X-Ray Particle Tracking of Dense Particle Motion in a Vibration-Excited Granular Bed

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ABSTRACT

The Brazil nut effect is a phenomenon in which large, dense objects migrate to the top of a bed of granular media when exposed to vibration. An example of this phenomenon is finding Brazil nuts on the top of a can of mixed nuts. The same phenomenon can be observed in almost any granular system, which includes numerous industrial processes. By understanding the Brazil nut effect, knowledge can be gained to create or prevent segregation within desired industrial processes.

In this project, the Brazil nut problem is examined through the use of stereoscopic X-ray imaging. The stereoscopic images are analyzed with a particle tracking algorithm to quantify large particle motion in three-dimensional space. Particle motion is quantified under a variety of operating conditions to both observe the particle motion and examine the accuracy of the particle tracking algorithm.

Keywords: Granular fluid flow, flow visualization, X-ray particle tracking, Brazil nut effect

INTRODUCTION

It was observed as early as the 1930s that the larger, heavier Brazil nuts tend to rise to the top of a can of mixed nuts [1]. However, the study of granular flows goes back much further, and many of the phenomena observed in granular flows are theorized to play critical roles in what has become known as the “Brazil nut effect” or the “Brazil nut phenomenon” [2, 3]. The understanding of this effect has broad application in industries ranging from agriculture to pharmaceuticals for both the sorting of granular media by size and the prevention of size segregation in processes that are intended to be homogeneous.

Numerous studies have examined the three predominant mechanisms theorized to cause the Brazil nut effect; these mechanisms are convection, geometric reorganization, and buoyancy [4-10]. Convection in granular flows was observed by Faraday, and is often seen coupled with a tilting of the surface of the bed from the horizontal, a phenomenon named “Faraday tilting” because of Faraday’s early research [2, 3]. Geometric reorganization (also known as void filling), however, is more specific to the Brazil nut effect. In geometric reorganization, the smaller particles fill voids under the larger ones as the system is vibrated, which ratchets the large particles upwards [10]. The third theory is the presence of air in the system causes the large particle to become buoyant [9]. Buoyancy has been less thoroughly researched than the other theories; however, even research concentrating on convection and geometric reorganization has found the air pressure in the bed can affect the movement of the particles [1, 3]. A comprehensive review of the available literature was compiled by Kudrolli [10].

It has been shown that under certain conditions the Brazil nut effect can be reversed, that is, the large particles forced to the bottom of the bed. The most researched way of creating this effect is to increase significantly the density of the large (intruder) particle as compared to the density of the bed [8, 11]. However, some researchers have been unable to replicate these results [1]. Other research has shown that changing the shape of the container holding the bed can also reverse the Brazil nut effect by preventing the intruder particle from reentering a convection current after it is trapped at the bottom [10].

The studies to date have a few limitations. First, most studies focused on pseudo-two-dimensional systems. This simplification allows for the use of a standard, visible light camera to image the system, and particles can then be tracked from the sequence of images [4-6]. However, this also induces a wall friction boundary condition on all particles that may affect the flow of the system [12]. Multiple studies have attempted to rectify this through the use of magnetic resonance imaging (MRI) and positron emission particle tracking (PEPT) [12-15]. The best results have been obtained using MRI technology; however, due to the time required to acquire one MRI image, the system must be excited through one cycle, stopped, imaged, and then the whole process repeated numerous times. This results in acceleration transients that would not exist under a continuous sinusoidal excitation and could influence the results [13]. While X-rays have been used to image granular fluid flows, at the time of this paper no other research group had been found using them to image the Brazil nut effect.

This paper presents updated research based on previous research by the same group [17] and addresses some of the shortcomings of the earlier work. First, in an attempt to replicate more closely the original phenomenon, actual nuts have been used for two of the bed materials, which is different from the fine powders used in many other experiments [3]. However, for the purposes of practicality and comparison with other studies, much of the research is conducted with finer granular material. Second, the motion of the bed container was constrained to translation in the vertical direction only. Third, a
particle tracking algorithm was developed to provide quantification of the qualitative results in the previous study.

EXPERIMENTAL METHODS

Vibration Apparatus

As shown in Fig. 1 and Fig. 2, the bed container consists of a 10.2 cm (4 inch) diameter acrylic tube with a height of 20.3 cm (8 inches) and a sealed bottom. This container is then bolted to a wooden base by threaded holes in the sidewall of the container. The wooden base is bolted to a lever arm used to obtain a higher amplitude vibration than a direct attachment to the vibration exciter would allow. This lever yields a maximum final amplitude of approximately 2.54 cm (1 inch) peak-to-peak. The vibration exciter is a Bruel and Kjaer Type 4809 vibration exciter with a force limit of 45 N (10 lb). The exciter is then clamped to a steel base with bar clamps.

