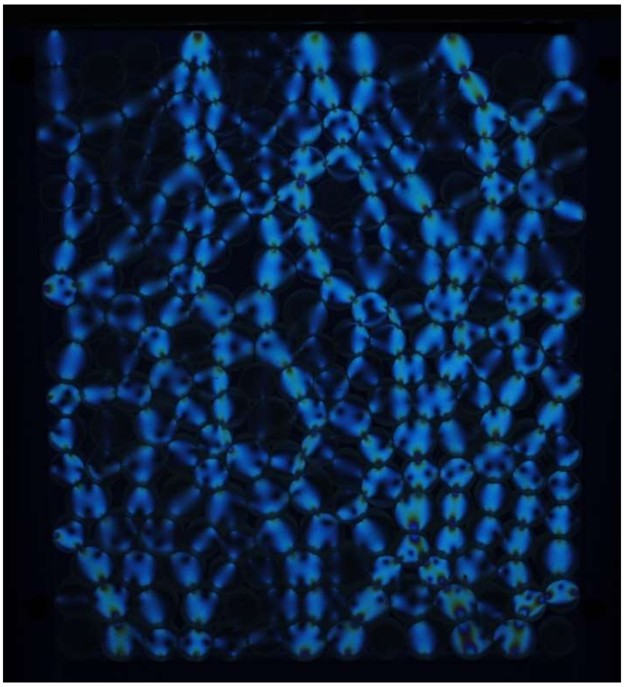
UNIVERSITY OF TWENTE.

NC STATE UNIVERSITY

Sound Propagation in Granular Materials of Two Stiffnesses



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Internship report
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Introduction

In this report I will describe the work I did during my internship at North Carolina State University (NCSU), as part of my Master in Mechanical Engineering at the University of Twente. I spent 14 weeks doing research in the lab of Dr. Daniels, which is part of the Physics Department of NCSU. My research was a collaboration between the University of Twente and NCSU. The subject of the research was wave propagation in granular materials by using photoelastic discs. The response of these particles is not trivial and highly non-linear since the wave follows pre-established force chains and the path depends on the frequency. Earlier research has shown that wave speed is strongly dependent on the yield modulus of the particles. In a mix of rubber and sand particles a sharp drop in wave speed can be found when increasing the volume fraction of rubber (Kim & Santamarina, 2008). This research focuses on finding the same drop in wave speed in a mix of two different kind of particles, but using yield moduli that are much closer together than sand and rubber. The second goal is to study sound propagation through the strongest force chains that are formed in the particle mix. Previous research at NC State showed wave speed is on average largest within particles experiencing the largest forces University (Owens & Daniels, 2011). Two complementary methods are used in order to reach these goals: high speed imaging and piezoelectric transduction. The high speed imaging is used to identify the force chains in the network and the propagation of the wave in these force chains. The particles that are used are photoelastic discs, so that the force chains can be made visible. Piezoelectric sensors (piezo's) are used to measure the time of flight (ToF) of the wave though the particles.

This report is not about presenting the results of this research, but it is a concise summary of my activities in the lab. Due to time limitations this report will only contain some of the problems I encountered. I will start with a short description of the experiment and the final set-up that was used. Next I will explain what problems arose during my time in the lab and the solutions to these problems. Then there is a chapter where I describe the experimental plan and I finish with a short summary of the results.

Contents

The experiment

It is known that wave speed decreases with decreasing stiffness of a material. The same holds for granular materials. However, how this speed decreases in a mix two materials with different stiffnesses is not clear. Earlier research in sand and rubber particles (Figure 1) showed that the wave speed decreases highly non-linearly with increasing rubber content. For low rubber content the wave speed is significantly higher than for high rubber content. It is thought this is caused by the fact that the strong force chains that transfer the wave consist solely of sand particles in mixes with low rubber content. In mixes with high rubber content, the force chains are dominated by the "slower" rubber particles.

