restrained the formation of lattice structures and made easier for the rising motion described below.

The cell containing grains and an intruder was mounted on a vibration device, controlled by a vibration system (see [3, 4] for the details). This system can give sinusoidal motions to the cell, both continuously and discontinuously, as illustrated in Fig. 1 (b). The motion is characterized by the vibration velocity $v = \omega A$, acceleration $a = \omega^2 A$, and frequency $f = \omega/(2\pi)$, with the angular frequency ω and amplitude A.

In the discontinuous cases of our interest, we gave one cycle of a sinusoidal wave (either down-up or up-down cycle) with a regular interval. The interval was set to equal to four cycles of the sinusoidal wave, which seemed enough for the granular system to relax to equilibrium positions in our parameter range [4]. The one cycle of a sinusoidal wave in the discontinuous mode will be called "tap," and the number of taps given to the system is denoted as n in the following.

For each run of the experiment, we set the disk position at $z = 20$ mm, and started vibration to observe the rising motion. We measured the position z of the disk as a function of n, using digital images obtained with a high-speed camera (FASTCAM Mini WX 100, Photoron), synchronized with the vibration system.

In this study, to reduce the effect of static electricity, after each run of the experiment, we removed all the grains from the cell and applied a volatile chemical liquid for removal of static electricity (HAS-150, HYOUSIN CO.,LTD.) on the front and back plates of the cell. We then dried the plates and refilled the cell with grains for the next run. By virtue of this process, we do not need to use a copper plate for the back plate. As seen below, in well-controlled cases, the data obtained from a copper back plate and those from an acrylic back plate were indistinguishable.

To control the friction on the side walls, we exploited a microfabrication technique using a cell with vertical side walls: they were not facing down with $W_1 = W_2 = 90$ mm ($H = 200$ mm) but with textures illustrated in Fig. 1 (c). In the triangle texture, the triangle that has two sides of equal length $1/\sqrt{2}$ mm are arranged with a pitch of 1 mm. In sawtooth textures, the sawtooth with its horizontal side of length 1 mm are arranged with a pitch of 1 mm.

3 Results

3.1 Up-down vs. down-up cycles

In Fig. 2, we compare the results of the rising motion, the disk position z as a function of $n - n_0$, obtained by up-down and down-up cycles with a cell with the triangle texture. Here, n_0 is the value of n at $z = 140$ mm. The shift of n by n_0 is introduced in order to highlight high reproducibility. Each curve is obtained as an average of 10 runs. Two curves (Data 1 and 2) were obtained on two different days with a copper back plate and the remaining one curve (Data 3) was obtained on another day with an acrylic back plate. Complete agreement of the three curves demonstrates a remarkably reproducibility in the up-down case. Compared with this, reproducibility is significantly deteriorated especially near the bottom of the cell in the down-up case. Here, Data 4 and 5 were obtained on two different days with a copper back plate and the remaining one (Data 6) was obtained another day with an acrylic back plate.

In Fig. 3, we visualize and compare the granular convective flow (without the intruder) in the up-down and down-up cases. These figures are obtained as follows. We put a steel bead (silver color) of the same diameter (1 mm) in a layer of alumina beads (white color) and track the movement of the steal bead (density 7.85 g/cm^3) by su-

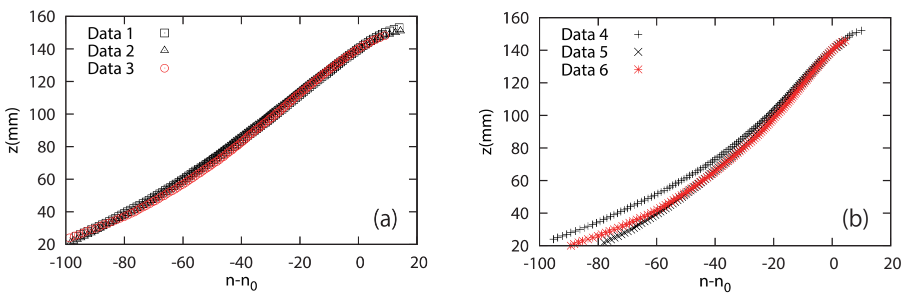

Figure 2. Rising motions obtained at $f = 30$ Hz and $a = 70$ m/s^2 on two different days with a cell with the copper back plate (Data 1 and 2, or Data 4 and 5) and on another day with a cell with an acrylic back plate (Data 3, or Data6). (a) Case of up-down cycles. (b) Case of down-up cycles.

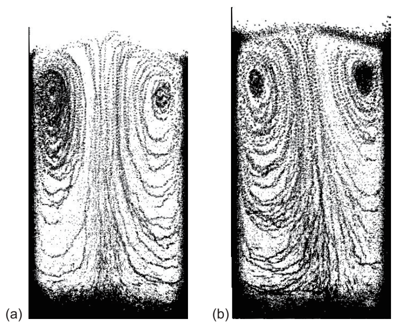

Figure 3. The granular convection flow obtained at $f = 30$ Hz and $a = 70$ m/s^2 (a) Case of up-down cycles. (b) Case of down-up cycles.

perposing snapshots (snapshots are taken with an interval 1/30 s, for the duration 145 s).

In Fig. 3 thus obtained, the convective role is more symmetric in the up-down case. This indicates the convective role is more effectively formed in the former case. Considering the convective role is the main cause of the rising motion, this is consistent with the following fact: the quality of reproducibility is higher in the up-down case than in the down-up case (as shown in Fig. 2).