Bed Materials

The bed materials are chosen to replicate the Brazil nut phenomenon as closely as possible. The first material is a commercial mixed-nuts blend, consisting of approximately 43% shelled peanuts, 23% whole cashews, 12% whole almonds, 12% whole Brazil nuts, 7% pecan halves, and 3% whole filberts by mass. The second bed material is 100% whole almonds. Almonds are used because their hard shells and low oil content reduces the bed packing. The final material is crushed walnut shell (used commercially as a blasting media), sifted to a size range of 500 – 600 microns. The walnut shell particles are too small to be imaged individually by the cameras, providing a smooth background, which improves the particle tracking accuracy.

Tracer Particle

The tracer particle was designed to emulate a Brazil nut while also being easy to track. This required a spherical particle because the particle tracking algorithm is not rotation invariant. The particle, shown in Fig. 3, is made of walnut wood, turned on a lathe, and sanded into a 1.8 cm (0.71 inch) sphere. It is then soaked in a solution of potassium iodide to increase its X-ray attenuation.

X-ray Imaging System

As shown in Fig. 4, the X-ray system consists of two Lorad LPX200 X-ray sources mounted at 90 degrees to each other. Across from each source is a Precise Optics PS164X image intensifier and a DVC-1412 Monochrome Digital Camera with a resolution of 1388(H) x 1024(V). However, for this study the cameras are set for 2 x 2 binning to obtain a maximum theoretical frame rate of 20 frames per second (fps), lowering the resolution to 640(H) x 512(V). The cameras are connected to a dual Intel Xeon quad-core with a processor speed of 2.66 GHz per core and 16 GB of RAM; however, the camera drivers limit the available RAM to 3.8 GB while imaging is in progress. Custom software is used to trigger the DVC cameras every 55 ms. This provides a slightly lower frame rate (18 frames per second) than the theoretical maximum; but also generates a more consistent frame rate. The exact time at which each frame is acquired is also recorded, accurate to 1 ms, to account for slight variations that might occur.

The images acquired directly from the camera are sequentially numbered 12-bit per pixel grayscale images. The same software that is used to acquire the images is also used to convert them from the native 12-bit format of the cameras (a format which is incompatible with most computers) to a standardized 16-bit per pixel grayscale format. The software also applies a correction for the pincushion distortion caused by the image intensifiers and tracks the location of the particle as described in the next section. More details on the X-ray amplitude. All of the control equipment was set up remotely so the vibration could be controlled while the X-ray sources were in use.
Fourier transforms to compute the convolution in the frequency domain. The denominator is computed using sum tables to eliminate redundant operations [22].

The template image used to track the particle is an image of the walnut wood tracker particle on a piece of foam; however, the X-rays are sufficiently powerful to saturate the foam, providing the radiograph template image in Fig. 3, with just the particle. This radiographic image is used as the template that is applied over the region of interest within the acrylic column for every image, for both cameras. The pixel location in the image wherein the maximum correlation resides is the center of the particle, and is exported to a Microsoft Excel file for further analysis.

For particle tracking to be most useful, the position of the particle should be relative to the bed material. This is not an issue in the x-direction and y-direction because the bed is constrained to prevent translation. However, the bed is vibrated in the z-direction, with a significant amplitude, causing the bed to move vertically in the image. To compensate for this further, the bed does not necessarily move in phase with the container.

As shown in Fig. 5, it is possible for a gap to occur between the bottom of the bed and the bottom of the container. The first frame in Fig. 5 shows the system as it is moving upward, compacting the bed of almonds. The next frame shows the system as it is moving downwards. The container is forced downward by the vibration exciter at a rate greater than the acceleration due to gravity. The bed however, moves downward primarily by gravitational forces (there is also a small downward force induced into the bed by friction with the downward moving container). This movement creates the gap beneath the bed, which must be compensated for to obtain z-positions relative to the bed. Furthermore, it is important to note that the bed stays as a cohesive block as it falls. Bed materials with a high oil content release oil from the impacts, which mixes with some of the powdered bed material inherent in the system to create an adhesive force that helps hold this block together.