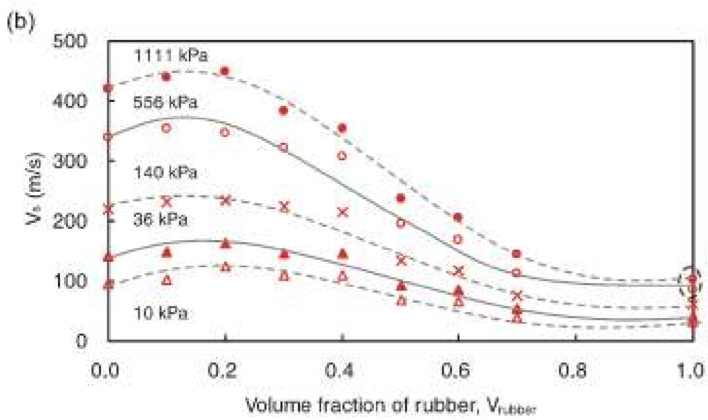

Figure 1 Wave speed depending on rubber fraction (Kim & Santamarina, 2008)

The main goal of our experiment is to create a graph as is shown in Figure 1, but instead of using a sand-rubber mixture, we will use photoelastic urethane of different stiffnesses. This way it is not only possible to show the drop in speed is also happening in mixes where the difference in stiffness is much smaller, but due to the photoelastic properties of the particles we can also visualize the force chains that transfer the wave.

The three different stiffnesses that are used are shown in the table below.

Name	Short name	Tensile strength
Urethane 30A	30A	0.54 MPa
Urethane 50A	50A	1.84 MPa
Urethane 60A	60A	9.93 MPa

For each stiffness particles of 9 mm and 11 mm are available. Later in this report I will go into more detail about which particles are used.

A wave will be sent through a bi-disperse mix of hard particles and soft particles by a shaker. Piezoelectric sensors are mounted on top of the particles to measure the time of flight (ToF) of the wave though the particles. With this ToF the wave speed can be calculated. The volume content of the soft particles will stepwise increased from 0 % to 100 %. The composition of the mix will always be expressed in the volume percentage of soft particles. With a high speed camera the propagation of the wave through the force chains of the network is recorded.

The set-up

In the image below, the final set-up is shown, where

1. Piezo cap
2. Piezo wires
3. Piezo's, each arrow is a piezo
4. Walls
5. Particles
6. Plastic shaker piece
7. Shaker connector
8. Shaker shaft
9. Shaker
10. Mounting base

The whole set-up was already built when I started my work, so I will not go into detail in how it was built. The way the set-up works is that the shaker (9) sends a wave which is transferred by the shafts (8) and the plastic shaker piece (6) to the particles. The wave travels through the particles and the force of this wave is picked up by the three piezo's (3), which are mounted in the piezo cap (1). The wires (2) connect the piezo's with the DAQ card where the signals are processed. On the shaker connector (7) two accelerometers are mounted, which measure the movement of the shaker. By measuring the start of the shaker acceleration and the start of the piezo output the ToF through the particles can be calculated. On the opposite side from where the picture is taken, a high speed camera and a photo camera are mounted. They take a polarized video and an un-polarized photo of each network. In the video the force chains in the network during the wave are visible, the photo is used for particle identification. In the next chapter I will explain what problems I encountered in preparing the set-up and getting ready for data collection.

