Axial segregation of horizontally vibrated binary granular mixtures in an offset-Christmas tree channel

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Axial Segregation of Horizontally Vibrated Binary Granular Mixtures in an Offset-Christmas Tree Channel

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Abstract. We investigate segregation in a horizontally vibrated binary granular mixture in a closed offset-Christmas tree channel. The segregation phenomenon occurs in two steps: vertical sorting followed by axial segregation. In the first step, sorting occurs via *Brazil-nut effect* or *reverse Brazil-nut effect* depending on the particles' size and density ratios. The two layers thus formed then separate axially towards opposite-ends of the channel with the top layer always moving towards root of the Christmas tree. We discuss the segregation mechanism responsible for axial segregation.

Keywords: axial segregation, granular mixture
PACS: 45.70.Mg

INTRODUCTION

Segregation is a commonly observed phenomenon in excited granular mixtures. A popular example is the *Brazil-nut effect*, where small and big species in a mixture are sorted vertically when shaken [1]. However, sorting can also be driven by a difference in particle densities, and this is known as the *reverse Brazil-nut effect* [2, 3]. Various studies have shown that segregation depends not only on the particle properties such as size and density, but also on the container's geometry, and friction between the particles and the container's walls [4, 5]. Segregation need not always occur along the shaking direction; indeed there are instances where the mixture separates transverse to the vibration direction [6, 7]. Most reported segregation studies are typically performed in vertically shaken and rotating granular systems [8, 9]. Comparatively, very few studies are reported on horizontally shaken granular systems, and most of those available are focussed on understanding pattern formation, crystallization, and phase transition [10-14].

In this paper, we explore segregation in a horizontally shaken binary granular mixture in a closed offset-Christmas tree channel aligned normal to gravity; see Figs. 1 and 2. The segregation process is observed to take place in two steps: a fast vertical sorting followed by slower axial segregation. Vertical sorting occurs normal to the channel's base along the Z-direction via the *Brazil-nut* or *reverse Brazil-nut effect* depending upon the particles' size and density ratios; see Fig. 2(a). The two layers formed after vertical sorting then separate axially in opposite directions, with the top and bottom layers separating towards the *root* (end-B) and *apex* (end-A) of the Christmas tree, respectively; see Fig. 2(b).

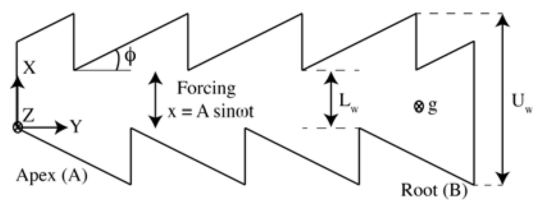

FIGURE 1. A schematic diagram showing top view of the offset-Christmas tree channel. L_w and U_w are, respectively, the lower and upper widths of a trapezoid. ϕ is the channel's taper, g is the acceleration due to gravity, and A and ω are the vibration's amplitude and frequency, respectively.

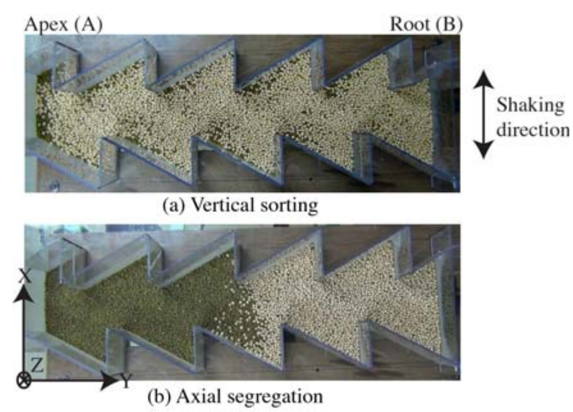

FIGURE 2. Axial segregation in an equal weight mixture of moong (green gram) and matar (pea). Just after vertical sorting, the top layer constitutes of matar (white), while the bottom layer contains moong (green). The vibration amplitude and frequency are 7 cm and 105 RPM, respectively.

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TABLE 1. Properties of the grains used in the experiments.