To compensate for the gap beneath the bed, the location of the bottom of the bed in the z-direction is identified with a two-step edge detection. First, the bolt that holds the wooden platform to the lever is tracked using the same normalized cross-correlation method that is used to track the particle except with an image of the top portion of the bolt used as a template image. Next, a region that contains the bottom of the bed material is selected in the first frame. The software finds the offset between the bottom of the selected region and the detected location of the bolt. This value is used to adjust the region up and down based on the detected vertical position of the bolt so as to maintain a constant offset. The final step is to use a row-averaged thresholding algorithm to find the bottom of the bed, graphically represented in Fig. 6. The average of each row within the region of interest is calculated, depicted as the non-linear function in Fig. 6.

Error Estimation

There are a number of sources of error in the final calculated particle position. The first source of error is the limits of the acquisition hardware. The size of the pixels on the camera limits the position accuracy to +/- 0.02 cm. The image intensifiers used to acquire the X-rays also induce error into the system by warping the image, which must be corrected. By measuring the variation in detected location of the tracer particle in a static bed, the error in the unwarping algorithm was determined to be negligible.
The largest error is introduced in the normalized cross-correlation algorithm for both the particle and bolt, and the bottom of the bed detection algorithm. For all three, the error is estimated by selecting 50 random images and then manually defining the best position for the feature and then finding the deviation from the selected best position. Using this method the error of the particle detection is +/-0.08 cm in the x-direction and y-direction, and +/-0.07 cm in the z-direction. The z-direction error for the bolt detection is +/-0.07 cm and the z-direction error for the bottom of the bed detection is +/-0.14 cm. The x-direction and y-direction error were not measured for the bolt detection and bottom of bed detection because the x-direction and y-direction values are never used in the analysis. When combined, the total error is +/-0.10 cm in the x-direction and y-direction and +/-0.30 cm in the z-direction.

RESULTS

Particle Tracking Error

Due to background variation in the image, the particle tracking algorithm does not always correctly identify the tracer particle. When the algorithm incorrectly identifies the position of the particle it creates a significant position error. As is shown in Fig. 7, the uncorrected position can be incorrect by as much as 50% of the corrected position. Currently, the only way to obtain data without false detections is to go through every frame, and manually correct any false identifications. The result of this correction is shown as the corrected position in Fig. 7. While this is feasible for small data sets with low error rates, it is impractical for larger data sets. All of the position data in this study has been corrected for false detections, which brings the positional error of the particle tracking algorithm down to the previously indicated level of +/-0.07 cm.

As shown in Table 1, the detection rate is very high for both the walnut wood tracer soaked in potassium iodide in a bed of crushed walnut shells and for the head of the steel bolt in the plywood base of the system. The high detection rate is closely related to the evenness of the background and the distinctiveness of the template shape. As shown in Fig. 8, the crushed walnut shell provides a very even background due to the small size of the individual particles. The small size of crushed walnut shell particles also means that, in comparison to the background, the round shape of the tracer particle is very distinctive.

TABLE 1: TEMPLATE MATCHING CORRECT DETECTION RATES FOR TRACKED OBJECTS

<table>
<thead>
<tr>
<th>Object</th>
<th>Detection Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walnut wood tracer in almonds</td>
<td>59.9%</td>
</tr>
<tr>
<td>Walnut wood tracer in mixed nuts</td>
<td>95.1%</td>
</tr>
<tr>
<td>Walnut wood tracer in crushed walnut shell</td>
<td>98.7%</td>
</tr>
<tr>
<td>Steel bolt head in plywood</td>
<td>98.4%</td>
</tr>
</tbody>
</table>

This also explains why the mixed nuts had a high detection rate. While the nuts in the mixed nut blend are significantly larger than the crushed walnut shell, which causes background noise, the nuts are shaped differently than the tracer particle and each other. This shape variation helps break up patterns in the background that can fool the normalized cross-correlation algorithm. In addition, the mixed nuts were also very susceptible to packing, which reduced the void fraction in the bed and made for a more even background.
The high detection rates obtained for crushed walnut shell and mixed nut beds are in sharp contrast to the relatively low detection rate achieved with the walnut wood tracer in the bed of almonds. The shape of the almonds increases the void fraction of the bed, which in turn creates a variable background. This variable background has a somewhat regular pattern to it, which creates shapes that appear to the computer to be similar to the particle template. The background variation also superimposes a texture over the image of the particle in the bed, creating a lower correlation between the particle template and the particle in the bed. The combination of the increase in background variation and decrease in tracer particle correlation is enough to cause the reduced detection rate.