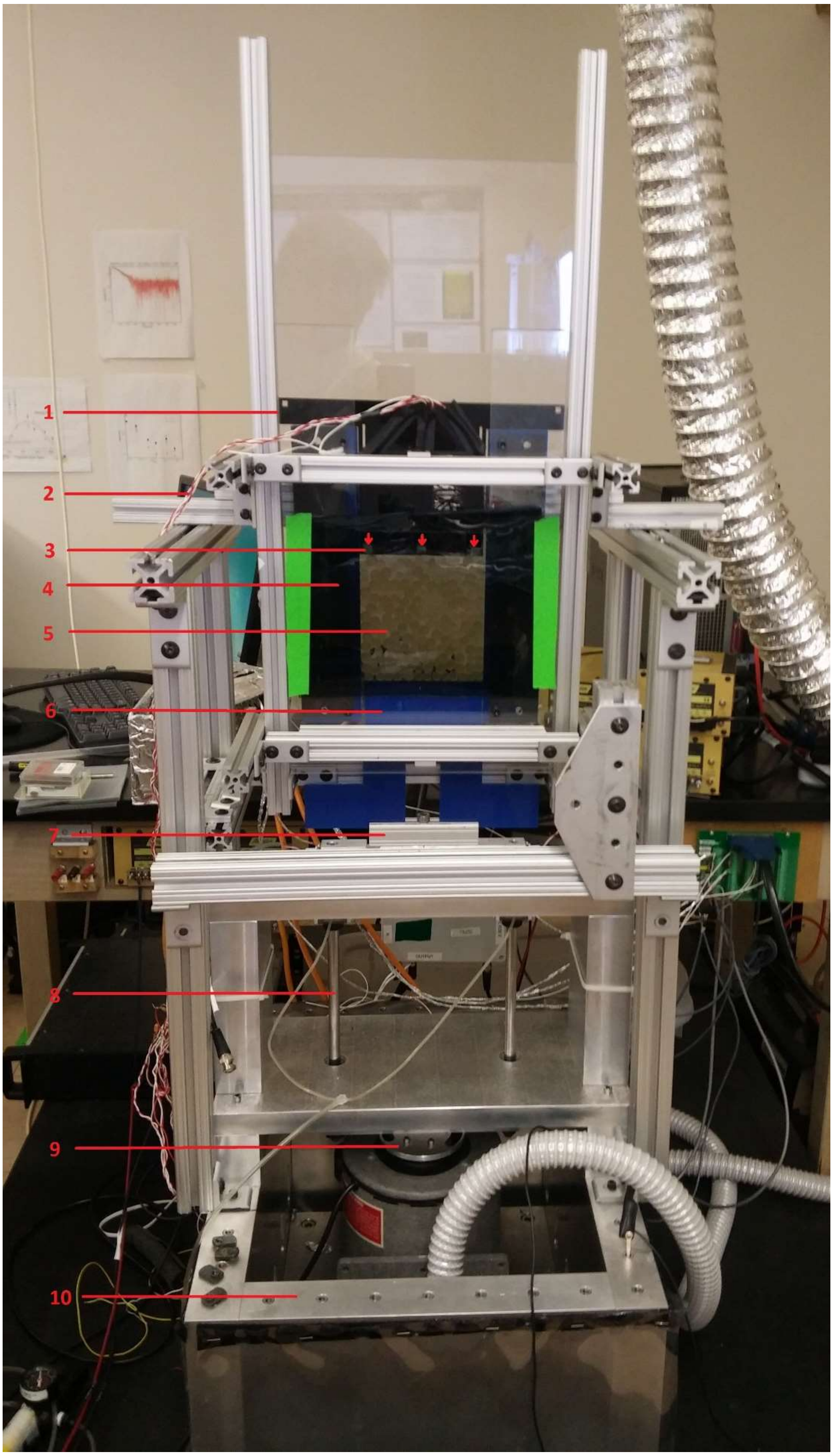

Figure 2 Complete set-up

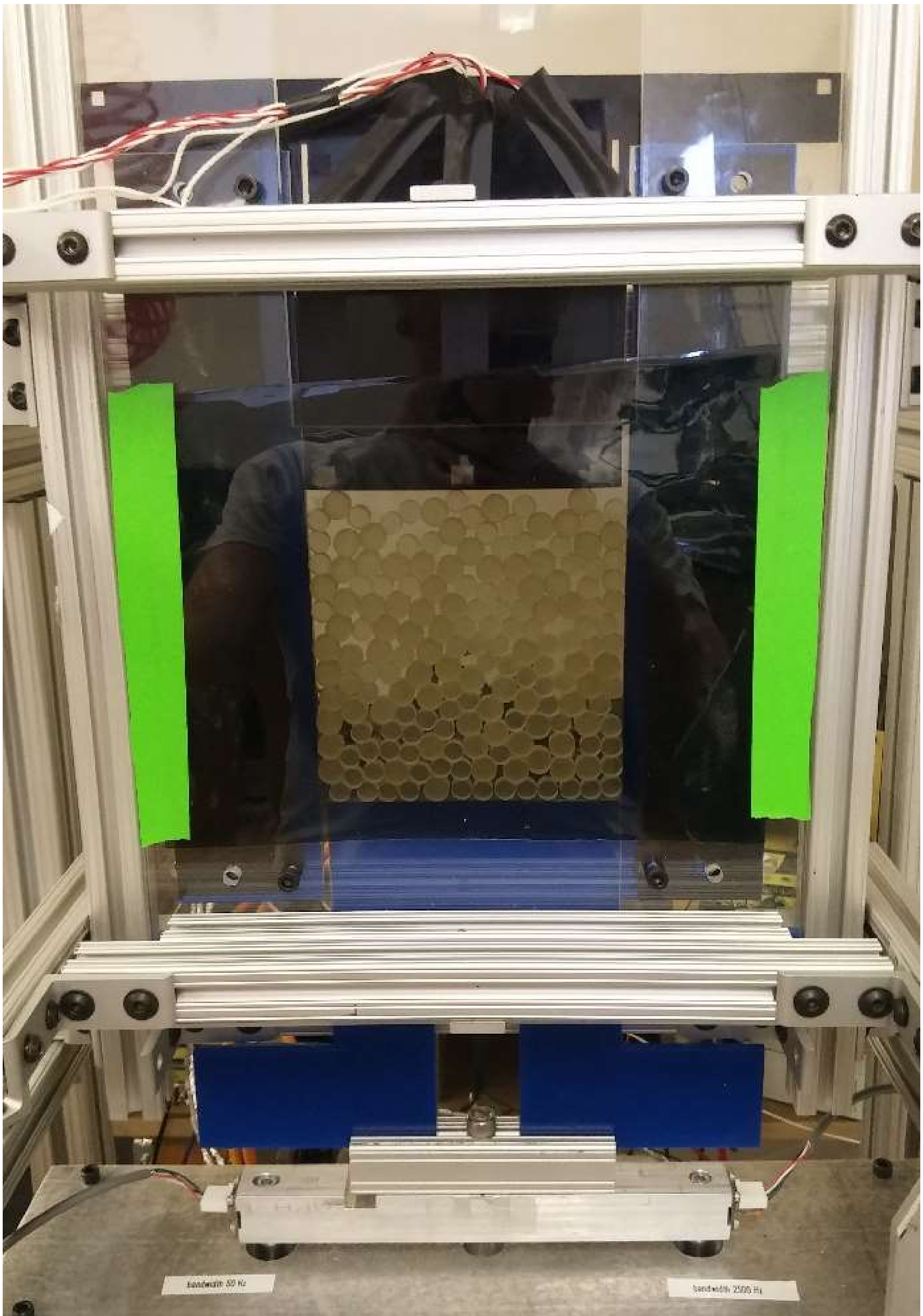

Figure 3 Set-up zoomed

Figure 4 Piezo cap

The piezoelectric sensors are embedded in the cap shown in Figure 4. The bottom of the cap, which is applying pressure on the particles, is 3.175 mm thick and 128 mm wide. In the insert a close up of one piezo is shown. The plastic between the piezo and the particles is 2 mm thick and there is +- 1,5 mm solder and glue between the piezo and the plastic.

Problems and solutions

The main issues that I came across in preparing for data collection are summarized in this chapter.

Particles

The first question that had to be answered was which particles we were going to test. Three different particles were available, with the following properties.

Name	Short name	Tensile strength
Urethane 30A	30A	0.54 MPa
Urethane 50A	50A	1.84 MPa
Urethane 60A	60A	9.93 MPa

Each material was available with two diameters: 9 mm and 11 mm. The original plan consisted of mixing the 30A with the 60A, since these materials have the biggest difference in stiffness (a factor 18.33). This would maximize the chance of finding a clear drop in wave speed in the wave speed plotted against soft particle content. However, during testing it turned out that the photoelastic range of both particles was too far apart. The 30A would be fully compressed before the 60A would even show any signs of photoelasticity (Figure 5).

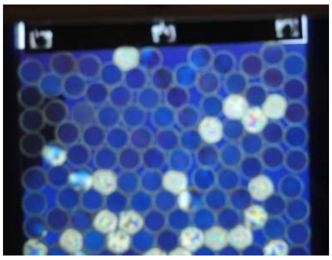

Figure 5 30A completely white, 60A no signs of photoelasticity

This would make it impossible to see any force chains. The weight necessary to create photoelastic fringes in the 60A would completely deform the 30A. In order to reduce this difference, 30A and 50A are used. The 50A is only 3.4 times as stiff as the 30A. This means the difference in wave speed will be much smaller, but the photoelasticity is in the same range. This makes is possible to see the force chains in the networks. By using large particles for the soft 30A and small (9 mm) particles for the hard 50A, the relative stiffness difference is maximized.

Using these both relatively soft particles led to another problem: the particles stick together. Especially after a long period in the set-up and with high weights, the particles would almost become a solid. This was solved by mixing some baking powder with the particles. This involved cleaning the face of each particle individually after mixing, but the particles did not stick together anymore.

The maximum weight that can be applied on top of the particles is 500 grams. For higher weights the Hertzian theory will no longer be valid, due to large deformation of the 30A particles.

Shaker

The shaker produced many problems in the early stages of preparing the set-up. The first one was that the shaker was not producing the sine that is sent as input. Instead of just producing a sine, the shaker first moved down instantly, after which the sine started. Also the shaker did not produce one sine as specified, but it generated multiple (decaying) sines before it stops moving.