Grain	Shape	Mean grain size (mm)	Angle of repose (deg.)
Matar	S*	7	24
Moong	E†	5×3.5	26
Sarson	S	2	27
Steel balls	S	4	30

* Spherical
† Ellipsoidal

The current study is motivated by an industrial process involving a channel of the same geometry, but one which has open ends 'A' and 'B', and is inclined to gravity with end-A being lower than the end-B. Segregation in that system is also seen to proceed via the aforementioned two steps. Open ends allow a continuous flow of grains. In this article, we focus our attention on the mechanism responsible for axial segregation. For experimental ease, we close both ends.

EXPERIMENTS

Experimental set-up

A sketch of an offset-Christmas tree channel is shown in the Fig. 1. The channel is not inclined, and closed at both ends 'A' and 'B'. The channel is a concatenation of many offset trapezoidal sections. In our experiments, the lower width l_w, upper width u_w and taper ϕ have been kept fixed at 10 cm, 30 cm and 30^o, respectively. Experiments were conducted at vibration amplitude of 7 cm sampling frequencies in between 90 RPM (1.5 Hz) to 120 RPM (2 Hz). We have employed both food grains and steel balls in our experiments, and their data are summarised in Table 1.

Experimental procedure

The binary mixture is prepared by mixing equal weights of two species by hand. It is observed that below a minimum vibration frequency ω_{min} the mixture moves as one solid mass, and segregation is not observed. In contrast, a forcing frequency, beyond which segregation does not occur, was not seen in our experiments. The diameter and density ratios are $d_r = d_s/d_b$ and $\rho_r = \rho_s/\rho_b$, respectively, where subscripts 's' and 'b' refers to small and big particles.

OBSERVATIONS

As discussed, the first stage involves vertical sorting into individual layers normal to the channel's base. The layers' ordering depends upon the particles' size and density ratios. Following vertical sorting, the two layers then axially separate to opposite ends. It is observed in all experiments with various grains combinations that the upper layer always moves towards the channel's root, while the lower layer goes down to its apex.

FIGURE 3. Axial segregation in an equal weight mixture of sarson (yellow) and moong (green). The vibration amplitude and frequency are 7 cm and 105 RPM, respectively.

In a binary mixture of about equal-density grains ($\rho_r \approx 1$)–and this is the typical industrial scenario involving food grains–the large particles rise to the top of small ones. Thus, in a mixture of moong and matar with $d_r = 0.714$, $\rho_r \approx 1$, moong sinks when vibrated. However, moong rises when matar is replaced with sarson (mustard) ($d_r = 0.4$, $\rho_r \approx 1$). We see that the layer of moong particles accumulates towards the channel's apex when shaken with matar, whereas it separates towards the root when mixed with sarson; see Figs. 2(b) and 3.
In a binary mixture with species of widely different densities ($\rho_r \ll 1$) and moderately different sizes, the heavy particles sink to the bottom during vertical sorting notwithstanding their relative size. Thus, in a binary mixture of steel balls and sarson ($d_r = 2$, $\rho_r \ll 1$), the steel balls sink to the channel's base when shaken. Consequently, during axial segregation the motion of sarson layer is completely reversed, i.e., it segregates towards the channel's root; see Fig. 4. Again the top layer moves towards the root. We attempt now to understand axial segregation.

FIGURE 4. Axial segregation in a 1.75:1 weight mixture of steel balls and sarson. The vibration amplitude and frequency are 7 cm and 105 RPM, respectively.

RESULTS AND DISCUSSION

Experiments

The net collisional momentum transferred to the grains from the tapered side walls is along the Y-direction. Thus, in a channel that is not inclined, particles tend to move towards the channel's root. This is confirmed by experiments on single species. Given this, the response of the upper layer is expected. However, the bottom layer's behavior is counter-intuitive. What causes the bottom layer to go in opposite direction towards the channel's apex? We now address this question.

After vertical sorting, both layers are almost uniformly distributed along the channel's axis; see Fig. 2(a). We note that the bottom layer is confined by the top layer. Consequently, its initial axial motion towards channel's root is slow relative to the top layer. As the top layer begins to accumulate towards the channel's root, its distribution over the bottom layer becomes non-uniform, thereby setting up a positive pressure gradient along the Y-direction. This reverses the bottom layer's motion. We have subjected this hypothesis to the following two experimental tests.

