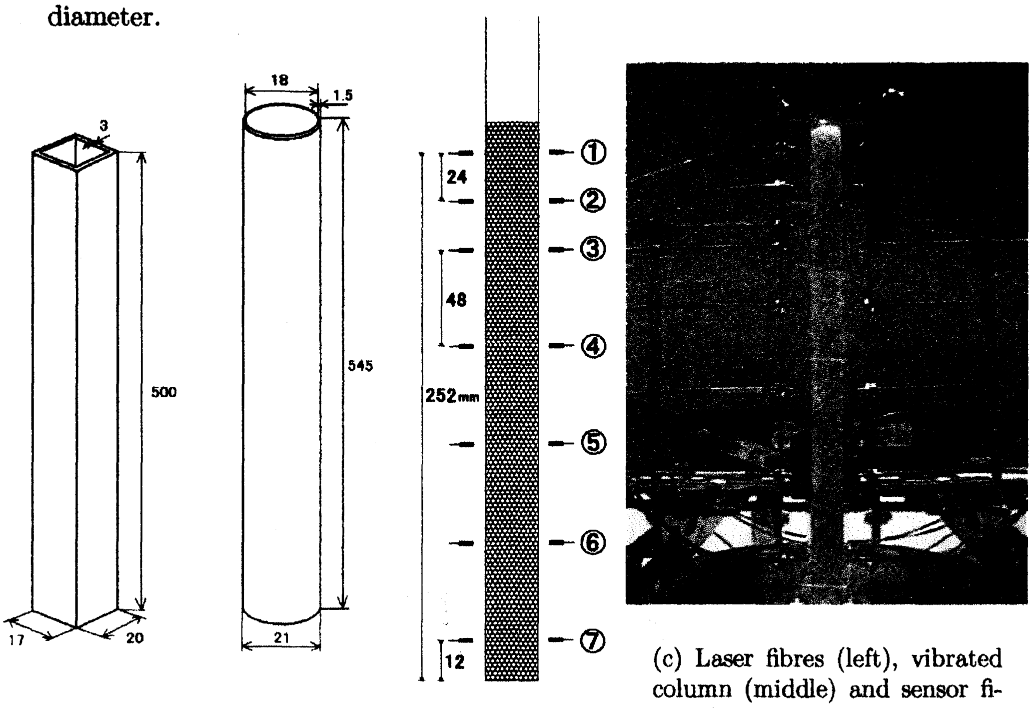
数理解析研究所講究録 1413 巻 2005 年 84-93

Vibration-induced compaction in elongated vessels

Hans-Georg Matuttis, Takumi Kinouchi, The University of Electro-Communications,
Department of Mechanical Engineering and Intelligent Systems,
Chofu, Chofugaoka 1-5-1, Tokyo 182-8585, Japan
Hide Sakaguchi, IFREE, JAMSTEC
3173-25, Showa-machi, Kanazawa-ku Yokohoma 236-0001, Japan

Abstract: We have succeeded in calibrating laser intensity measurements so that we can resolve density differences of less than one percent for static packings and fluidized beds. We measured densities for granular material ensembles in a vibrated elongated vessel for variously shaped beads. The density measurement allows to identify the depth of convection cells. It is found that the depth of the convection cells decreases with vibration frequency and smooth, but irregular shaped glass beads form shallower convection cells than spherical glass balls of the same average diameter.



(a) Dimensions of the vessels

(b) Laser Positions

(c) Laser fibres (left), vibrated column (middle) and sensor fibres (right)

Figure 1: Dimensions of the setup

1 Introduction

A general problem in granular material research is that ideal setups for experiments (including e.g. the roughness of the grain surface) are usually "too dirty" for the simulation, whereas the idealized assumptions of e.g. spherical particles don't reproduce the results found in experiments wit actual granular materials. We want to investigate the density for vibrated granular materials in narrow vessels to gain an understanding of compaction and fluidization. We decided to use an optical measurement, because for the frequencies we are interested in (up to 800 Hz), it is faster than NMR[1], saver then X-ray[2] measurements and can be realized at lower costs and a more versatile setup.