In order to determine where the error was produced (Labview, amplifier or shaker), I tested the output of each with an oscilloscope. The output of the amplifier was a (almost) pure sine (Figure 6), so the shaker was the problem.

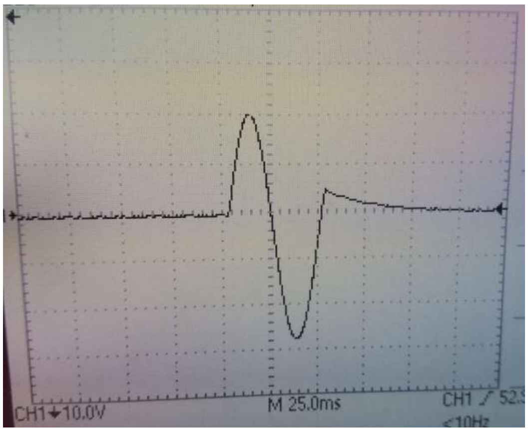

Figure 6 Output amplifier

The problem is that the shaker is not suited for sending a single wave. In previous research (Puckett, 2011) the shaker was used for sending waves continuously and the transient behavior was discarded. However, in this research we are only operating in the “transient” area of the shaker.

In order to solve the bad output of the shaker (Figure 7), I used the simple solution of sending a wave with zero amplitude before and after the generated single sine wave, which led to Figure 78. Still, the shape of the sine is very unsatisfactory.

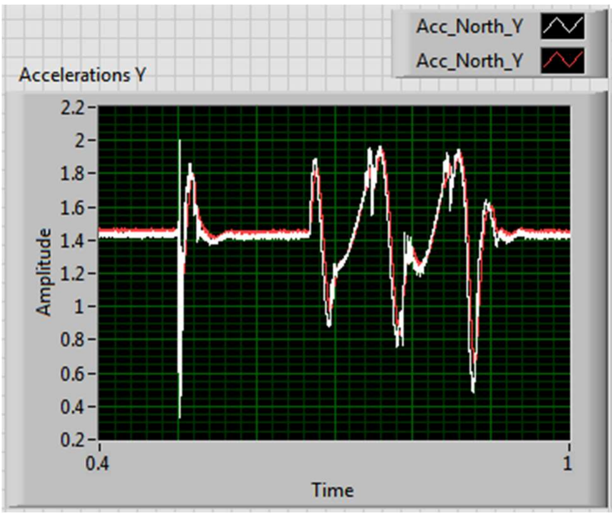

Figure 7 Instant drop and two sines shaker

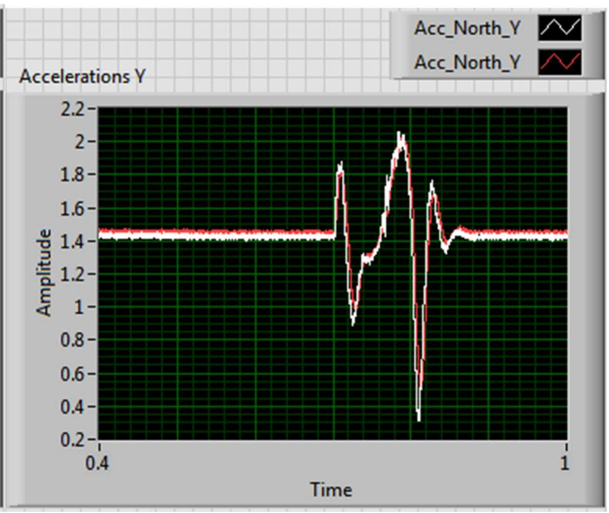

Figure 8 Instant drop removed and one sine shaker

After many trails, it looked like the shaker was not capable of producing low frequent sines. It would produce a high frequent (parasitic) sine before it would generate a badly shaped low frequent sine, as is also visible in the images above. In the figures below the frequency of this parasitic wave is plotted against the frequency of the actual wave that I sent. In the second figure the ratio of these waves is plotted.