An attempt was also made at tracking another object, a Brazil nut soaked in potassium iodide and painted with silver paint (both treatments were to increase the X-ray attenuation of the nut). However, because the normalized cross-correlation algorithm is not rotation invariant, a suitably high detection rate could not be obtained despite being easily detectible to the human eye.

Particle Tracking Base Condition

In order to have a consistent basis of comparison, a base condition was chosen from which all other conditions could be compared. The base condition was a 5.08 cm (2 inch) high walnut shell bed vibrated at 10 Hz with the walnut wood tracer particle placed at approximately the center bottom of the bed prior to each test. The bed was also mixed by hand prior to each test to help eliminate the effects of packing. This base condition was chosen because it clearly demonstrated the Brazil nut effect, and worked well with the particle tracking algorithm.

The analysis of this condition with the tracking algorithm can produce either temporal graphs as in Fig. 9 or positional graphs as in Fig. 10. While the temporal graphs are useful for identifying when specific movements occur, the movement of the particle from the bottom of the bed to the top is of primary concern, and thus Fig. 9c is most useful. The positional graphs are most useful for observing the
movement of the particle as viewed from the top (Fig. 10a) and to observe any planar patterns in the flow. Ideally, the observation plane would be parallel to any flow patterns; however, in many cases it is not, so the closest plane is chosen, in this case Fig. 10b.

A note about the coordinate system is also necessary. All figures showing particle tracking data, including Fig. 9 and Fig. 10, show the center of the particle relative to the bottom center of the bed. This means x-position and y-positions may be positive or negative depending on the location relative to the center of the bed as viewed from above. The z-position however, will always be positive, as the zero is located at the bottom of the bed. It is also important to note that the bottom of the bed and the bottom of the container are not always the same, as the bed moves out of phase with the container. In addition, the particle tracking algorithm detects the center of the particle instead of the edge, therefore the closest the particle tracking algorithm will ever show to the edge of the bed is one particle radius, or 0.9 cm.

All four tests at the base condition show very similar movement. As seen in Fig. 10b, the particle has a tendency to move outward from the center of the bed as it moves upward. Once the particle reaches the top, it moves across the top of the bed at a rapid pace, in a direction opposite to the direction it moved as it rose. The rapid movement across the top of the bed is caused by a significant tilt in the top of the bed with respect to the horizontal. Once the particle reaches the top negative x, negative y edge of the container, it has trouble entering the downward portion of the current, and remains stuck at or near the top of the flow.

The motion of the intruder particle indicates that for this condition a single large, pseudo two-dimensional current is established within the bed. This current flows across the bottom of the bed in the positive x, positive y-direction, up along the positive x, positive y edge of the bed, down and to the negative x, negative y-direction along the top of the bed, following the inclination of the top of the bed, and then downward along the negative x, negative y edge. The current always appears to be established in this counter-clockwise (as viewed in Fig. 10b, looking to the positive y-direction) fashion. The reasoning for the bias towards a counter-clockwise motion is still undetermined.

For clarity, all further conditions will only show the z vs. t, y vs. x, and z vs. x plots.

**Variation in Bed Materials**

The base condition used for comparison is intended to be an analogue to the true Brazil nut effect as observed in cans of mixed nuts. To determine the effect of bed material, the 5.08 cm bed was filled with three different materials (crushed walnut shell, almonds, and mixed nuts) and vibrated at 10 Hz. Based on the information in Fig. 11, the crushed walnut shell bed does exhibit similar characteristics to beds of nuts.

The bed of almonds also appears to move along convection currents (Fig. 11b). However, as shown in Fig. 11a, these convection currents are not the single, pseudo two-dimensional currents that appear in the walnut shell. The movement of the tracer particle in a nearly vertical fashion from the start, along the top of the bed, and then downward at the edge indicate that the granular flow is establishing a toroidal convection current. That is, the flow moves upward at the center of the container, radially outward across the top, back down at the edges, and back to the center across the bottom. Unlike the walnut shell bed, when the tracer particle reaches the top, outside edge of the flow it appears to be able to enter the downward portion of the flow. This is likely due to the much smaller difference between bed particle and intruder particle size.

