Ignaz-Günther-Gymnasium

Seminararbeit

Thema: Flat Self-Assembly

Zusätzlich Kurztitel (Nur falls das Thema mehr als 3 Zeilen zu je 44 Zeichen lang ist):

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Leitfach: Physik

Seminarkürzel: 2PH_W

Lehrkraft: Dr. Th. Grillenbeck

Abgabe der schriftlichen Arbeit am: *[Datumsstempel Sekretariat]*

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Bewertung	*Note*	*in Worten*	*Punkte*		*Punkte*
schriftliche Arbeit				*x 3*	
Abschlusspräsentation				*x 1*	
				Summe	
Gesamtleistung** nach § 29 (7) GSO = **Summe : 2 (gerundet)					

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Unterschrift der Lehrkraft

Content

1 Introduction

Flat Self-Assembly describes the phenomenon of the crystallisation of particles on top of a vibrating surface. I came across this phenomenon, when I participated in GYPT[1] 2019, the German young physicists' tournament. In that competition every participant had to select one of 17 physics problems[2], do experiments regarding that problem and in the end present their results to an opposing team and a jury. The problem I selected was problem number 11, "Flat Self-Assembly" with the following task:

> "Put a number of identical hard regular-shaped particles in a flat layer on top of a vibrating plate. Depending on the number of particles per unit area, they may or may not form an ordered crystal-like structure. Investigate the phenomenon."

So, if I were to take some small particles, for example screw nuts, and put them on some sort of vibrating plate, e.g. a shaker or a big loudspeaker they should arrange themselves in an ordered crystal-like structure. To investigate this phenomenon, I first needed to know what exactly a crystal structure is, so I will first talk about the definition of crystal structures. Then I will present the different setups that I used for my experiments. After that I will take a closer look at the phenomenon by sharing my observations and then illustrate how different parameters like the frequency, the amplitude and the waveform and the properties of the particles, such as their material and their weight influence the process. I will then talk a bit about real-life applications of the experiments and finish off with a summary.

[1] https://www.gypt.org/
[2] https://iypt.org/wp-content/uploads/2019/01/problems2019_signed.pdf

2 Crystal structure

A crystal structure is a structure whose smallest particles are arranged in a repeated pattern. The overall structure depends on the size and shape of the particles. In material science, there are two main types of solids, crystalline and amorphous [1], which are shown in Fig.1.

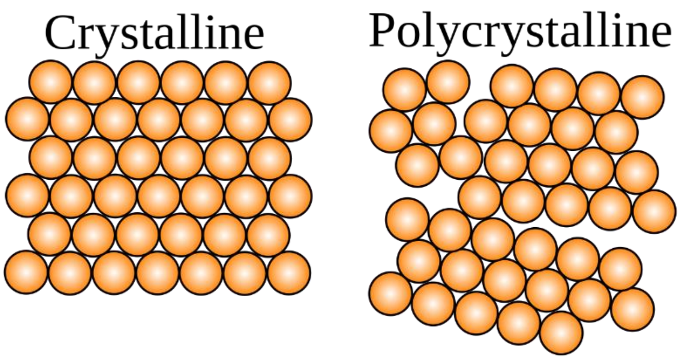

Fig. 1 two main types of solids, left: crystalline, right: amorphous, centre: polycrystalline

The crystalline structure is an ideal state and most crystals are polycrystalline, which means that they consist of multiple clusters of crystalline structures, because there are often particles in between that do not fit into the pattern and therefore inhibit the formation of a monocrystalline structure [2]. In the experiments I conducted in preparation for this paper I aimed at achieving the transition of the particles from an unordered to a polycrystalline structure.

3 My experiment

3.1 Setup

For my initial experimental setup, I used a “Leleux Vibrator 7032”, a device that is usually used for mixing fluid compositions. This setup, however, turned out to have many disadvantages, such as a fixed frequency of 50 Hz and a very small range of adjustable Amplitude. In addition to that, it didn’t have a flat surface to put the particles on, which is essential for the experiments to be valid. These downsides made the vibrator very impractical, so I had to come up with another setup.