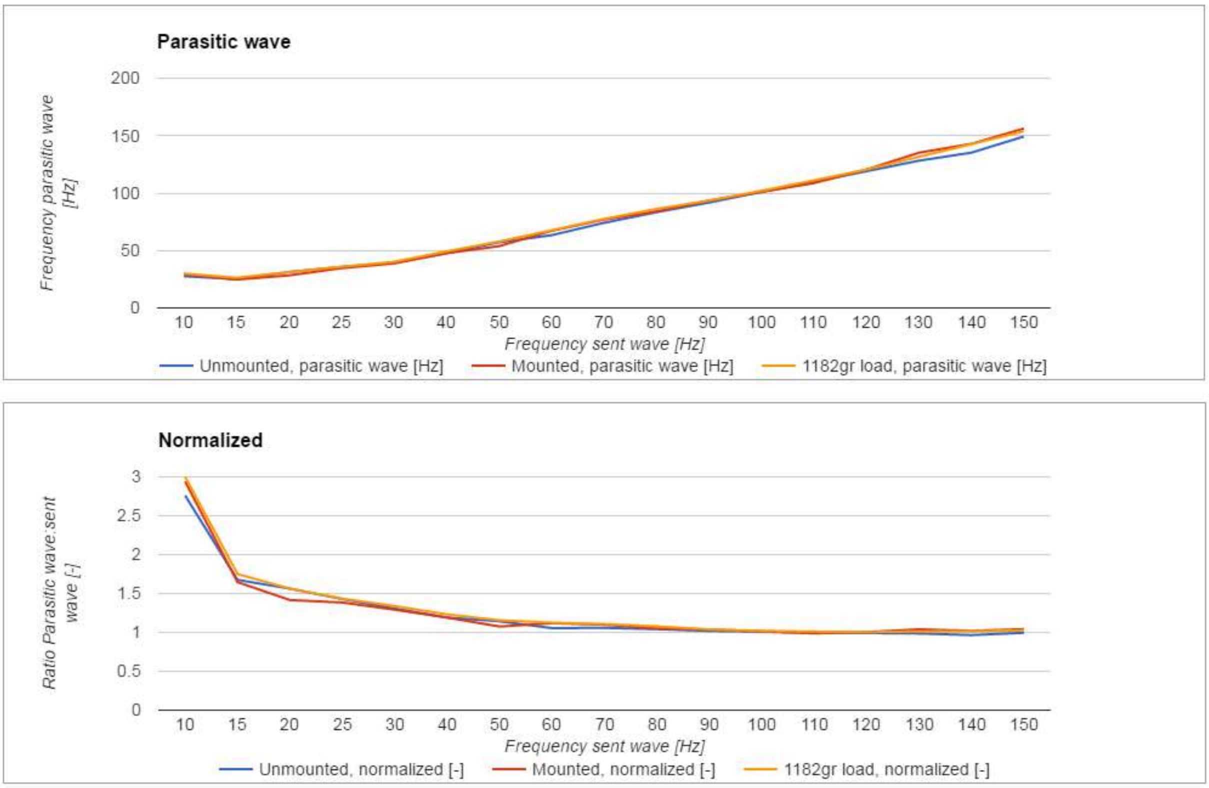

Figure 9 Frequency parasitic wave and ratio of parasitic / sent wave as a function of the frequency of the sent wave

It becomes clear that only for frequencies smaller than 50 Hz the shaker is not capable of producing the input frequency in the first wave, even though the specifications state that the range of the shaker has no lower bound. For frequencies greater that 50 Hz the "parasitic" wave transforms into the actual first wave, with the desired frequency.

With these results in mind, it was decided a higher frequency would be used for the wave. However, this led to another problem. Using a higher frequency required a larger excitation amplitude of the shaker, since the signal would be damped by the particles before it reached the piezo's otherwise. But increasing the amplitude caused high frequent noise in the output of the shaker, as seen in Figure 10.