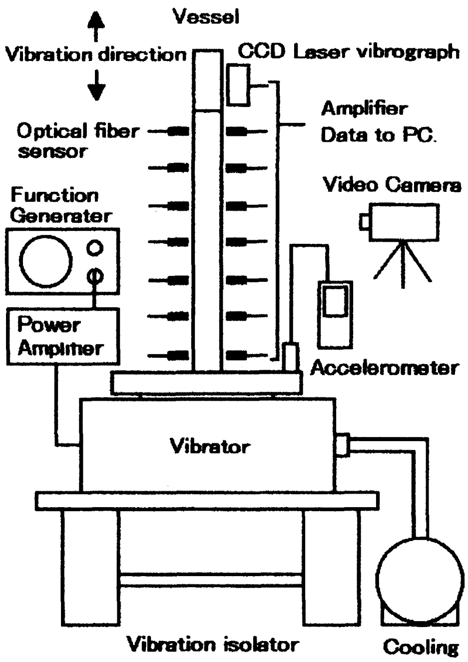


Figure 2: Full setup

For the compaction by vibration in a narrow pipe, we want to set up an experiment which allows to vary the experimental conditions to develop a better understanding about which "idealized" conditions can be taken for granted in the simulations for the sake of reproducing experiments, and which "idealized" conditions for the sake of the simulation can be realized in the experiments. From the point of simulations, spherical particles are easier to simulate than non-spherical particles. Also, in a simulation, it saves computer time to "throw in all particles at once", then to slowly fill up the vessel, which is easy experimentally. To avoid the problem, often encountered in granular media research, that different processes are investigated in experiments and simulations, we design the experiment from a theoretician point of view, and then vary the experimental conditions from "simulation type" to "experimental type" to understand the effect of subtle changes in the setup.

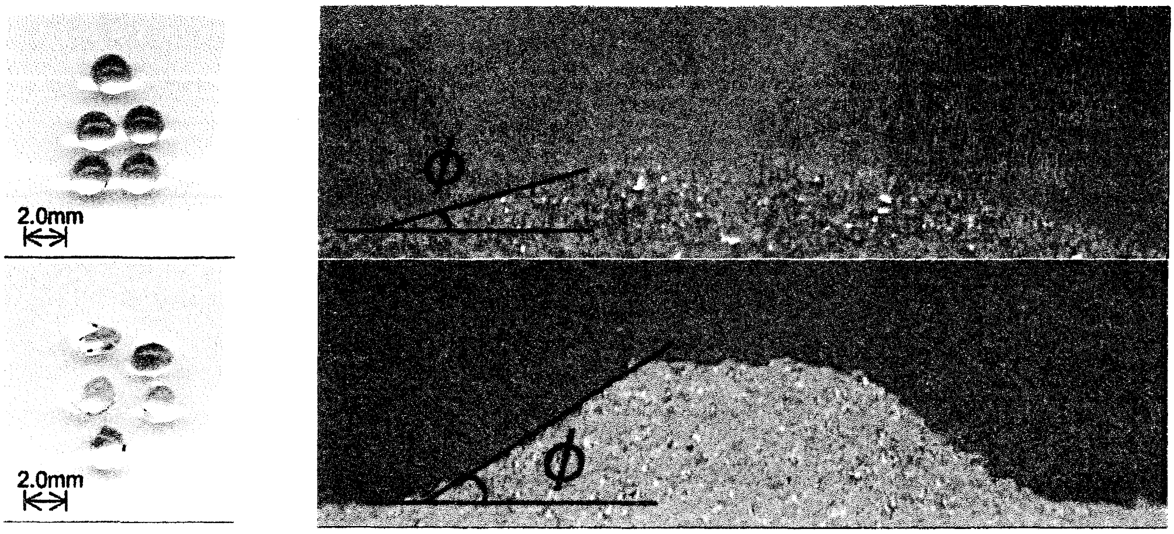
2 Measurement Setup

The setup[1] is shown in Fig. 2. Because we cannot assume that the density for ongoing vibration the same as when the vibration is stopped, we decided to measure the density both with and without vibration by laser light transmission intensity, instead of the more mundane weight- and volume determination. The Froude number was fixed at 0.55 G and the vibration behavior was observed over a wide frequency range (from 40 Hz to up to 800 Hz in some cases), whereby the amplitude was adapted accordingly. The accuracy for the amplitudes can be seen in Tab. 1.

Freq. (Hz)	Amp. (mm)	error-bars (mm)
40	0.78	±0.005
70	0.28	±0.005
80	0.22	±0.005
100	0.14	±0.005
200	0.033	±0.005
300	0.0155	0.015-0.016
400	0.0095	0.009-0.011
500	0.0065	0.0062-0.0067
600	0.0055	0.005-0.006
700	0.004	0.004-0.0049
800	0.0035	0.0032-0.0045

Table 1: Accuracy for the amplitudes for vibration measurements with 0.55 G

[1]Vibration Test System: IMV CORPORATION (/Power Amplifer VA-ST-03 with Vibrator /VE-50) /VS-30-03; Frequency Generator: NODE COPORATION Oscillator /6111; Cooling: Fuji Electric CO. LTD, Ring Blow /VFC108P; Vibration table: HERZ CORPORATION, Air-suspended Vibration Isolater /HOA-LM series; CCD Laser vibrograph: Keyence CCD Laser Displacement Sensor /LB-62, LB-02, KZ-U3



(a) Spherical and non-spherical beads

(b) Critical angle for the spherical beads (17^o,above) and non-spherical beads (32^o, below)

Figure 3: Shape and critical angle for spherical and non-spherical (but still convex) beads used in the experiments

2.1 Choice of Particles

The smaller the particles are, the more air-glass interfaces meets the laser beam and the more scattering occurs. We had to adapt the material for a given vessel diameter to the fact that the necessary resolution < 1 % could only be obtained if the readings in Fig. 4 were well above 100 counts, down from maximal 4000 counts. For too small particles the intensity decreased too strongly. Because the particle diameters where close around 2 mm for all particles used, no segregation effects during the convection are to be expected.