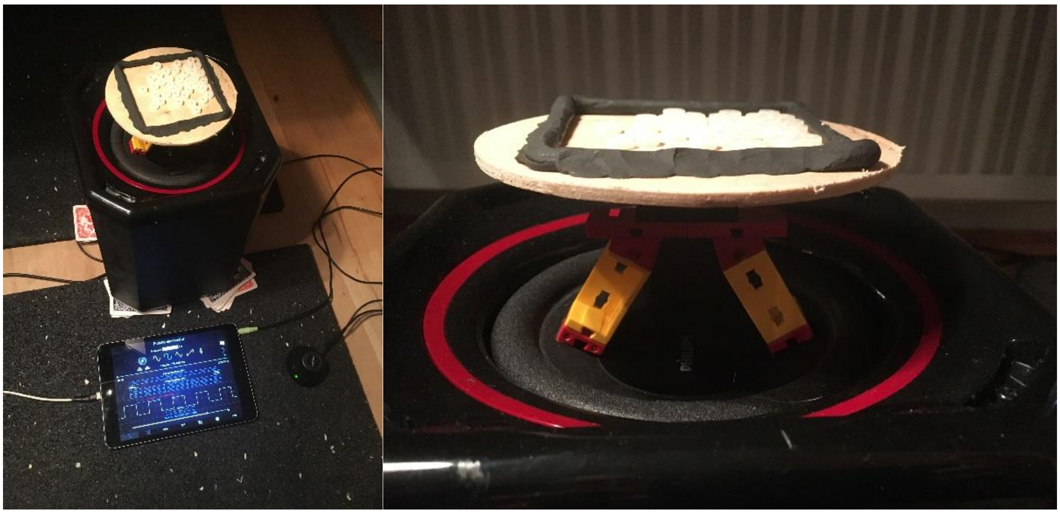

Fig. 2 second setup
left: loudspeaker (black), plate, particles, modelling clay, iPad with function generator app, playing cards, amplifier (bottom right),
right: plate, particles, modelling clay, Fischertechnik construction

For the second setup [Fig. 2], that I used for my experiments, I partially disassembled my loudspeaker and put it upright. I then glued some Fischertechnik[3] parts directly to its diaphragm, in a way that I could easily mount plates of different sizes on top of the speaker. Because a flat, horizontal surface is necessary to allow free movement of the particles, I put a pile of playing cards beneath each of the speaker’s corners, so that I could easily add and remove cards in order to adjust its orientation and therefore the orientation of the plate. To make sure the particles would not fall off the plate, I used modelling clay as confines, because it could be easily formed, applied to, and removed from the plate. To create the sinusoidal vibration, I connected the speaker to an iPad via an amplifier and used an app called “Audio Function Generator”[4] with which I was able to easily adjust the frequency and the amplitude as well as the form of the vibration. Despite the easy build, this design still had two downsides: on the one hand it was very noisy, and on the other hand the amplitude of the vibration decreased with increasing frequency which is a quite common behaviour for loudspeakers but it created some complications in my experiments, which I will address again later.

[3] https://www.fischertechnik.de/en
[4] https://apps.apple.com/us/app/audio-function-generator/id768229610

3.2 Execution

For measuring the results of my experiments, I usually spread the particles on top on the plate and made sure that they were not obviously arranged in a crystal structure beforehand but rather just distributed randomly among it. For some experiments I filmed the particles from above with an iPhone so that I could examine them again afterwards, but usually I just took notes on the parameters and on what I observed.

4 Phenomenon

4.1 Observation

When the parameters (frequency, amplitude, number of particles, particle mass and size) were right, the following behaviour could be observed: The particles move freely on the surface of the plate within the boundaries of the modelling clay. When two particles collided, they seemingly sticked together until most particles were arranged in a polycrystalline structure. [Fig. 3] The duration of this process depended strongly on several starting conditions such as the deployment of the particles and therefore varied a lot, but on average, it took about 40 to 60 seconds, until a (poly-)crystalline structure was observed.