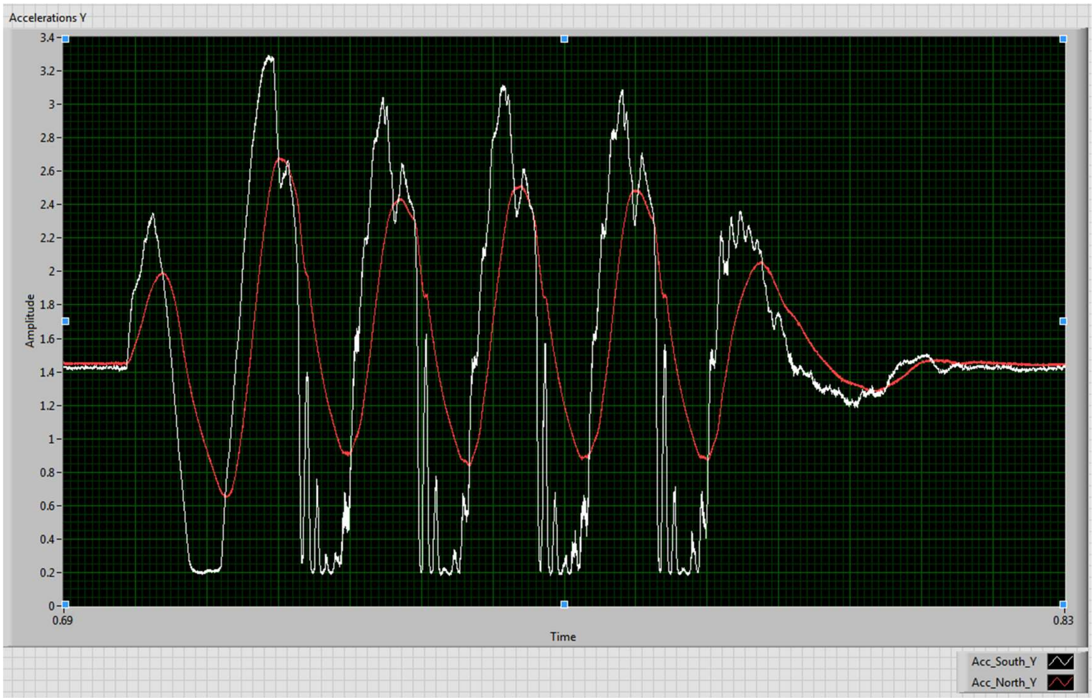

Figure 10 High frequent noise output shaker

After many tests of different configurations, amplitudes, frequencies and testing the accelerometers it was still not clear where the noise originated from. Finally, I found out that two screws were missing in the shaker set-up. In a previous experiment these were removed from the apparatus. Since that experiment used only low frequencies with a high load on top of the shaker, the removed screws did not have any effect. But by using a higher frequency, higher amplitude and no significant weight on top, the missing screws caused the whole set-up to bounce on top of the shaker. With the naked eye this was not visible and no one knew the screws were removed from the shaker, which is why it took a while to find the cause of the noise.

In the schematic drawing in Figure 11Figure 11 the location and configuration of the missing screws is shown, this corresponds to (3) on the photo. The whole upper half of the configuration was bouncing on the lower half.