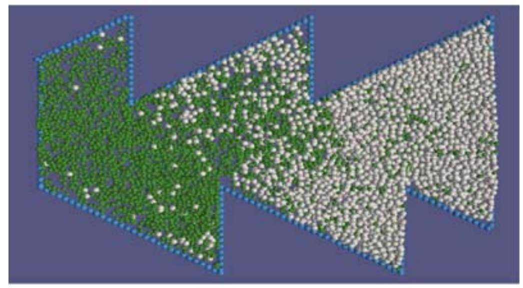
Open-ends

When both ends are kept open, no segregation is observed. All particles move out from the channel's root. This emphasizes the role of end walls and supports the hypothesis that the top layer's accumulation at the root drives segregation.

No accumulation

In this experiment, the channel's apex is closed, while its root is partially open in a manner that limits the grains' height at the channel's root to its initial value. This then prevents the top layer from accumulating at the channel's root. We again observe *no* segregation. The top layer exits continuously, while the bottom layer remains unchanged until most of the upper layer particles have exited; there is *no* motion of the lower layer's grains towards the channel's apex. This reinforces our claim that it is the top layer's accumulation at the root that causes the lower layer to be 'squeezed' out towards the channel's apex.

(a) Experiment



(b) Simulation

FIGURE 5. Outcome of experiments and simulations. All parameters except particles' stiffness are same.

Simulations

We have also studied the system via simulations employing the Discrete Element Method (DEM) [15]. The simulations were run with fewer trapezoidal sections, and a qualitative agreement was observed between experiments and simulations; see Fig. 5. It is evident from Figs. 6 and 7 that the phenomena of axial motion and vertical sorting occur simultaneously in the beginning over a small duration of about 25-30 oscillations. Both layers move towards the root initially with the upper layer moving fast; see Fig. 7's inset. The more rapid accumulation of the large particles at the root creates a positive pressure gradient driving the motion reversal of the small particles; see Fig. 7.

CONCLUSION

We study segregation of a binary mixture in an offset-Christmas tree channel. The segregation proceeds in two steps: vertical sorting followed by axial segregation wherein the upper layer always moves towards the channel's root. Experimental and numerical studies support the hypothesis that faster accumulation of the top layer at the channel's root creates a positive pressure gradient that causes the lower layer to move towards the channel's apex. We envisage important industrial applications

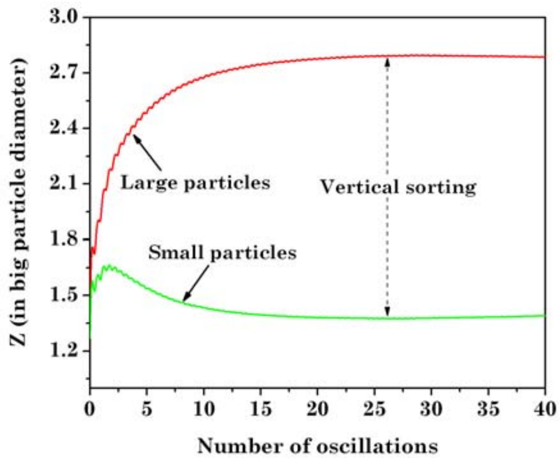


FIGURE 6. Center of mass of each species along the vertical direction (Z). Large particles rise, while the small ones sink. Particles are initially randomly mixed. The diameter and density ratios are $d_r = 0.714$ and $\rho_r = 1$, respectively. The vibration amplitude and frequency are 7 cm and 105 RPM, respectively.

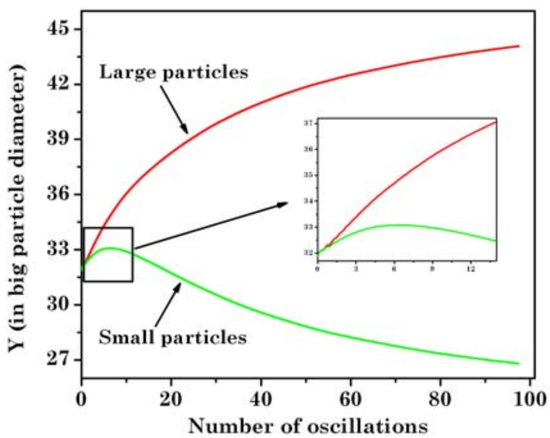


FIGURE 7. Center of mass of each species along the axial direction (Y). See also Fig. 6's caption.

of this segregation process.

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