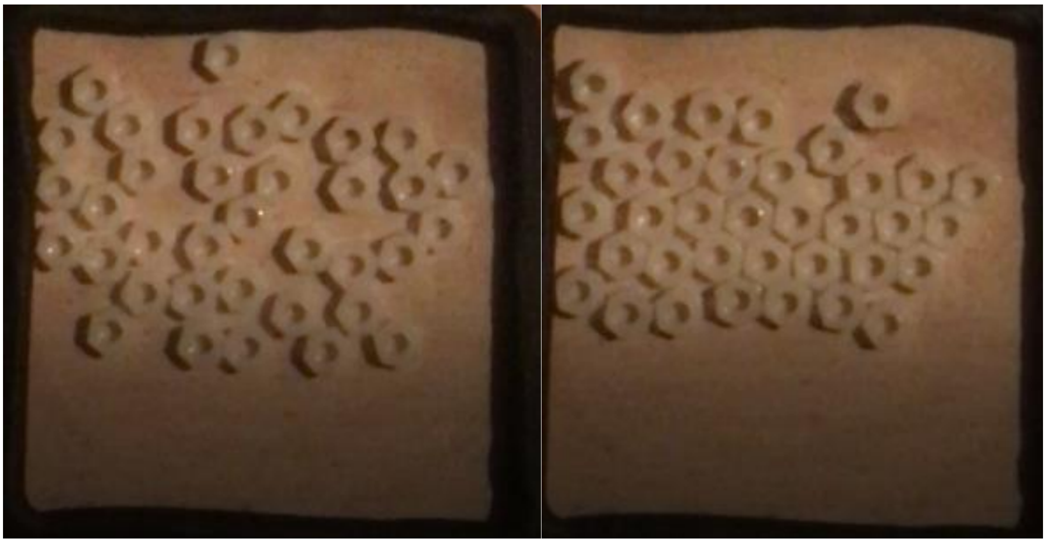

Fig. 3 left: initial amorphous configuration
right: crystalline structure after vibration

4.2 Parameters

Once I had achieved a (poly-)crystalline formation of the particles, I investigated how different parameters affected the arrangement. The most obvious and most easily changeable parameters were the Frequency, the amplitude (volume) and the waveform. I will take a close look at these parameters and afterwards outline what they have in common.

4.2.1 Frequency

I conducted the experiments with frequencies from 50 Hz to 250 Hz. The lower boundary was given by my speaker that couldn’t go below 50 Hz without having disruptions that would throw the particles off the plate, probably because the socket has a frequency of 50 Hz, which seems to create problems. The upper boundary was defined by the fact that my ears would have burst if I had gone higher up. The phenomenon did not only occur with one specific set of parameters but also if I changed two or more parameters at the same time so that their effects cancelled out. Because of this there are two ways to look at the influence on the phenomenon of different frequencies: One is changing the volume at the same time as the frequency in a way that the particles would still assemble, the other is changing only the frequency and see what changes that makes.

Constant volume

At constant volume an increase in frequency resulted in the particles sticking to the plate and not being able to move freely anymore and therefore not forming a crystal structure. If the frequency went too low, the repulsion between the particles would become too strong for a crystal structure to form, and they would start bouncing around until they overlapped with each other, which creates a three-dimensional problem, which is not part of my study.

Changing volume

Here I tried to counter the effect of the change in frequency by adjusting the volume accordingly. When the frequency went up, I had to increase the volume, so that the particles would be in the desired fluid state again. Correspondingly, when I decreased the frequency, the volume had to be decreased as well. The phenomenon occurred at lower frequency and volume just as well as at higher frequency and volume.

4.2.2 Amplitude

The effect of the volume is opposite to the one of the frequencies at constant volume. Since I wasn't able to measure the exact amplitude, however, I can only use relative values for describing it. Once I had found a working set of parameters, if I increased the volume, and therefore the amplitude, the particles would repel each other and start bouncing around and overlapping and if I decreased the volume, the particles would stick to the plate and not move freely anymore.

4.2.3 Waveform

With my function generator app, I was able to use four different waveforms. Besides the classical sine one, I could set up a square, a triangle, and a sawtooth waveform[5]. Fig. 4 shows the amplitude of each wave function depending on the time.