Densities in the following are normalized so that massive glass has density 1, the hexagonally closest packed density for mono-disperse particles corresponds to a density of 0.72. We prepared the initial densities in two different ways: The high density (66 % for for glass beads, 68 % for non-spherical beads) was realized by filling particles into vertical the vertically standing vessel from a hopper. The low density packing (62 % for glass beads, 61 % for non-spherical beads) was realized by filling the material into the horizontally lying vessel and then tilting it upright. Because our particles are not strictly mono-disperse, higher densities are in principle possible in our setup.

Yamazaki et al.[3] had used a laser sheet for the density-wave measurements in pipe-flow, but in such setup, densities had to discriminated which varied from 0 to closest packing and even varied by a factor of two in the dense case. Whereas these density variations are visible already for the naked eye, nothing can be done without instruments for a vibrated vessel filled with glass beads. The densities can be expected to be around 0.72. For dense granular materials, the density deviations due to the packing process/ shearing have been found to be of the order of 5 % in experiments[4] and simulations[5, 6].

2.2 Laser Measurements

We decided to use point-like laser beams, not a laser-sheet, because we can expect that if the light is scattered away from the laser beam axis and is not detected any more, we will obtain a better resolution than if the light of the laser sheet it scattered in the plane and can still reach the detector. We performed measurements for the "static case", where the vibration was interrupted after five seconds, and the reading was taken from the instruments[2] directly, see Fig. 4. In the "dynamic case", where the vibration continued without interruption, the measurement was also taken continuously[3].

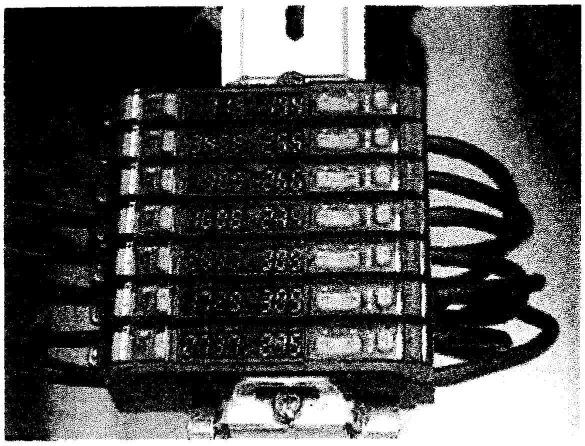
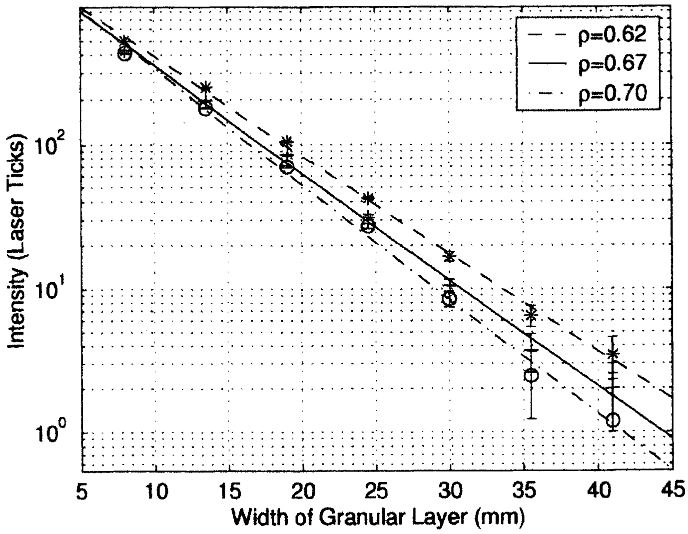
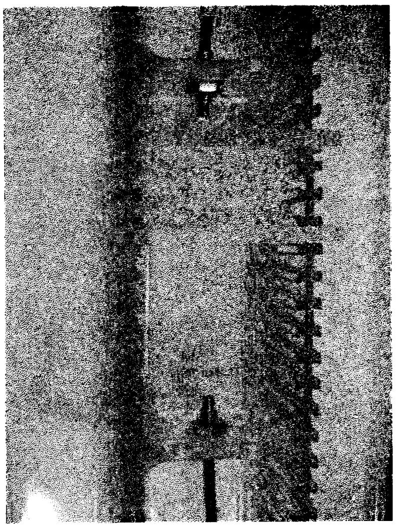


Figure 4: Outgoing (left) and incoming (right) laser intensity reading



(a) Calibration-curve for the non-spherical beads; Error bars for four independent measurements



(b) Reference vessel with adjustable width used for the calibration

Figure 5: Calibration for the laser transmission

On top and near the bottom, we reduced the distance between the measurement points (see Fig. 1(b) and Fig. 1(c)) to obtain a higher resolution where the boundaries (free on the top, fixed on the bottom) can be expected to have an influence on the packing. Our laser light comes through fibres, not from the laser directly, so the beam is conical, not cylindrical. The distance between the outlet of the laser fiber and the vessels, especially for the cylindrical pipe, had to be adapted in such a way that the acryl of the pipe could neither act as a lens nor as a light conductor to the sensor. Additionally to the density

[2]Keyence Fiber Optic Sensor /FS-V21RM, FU-77, MS-H50

[3]Keyence Data Acquisition • Monitoring System /NR-110

measurement, we used a laser distance sensor (visible in Fig. 1(c) as black square box from with a thick cable) to verify the vibration amplitude (see Tab. 1).