![FIG. 10: POSITION GRAPHS OF A 5.08 CM BED OF CRUSHED WALNUT SHELL, VIBRATED AT 10 Hz, FROM t = 0 TO t = 46 SECONDS. THE ARROWS INDICATE THE APPROXIMATE DIRECTION OF PARTICLE MOVEMENT.](image)
When the mixed nut blend is used for a bed material, a convection flow is either not established, or is stopped before size segregation fully occurs. As shown in Fig. 11b, the tracer particle moves almost vertically in the bed of mixed nuts. This movement occurs at a similar speed to that of the almonds and walnut shell beds; however, it stops once the particle reaches a height of 3 cm. There are three main possibilities for the cessation in movement. First, and most likely, the mixed nut bed is creating a toroidal convection current like the bed of almonds; however, after a short period of time packing begins. The higher oil content of the mixed nut blend causes oil to leach out of the nuts with each impact and this oil causes the nuts to begin to adhere to one another. This adhesion creates a single block of nuts, effectively halting all motion of the nuts relative to one another. The second possibility is that the movement of the tracer particle is caused by a different mechanism in the mixed nut bed, most likely geometric reorganization. Finally, it is also possible that a very heavy nut is directly over the tracer particle, creating enough downward force to counter any upward movement.

**Variation in Vibration Frequency**

Four different frequencies were tested in a 5.08 cm bed of crushed walnut shell, and all showed evidence of convection currents. As shown in Fig. 12, the 10 Hz, 15 Hz, and 20 Hz vibrations all appear to set up planar convection cells similar to the original 10 Hz vibration. The primary difference is the speed of the convection current, which decreases as the vibration frequency increases (Fig. 12c). This could be because the amplitude of the system decreases as the frequency increases, due to the power-limited nature of the vibration exciter. A larger system capable of increasing the frequency of vibration without changing the amplitude would be necessary to make a conclusive observation.

However, the 5 Hz vibration appears to create a different mode of convection than the other three frequencies. As shown in Fig. 12b, the tracer particle moves upward at almost the exact center of the bed, and then moves outward radially. This indicates that at 5 Hz the walnut shell bed is creating a toroidal convection current like the one observed in the bed of almonds vibrated at 10 Hz. However, because of the greater size difference between the crushed walnut shell particles and the tracer particle, the particle could not sink enough to reenter the flow as it did in the almonds.

**Variation in Bed Height**

Fig. 13 shows the effect of bed height on the tracer particle movement for bed heights of 5.08 cm, 7.62 cm, and 10.16 cm. From Fig. 13b, it is observed that all three cases move across the whole bed in a counter-clockwise convection current, exactly as the base condition did. In fact, through the first 5.08 cm of the current, the particles for all three heights took almost the exact same path. However, as shown in Fig. 13c the rate at which the tracer particle moves upward decreases as the bed height increases. The extra height of bed clearly slows the velocity of the current. This difference is likely caused by a change in amplitude due to the extra weight on the system. Further testing with a system that can hold a constant amplitude when the bed height is varied is necessary to determine for sure.
FIG. 12: 5.08 CM WALNUT SHELL BED VIBRATED AT 5 Hz, 10 Hz, 15 Hz, AND 20 Hz.

FIG. 13: WALNUT SHELL BEDS OF HEIGHTS 5.08 CM, 7.62 CM, AND 10.16 CM, VIBRATED AT 10 Hz.
FUTURE WORK
To determine the nature of the Brazil nut effect conclusively, three changes are required for future work. First, multiple individual particles in the bed should be tracked in addition to the larger tracer particle used in this study. This will show if the large particle follows the same currents as the bed, or if it is moving independently of the bed movement. Second, a more powerful system should be built, capable of changing frequency without affecting the amplitude so a determination can be made if the reduced speed as frequency increases is due to the change in amplitude or another effect. Finally, the particle tracking algorithm should be improved to yield fewer false detections, particularly with images containing an uneven background, thereby allowing a larger amount of data to be processed.

CONCLUSIONS
A normalized cross-correlation method of template matching was used effectively to track the location of a particle in a vibration-fluidized granular bed. It was shown that strong convection currents occur within vibration fluidized granular flows. The convection currents appear to occur in two predominant modes. The first mode observed is a pseudo two-dimensional current across the entire bed. The second mode is a toroidal current with the center of the bed rising and the edges sinking. Different bed materials were shown to create different modes of convection, with the larger bed particles tending to show a toroidal current. This same current was also found in low frequency vibration of a bed with smaller bed particles; however, as the frequency was increased, the convection mode switched to a single large, counter-clockwise current across the entire bed. This same current was observed in all variations of the bed height; however, the velocity of particle movement decreased as the bed height increased.

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