[5] https://www.perfectcircuit.com/signal/difference-between-waveforms

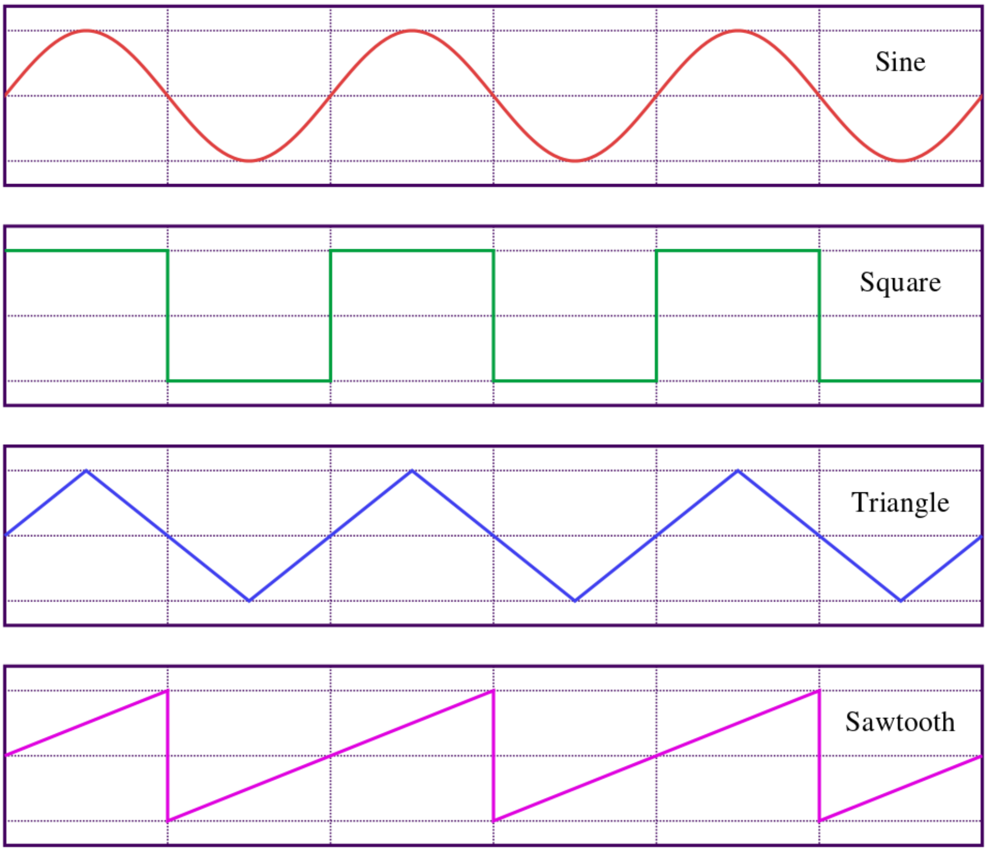

Fig. 4 sine, square, triangle, and sawtooth waveforms

Again, the waveform had similar effects as the frequency in the way that once I changed it, I had to adjust the volume again in order for the crystal structure to appear. Starting off, with the square wave, the necessary volume was the lowest. After that, in exactly that order, the sine wave, the triangle wave and the sawtooth wave each required more volume for the phenomenon to occur.

So, all three of these parameters only influenced, whether or not the particles were able to move freely in their two-dimensional space. They did not affect the time needed for a crystal structure to be formed or other properties of the structure. So, it became clear pretty soon, that they must have something in common that is crucial for the phenomenon. When you consider the effect of each parameter on the vibration wave, it becomes clear pretty soon, that the peak acceleration (upwards) plays a very decisive role. The effect of the waveform, for that matter, confirms that, as the peak acceleration is the highest in the square waveform and gradually decreases with the sine-, triangle-, and sawtooth waveforms, which corresponds to the necessary volume. The Volume itself affects the acceleration in the way that a higher volume results in a higher acceleration, which is proven by the derivative of the sinewave. Only the frequency doesn’t seem to fit, since we had to increase the volume with increasing frequency, which would indicate for a lower peak acceleration, however, if we look at the maths, a higher frequency should result in a higher peak acceleration. For example, if we double the frequency, we also double the peak acceleration, as the amplitude of the derived wave function is doubled.

$$f(x) = sin(2x)$$
$$f'(x) = 2 \cdot cos(2x)$$

This can be explained with the properties of the speaker, which, as stated above, reduces the amplitude with increasing frequency and apparently this effect is so pronounced that the peak acceleration is lower at higher frequencies.