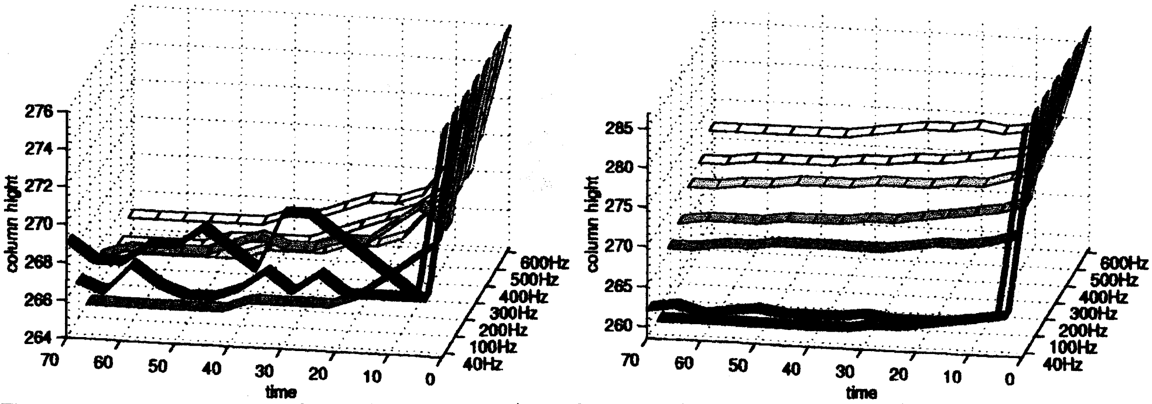


Figure 6: Compaction for spherical (left) and non-spherical particles (right), as indicated by the height of the granular column

2.3 Calibration

The idea behind the density measurement is, that in an assembly of white glass beads, the light scattering occurs only on the grain-surface; The higher the density, the more grain surfaces are found in a given volume. The system was calibrated by measuring the transmission loss for different granular volumes prepared with identical particle densities (measured by a volumetric and a mass measurement), and the curves fell nicely on an exponential curve (for an example, see Fig. 5(a)).

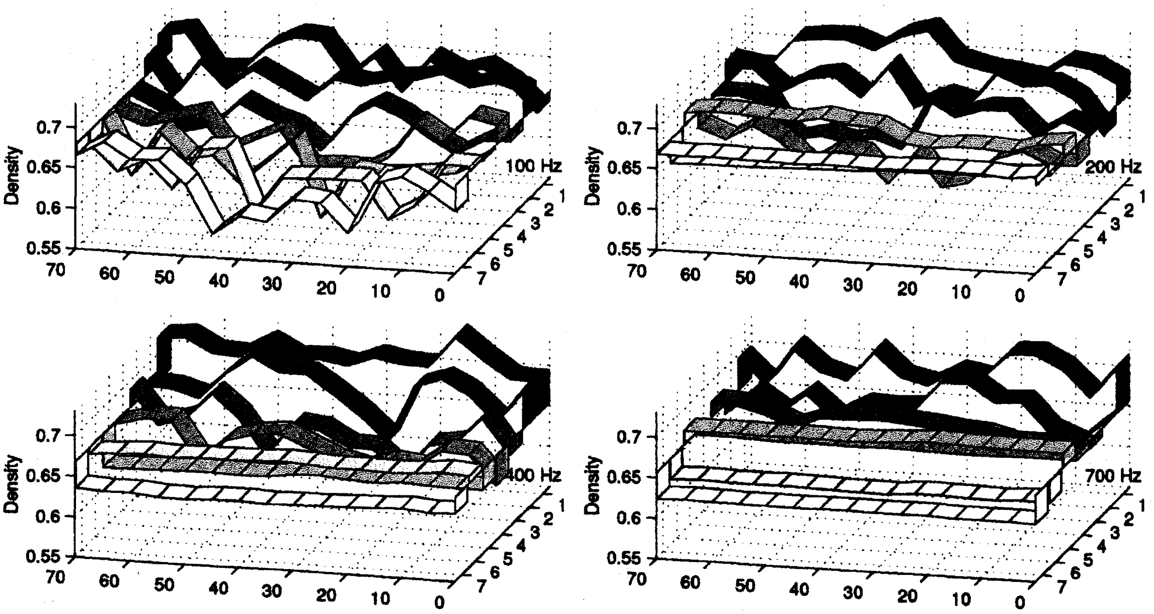


Figure 7: Density response for spherical glass beads with an an average density of $\rho = 0.66$, for all seven sensors (x-axis) between 0 and 70 seconds (z-axis).