3.2 Triangle vs. sawtooth textures

In Fig. 4, we compare the curve z vs. $n - n_0$ (average of 10 runs) obtained from three different textures created on the vertical side walls in the up-down case. As seen in Fig. 4 (a), the upwards and downwards sawtooth cases are almost indistinguishable with the triangle case although the downwards sawtooth case is slightly different from the triangle case. As for the reproducibility among 10 raw data sets used to obtain an averaged data, there were no significant difference in the three cases (the case of down-facing side wall was distinctly different: reproducibility among raw data was lower and rising speed is slower than the case of the vertical walls with textures). Note that, in a recent study [12], they made similar sawtooth textures on the cell wall and observed the convection roles in the opposite direction (they observed downwards flow in the center), although their granular system is three-dimensional and much more dilute.

3.3 Velocity-controlled rising motion

In Fig. 5, we plot the rising "velocity" U defined as the slope of the z-vs-$(n - n_0)$ curve in the range from $z = 90$ mm to $z = 130$ mm, where the curve is almost linear. This velocity is given as a function of the vibration velocity v in Fig. 5 (a), and as a function of the vibration acceleration a in Fig. 5 (b). These two plots demonstrate that the rising motion is controlled by the vibration velocity v.

Each value of the rising velocity U is obtained from an averaged curve obtained from 10 experiments. To demonstrate the error in the analysis, we pick up three cases and add error bars. These error bars are obtained as the standard deviation of 10 slopes obtained from 10 z-vs-$(n - n_0)$ curves.

The data in Fig. 5 (a) satisfies the relation

$$U = k_1 d \cdot (v - v_c)/v_c \tag{1}$$

with $k_1 = 2.49 \pm 0.20$ and $v_c = 230 \pm 8$ mm/s. These values are qualitatively in agreement with those obtained in the previous study in the discontinuous down-up vibration [4].

4 Discussions

We observed distinct differences between the up-down and down-up cases in reproducibility. This difference may originate from inhomogeneity in the position distribution of grains at the starting stage of one cycle. In an up-down cycle, the inertial force tends to compact the grains among others during the first upward motion, increasing the grain density and thus reducing the inhomogeneity in the position distribution at the beginning stage of one cycle, before the grains tend to lose contact among others during the ensuing downward motion. Contrary to this, in a down-up cycle, the grains tend to lose contact among others during the first downward motion, with enhancing the inhomogeneity of the position distribution at the starting phase, before the grains tends to be compacted during the ensuing upwards motion. Because of this difference, the effect of inhomogeneity is more reduced in the up-down cycle.

Under the continuous vibration, two regimes have been reported using the same setup [3], and two different mechanism, a certain arch effect and formation of convective roles, have been discussed. Under the discontinuous "down-up" vibration, using the same setup, the first

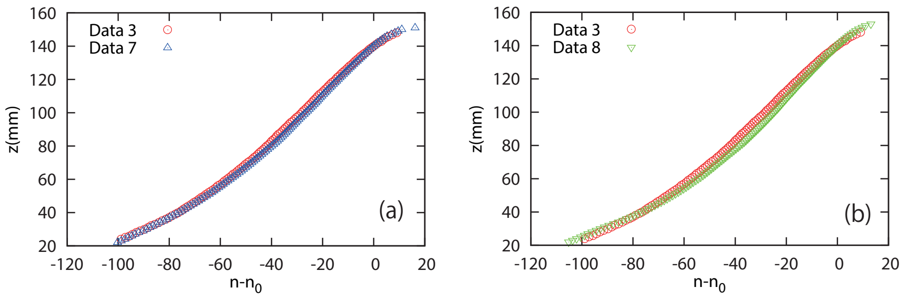

Figure 4. Rising motion obtained in the up-down case at $f = 30$ Hz and $a = 70$ m/s^2. (a) Upwards sawtooth (Data 7) vs. triangle (Data 3). (b) Downwards sawtooth (Data 8) vs. triangle (Data 3).

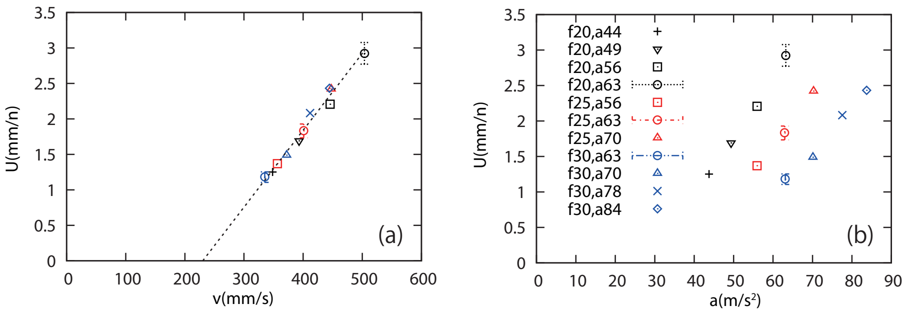

Figure 5. Rising "velocity," obtained as the slope of the z-vs-$(n - n_0)$ curve, as a function of the vibration velocity v and the vibration acceleration a.

regime have shown a low reproducibility whereas the second regime have exhibited a relatively high reproducibility [4], which is consistent with Fig. 2 (b). However, in the present study, it is shown that, even when the vibration is given discontinuously, by exploiting a careful process for removing static electricity and by using up-down cycles, a significantly high reproducibility can be achieved for the entire dynamics. Currently, we have yet to interpret the initial regime of the highly reproducible data as in Fig. 2 (a). To address this issue, we are now revisiting the continuous case in the same set up but with the above-mentioned new process, which allowed us to use an acrylic plate for the back plate.

The present study indicates that the granular convection is universally controlled by vibration velocity and provides a way to perform experiments on granular flow with a high reproducibility, which will be useful for physical understanding of granular dynamics.

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