4.3 Particles

I conducted experiments with particles of different sizes and densities. Although all my experimental data comes from hexagonal particles, for which I used plastic and metal screw nuts and some 3D-printed particles as well, I have also used small soft-gun bullets as spherical particles, with which I did not achieve a crystal structure formation. I am now going to present my observations with different amounts of particles and then take a look at the influence of the size and density of the particles on the phenomenon.

Fig. 5 All the particles used in my experiments, sorted by mass

4.3.1 Number of particles

The number of particles itself is not really representative, because there can be many particles on a big space and fewer particles on a very small space, so instead we have to define a particle density first which describes, how many particles with the area A_ρ there are on the plate with a specific area. For that we take the number of particles times the area of one particle and divide that by the total area of the confined plate. The particle density can therefore theoretically take values from 0 to 1.

$$Particle\ density\ \ p = \frac{N \cdot A_\rho}{A_v}$$

N: number of particles
A_ρ: area of one particle
A_v: area of the confined plate

I approximated the area of the hexagonal particles with the formula for the area of a circle. The confined plate had an area of about 95 cm^2. As a reference, the particle density I used for most of my experiments including the ones with which I investigated the parameters had a particle density of about 0.25. The particle density had the same effect regardless of the density or the size of the particles. It again influenced, whether or not a crystal structure would be observed, but also the time the particles needed for their arrangement. Below a particle density of about 0.1, there was no ordered formation observed simply because the number of particles was not sufficient for a crystal-like structure and they were too far apart to meet each other. Above a particle density of about 0.7, however, the particles were so packed, that in order for them to fit onto the plate, they already had to be positioned so that their formation was similar to a crystal structure and therefore they did not form a crystal-like structure by themselves but rather just maintained their current state. Between a particle density of 0.1 and 0.7, the time needed for the particles to arrange decreased with increasing p, as they were simply more packed from the beginning and closer to each other. The number of clusters in the polycrystalline structure also increased with increasing p, because there were more particles that prevented the clusters from joining and forming a monocrystalline structure, and because the particles were more packed, these inhibiting particles couldn't move out of the way.

4.3.2 Size

The particles I used had diameters ranging from 0.7cm to 1.28cm. The size of the particles neither affected the overall structure of the formation, nor did it influence the time necessary to form a crystal structure.

4.3.3 Material

I used Plastic screw nuts, metal screw nuts and 3D-printed hexagons for my experiments. I did not observe any pronounced differences between these materials regarding the time needed for the formation or the overall structure.

4.3.4 Mass

The mass, as well, did not influence the phenomenon regarding the necessary time for the formation or the overall structure. With the mass of one particle ranging from 0.5g to 4.7g their only effect was, that I had to slightly increase the volume when I used heavier particles.

5 Real-Life Application

This phenomenon and these experiments could be used for the simulation of crystal structures and fluids. If you see the acceleration/the vibration of the particles as the equivalent to the oscillation of atoms or molecules, you could predict their behaviour by looking at these kinds of experiments.

6 Summary

To refer to the GYPT-Task again, I have put different numbers of hard regular-shaped particles in a flat layer on top of a vibrating plate. I have achieved an arrangement of the particles in an ordered crystal-like structure. I have investigated not only the effect of the number of particles per unit area, but also of several other parameters such as the frequency, the amplitude, the waveform, and the mass, material, and size of the particles. I have investigated the time the particles needed in order for them to form the crystal-like structure and their polycrystalline structure. I have described my experimental setup and the way I measured the outcome. Finally, I have addressed possible real-life applications of this phenomenon.

Sources

[1] https://www.toppr.com/guides/chemistry/the-solid-state/crystalline-and-amorphous-solids/

[2] https://www.britannica.com/science/crystal/Structure#ref51807