The experiment was repeated for the same volumes, but different densities (e.g. by tapping, higher densities would be obtained), so that different transmission loss curves were obtained, in a test vessel, see Fig. 5(b). Of course, these calibrations had to be

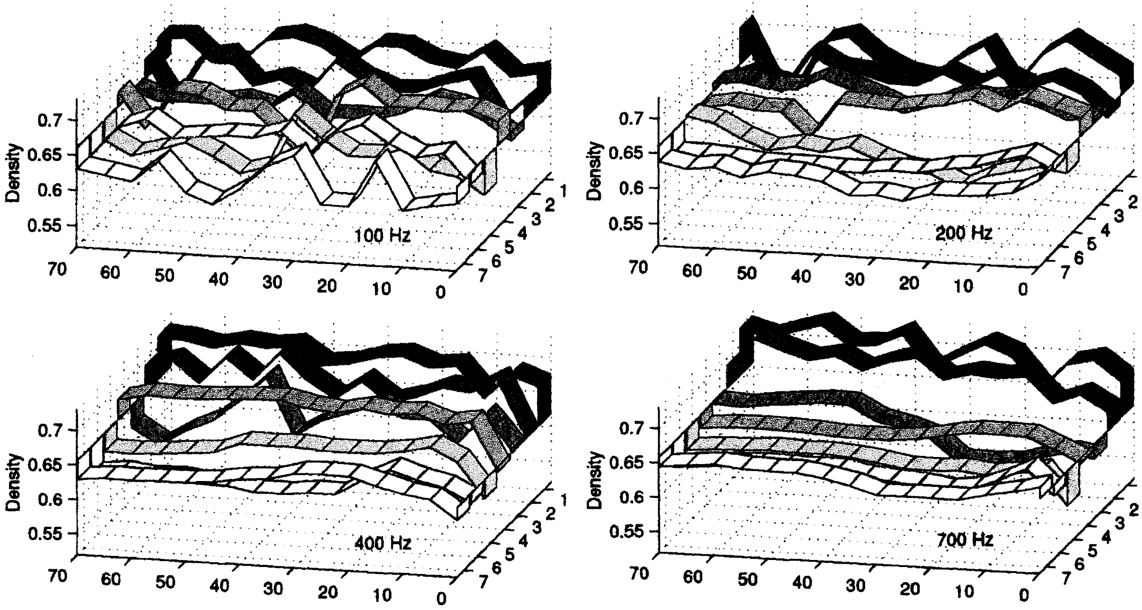


Figure 8: Density response for spherical glass beads with an average density of $\rho = 0.62$, for all seven sensors (x-axis) between 0 and 70 seconds (z-axis).

repeated for each different kind of beads used in the experiments. In this sense, the measurement methodology is an averaging mechanism. Because the detectors of the opposite sight are sensitive only to the wavelength of the laser, other light sources have no influence on the intensity and the experiment can be performed in broad daylight. The occurrence of an exponential intensity loss is by no way trivial in soft-matter physics: For foams, a power-law for the time behavior[7] makes also a power law-dependence on the system size likely, due to the connection of finite-time and finite-size scaling. From the possible measurement speeds (i.e. the time intervals for which the intensity was accumulated) "Fine" (250 μs), "Turbo" (500 μs), "Super Turbo" (1 ms), and "Ultra Turbo" (4 ms), we used the latter. The highest speed, "Fine", gave erratic results, which are probably due to laser speckles.

3 Results for static experiments

In the first part of the experiments, we show the results for the "static" measurements where the vibration was stopped after 5 seconds. The size of the convection cell stays constant, also if the filling height is changed; only if the bottom of the convection cell comes near the bottom of the vessel, interaction/interference effects result The location/ direction of the convection cell changes with the frequency, as the dissipation strength of the different volume elements changes.

3.1 Result for compaction

As preparation, we measured the height of the vibrated column in Intervals of 5 seconds without spatial resolution for the low-density regime both for the spherical (density 0.62) and the non-spherical (density 0.61) particles. The result in Fig. 6 shows cause a marked periodic variation of the column height for small vibration frequencies, which is practically

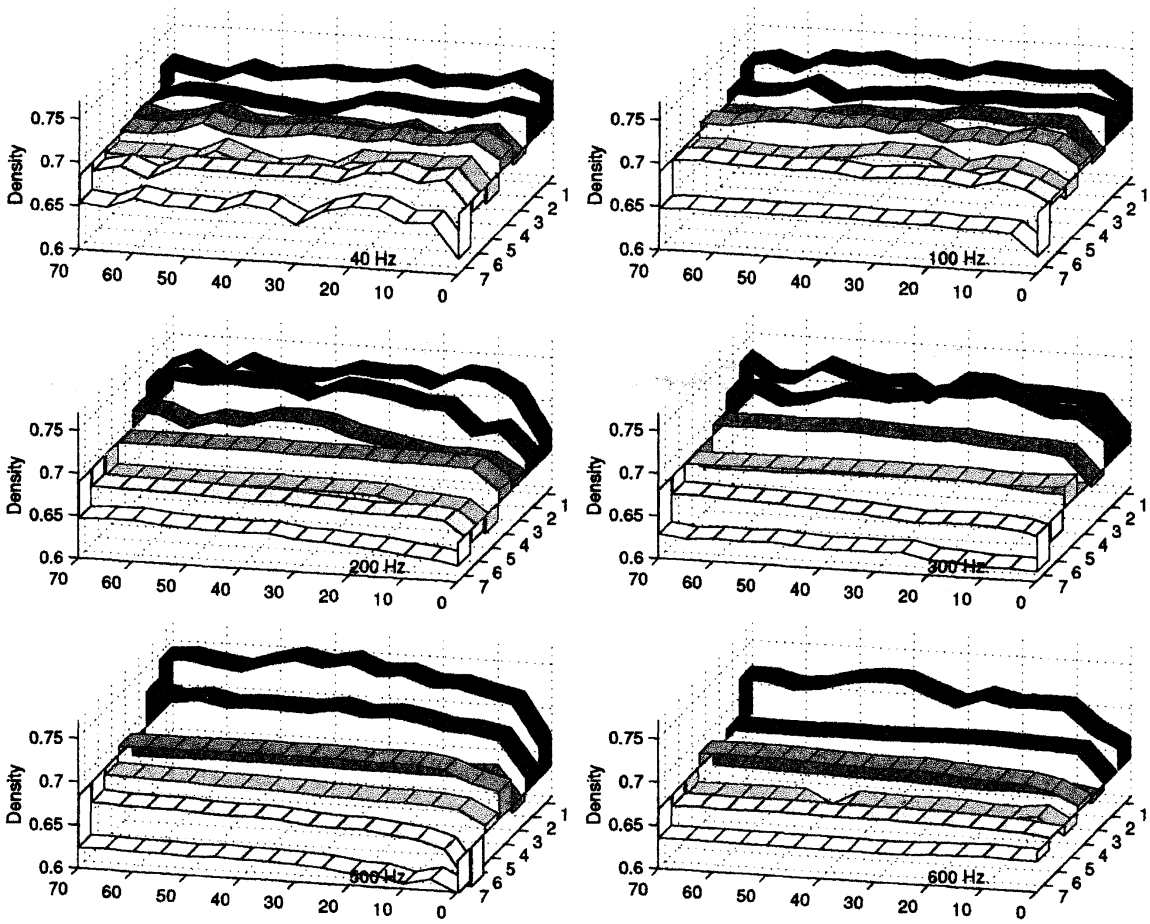


Figure 9: Density response for non-spherical glass beads with an an average density of 0.61.

absent for the non-spherical beads, which is due to convection cells. The decay of the column height for both kinds of particles from 5 s on are consistent with power law decay (except for parameters for which no decay takes place at all, e.g. for 40 Hz and 100 Hz for the round particles). The decay of the height before 5 s is definitely faster than power-law decay: There is the impression that the system basically relaxes into the high-density state (density 0.66 for spherical and density 0.68 for non-spherical particles). In the following sections, we use time-resolution to investigate whether the low-density state after a vibration time of 5 s can really be considered to the initial state at high density.

3.2 Spherical Glass Beads

For spherical beads (see Fig. 3(a), above) the time series for the densities $\rho = 62$ are shown in Fig. 8 and those for the densities $\rho = 66$ are shown in Fig. 7, where the density change indicates convection, whereas constant density indicates a non-moving, compactified volume element. The convection cell, which from 40 Hz (not shown) to 100 Hz reached from the bottom of the cell to the top, becomes shallower for increasing frequency/ decreasing amplitude. The surprising result is that the density of the granular material in the height where convection cells exist are higher than for the resting material below.

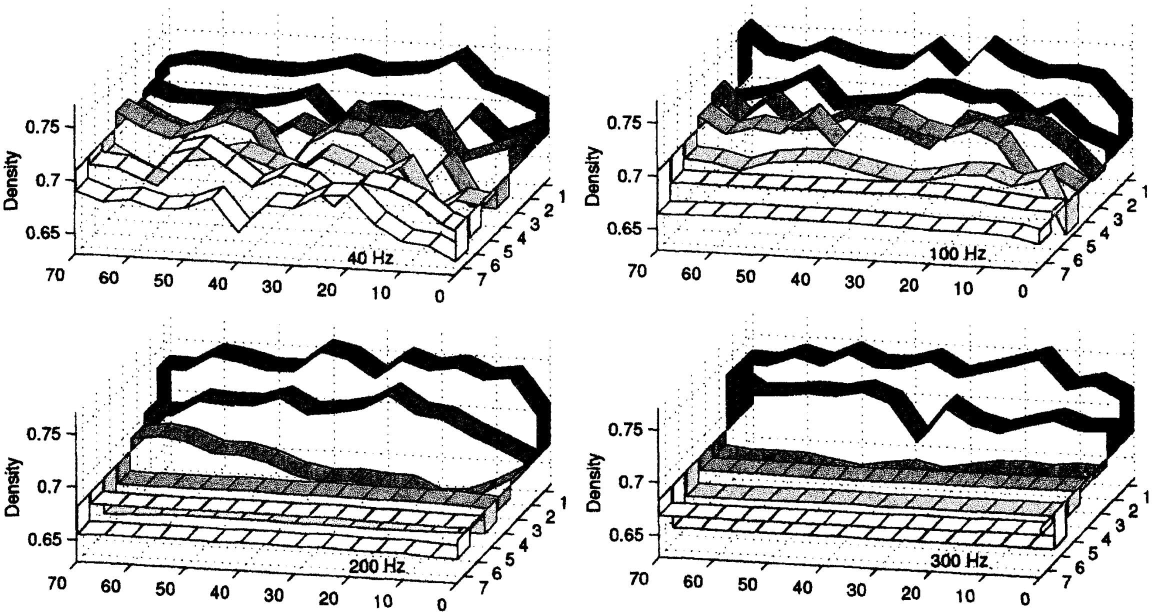


Figure 10: Density response for non-spherical glass beads with an an average density of 0.68. .

3.3 Non-Spherical Glass Beads

For non-spherical beads (see Fig. 3(a), below) the time series for the densities $\rho = 61$ are shown in Fig. 9 and those for the densities $\rho = 68$ are shown in Fig. 10. Again, density changes indicate convection, whereas constant density indicates a non-moving, compactified volume element. The convection cell, which for 40 Hz reached from the bottom of the cell to the top, already does not reach the bottom any more for 100Hz, in contrast to the round beads. The convection cell becomes shallower much faster than for the round beads, and at the highest amplitude, the movements of the material can only be detected with the highest sensor. Again, as in the case for round particles, the higher layers show higher density than the lower layers. The results (not shown) obtained when using the round pipe (see Fig. 1(a), right) as a vessel were not significantly different.

4 Dynamical Density Measurement

In addition to the "static" density pressure measurement described in the previous section, where we stop the measurement after a certain duration for the vibration and measure the density, with our setup we can also measure the density continuously during the vibration. The results can be seen in Fig. 11 for non-spherical particles for various Frequencies. The time-resolution for 50, 100 and 200 Hz was 20 ms, 10 ms and 5 ms, respectively. The rather surprising result is that in cases where, for e.g. 200 Hz, the "static" measurement showed a rather oscillating behavior, the continuous measurement reveals a monotonic increase of the density, up to saturation. In general, the system with smaller densities show larger density fluctuations. As for the "static" case, the densities for the sensors at the highest position tend to be higher than the densities for the lower positions: Arching prohibits the compaction/densification in the lower layers also for continuous, ongoing vibrations and high sampling rates.

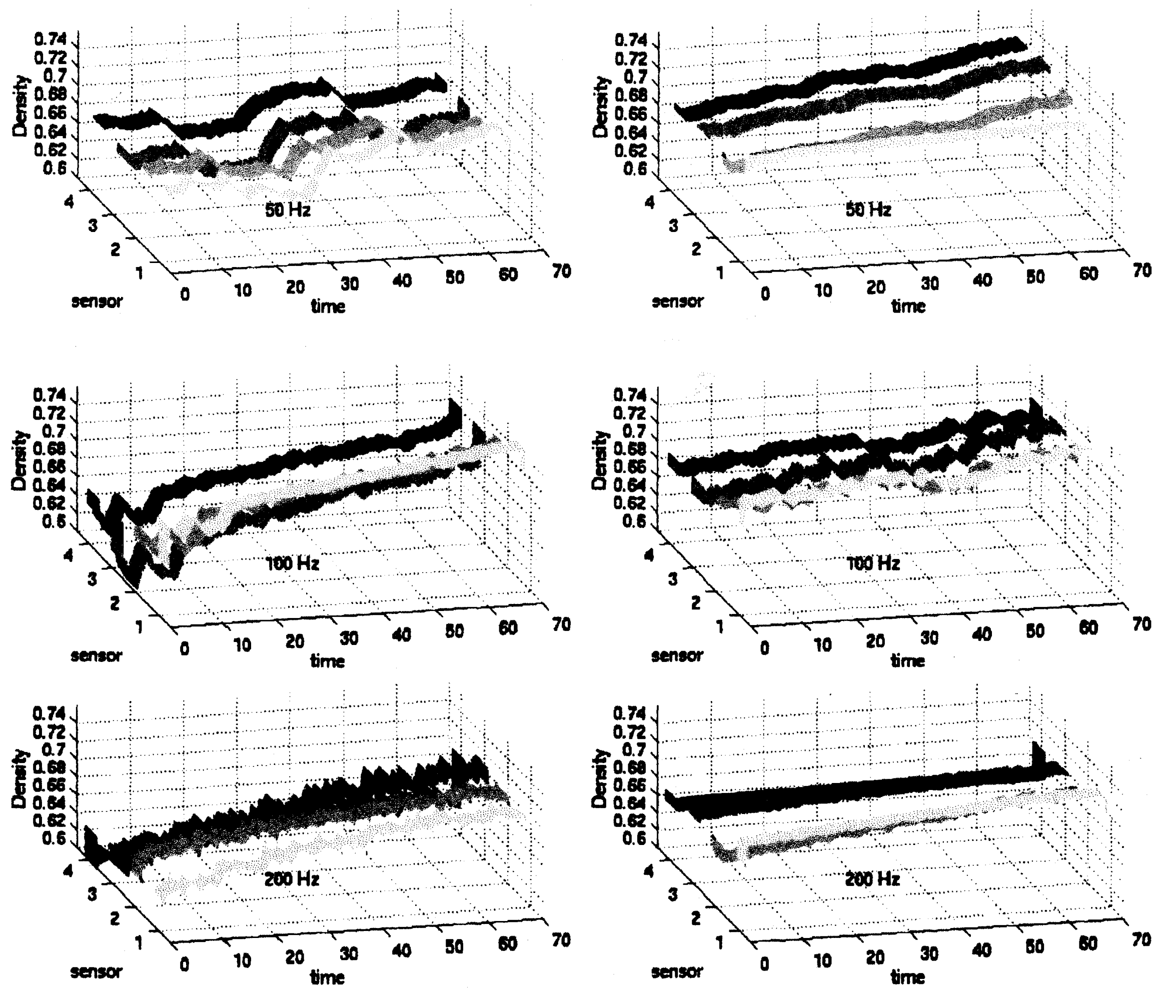


Figure 11: Continuous density response for non-spherical glass beads for initially low (left) and high (right) density with moving averages of 200 measurement points. .

5 Conclusions

We have successfully tested laser transmission as a feasible approach for fast and accurate density measurements of glass beads if the layer size is not too large. "Mechanical" measurements are not able to resolve the actual densities during "fast" processes like vibration.

The density in the vibrated column is far from homogeneous, especially for high frequencies, the pressure lasting on the lower layers seems to stabilize arches in the lower regions and therefore the "solid" material has a higher density than the more "fluid" phase on top. "As usual", round/spherical particles turn out to from less stable aggregates then non-spherical particles with comparable surface roughness, as indicated by the deeper convection cells. For simulations, even in the presence of walls, one can conclude that round particles are a "bad approximation" for processes where granular convection occurs. If if one finds strong fluidization tendencies for round particles, this tells nothing about "real" granular materials.

The different height of the convection cells for for high and low densities, both for spherical and non-spherical grains, indicates history effects even in vibrated systems: The initial state is remembered even if the frequency is as low as 40 Hz and the amplitude is nearly the particle radius.

For vibrated systems, continuously sampled systems will show different results than measurements taken when the vibration is interrupted, be it in simulations or experiments.

Whereas the angle of repose can characterize granular materials only in the absence of external vibration, the size of the convection cells in an elongated column seems to bee a good parameter to classify the effects of irregularity of the particle shape/surface in dependence of an external vibration frequency.

References

[1] E. Ben-Naim, J. B. Knightband E. R. Nowakd, H. M. Jaeger, and S. R. Nagel. Slow relaxation in granular compaction. *Physica D*, 123:380–385, 1998.

[2] P. Philippe and D. Bideau. Compaction dynamics of a granular medium under vertical tapping. *Europhys. Lett.*, 60(5):677–683, 2002.

[3] Yoshihiro Yamazaki, Sayako Tateda, Atsushi Awazu, Taichi Arai, Osamu Moriyama, and Mitsugu Matsushita. Dynamics of granular flow through a vertical pipe under the control of inflow rate. *Journ. Phys. Soc. Jap.*, 71(12):2859–2862, 2002.

[4] J. Šmid, Pham Van Xuan, and J. Thýn. Effect of filling method on the packing distribution of a catalyst bed. *Chem. Eng. Technol.*, 16:114–118, 1993.

[5] Alexander Schinner, Hans-Georg Mattutis, Junya Aoki, Satoshi Takahashi, Keiko M. Aoki, Tetsuo Akiyama, and Klaus Kassner. Towards a micromechanic understanding of the pressure distribution under heaps. In *Mathematical Aspects of Complex Fluids II*, volume 1184 of *Kokyuroku*, pages 123–139, Kyoto University, 2001. Research Insitute for Mathematical Sciences.

[6] Alexander Schinner, Hans-Georg Mattutis, Junya Aoki, Satoshi Takahashi, Keiko M. Aoki, Tetsuo Akiyama, and Klaus Kassner. History-dependent structure in granular piles. In Y.Kishino, editor, *Powders & Grains 2001*, pages 499–502, Rotterdam, 2001. Balkema.

[7] D. J. Durian, , D. A. Weitz, and D. J. Pine. Scaling behaviour in shaving cream. *Phys. Rev. A*, 44(12):R7902–R7905, 1991.