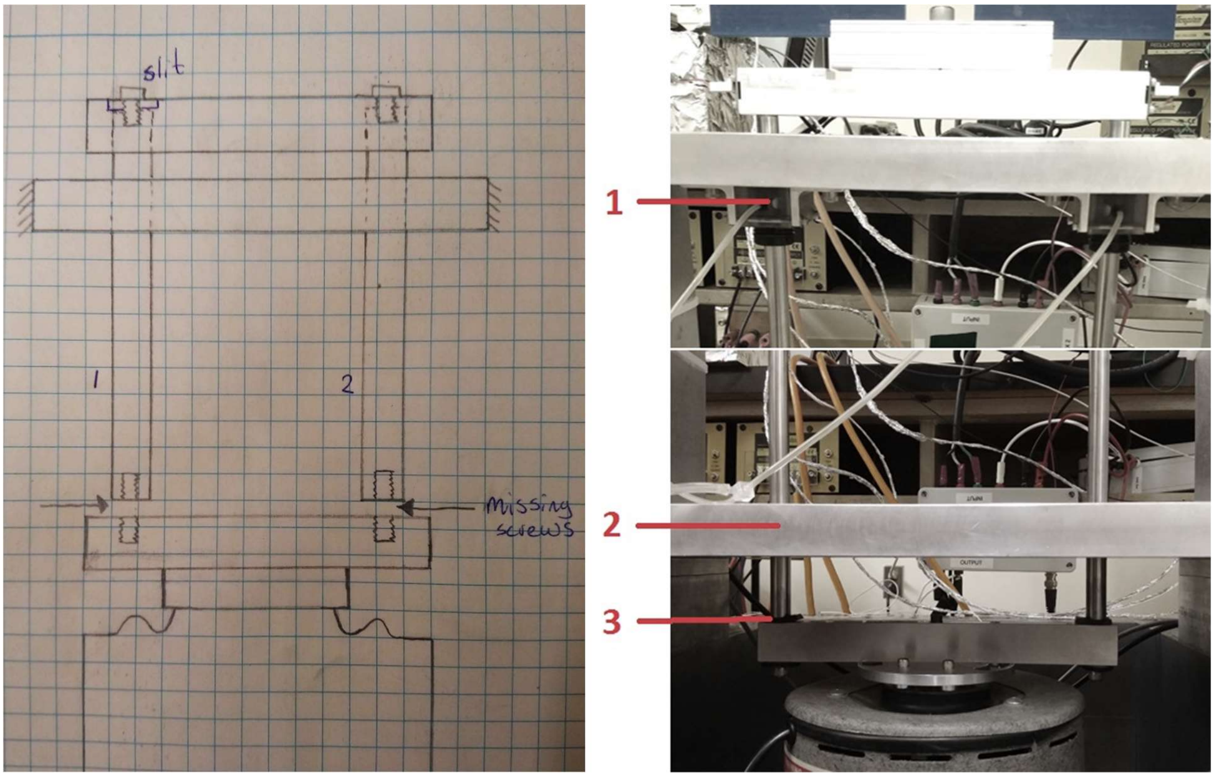

Figure 11 The shaker configuration

Now that I found the cause of the noise, it should be easy to solve. Just insert two screws to connect both parts and everything is fixed. However, inserting the screws showed me why they were removed in the first place. In (1) on the photo the shafts go through two air bearings. In an earlier stage these were ball bearings, but to lower the friction these have been replaced by air bearings. By fixing the shafts into the lower bar that is connected directly to the shaker, the whole construction is severely over constrained. The whole rectangle is now one part and each air bearing is constraining four degrees of freedom, so eight constrained DoFs in total. One DoF (vertical translation) should be free, meaning that only 6 – 1 = 5 DoFs should be constrained. This means the construction has 8 – 5 = 3 constraints to many.

The reason for this configuration is that the shaker is not perfect. It is not mentioned in the specifications, but for certain frequencies the shaker can vibrate horizontally up to 10 % of the vertical input amplitude (Harris and Bush 2014). Since a pure plane wave is wanted, without any shear effects, this is a problem. By using two vertical air bearings this horizontal movement is prevented, leading to a pure plane wave. However, the holes for the screws in the lower bar are not perfectly aligned with the air bearings. This means that when screws are inserted, a momentum is exerted on the bearings, leading to a lot of noise. If the screws are completely tightened, the shaker even jams. In Figure 1211 the output resulting from inserting screws is shown. The high frequent bouncing behavior is gone, but now the friction from the bearings causes a lot of noise in the output. A better shaker set-up would be to use only one air bearing, and connect the shaft through the bearing with the shaker by using a thin rod that is stiff in the driving direction, but compliant in all other directions. This way it will only transfer pure vertical motion. However, there was not enough time to completely redesign the shaker set-up, so I tried to fix the shaker as good as possible in the way it is set-up now.

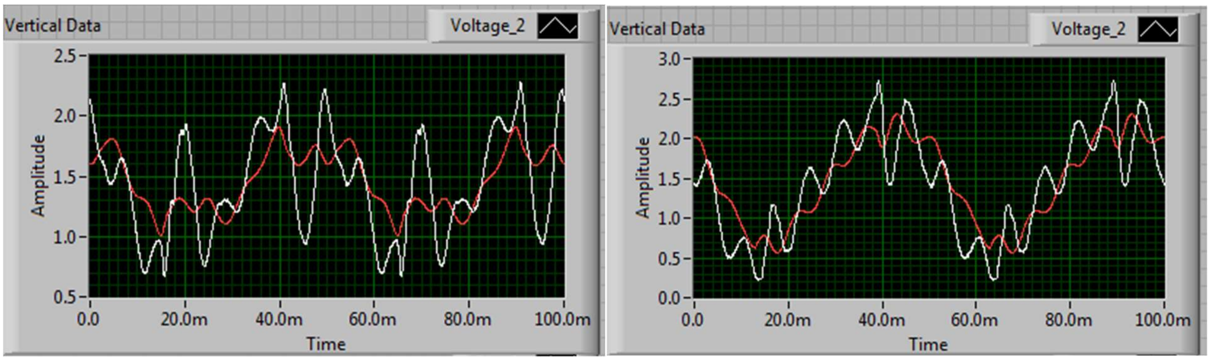

Figure 12 Fully and slightly tightened screws

First, I tried giving the shafts more freedom, by inserting many combinations of washers, disc springs and different kinds of rubber. Eventually in Figure 1313 the best achievable result is shown.

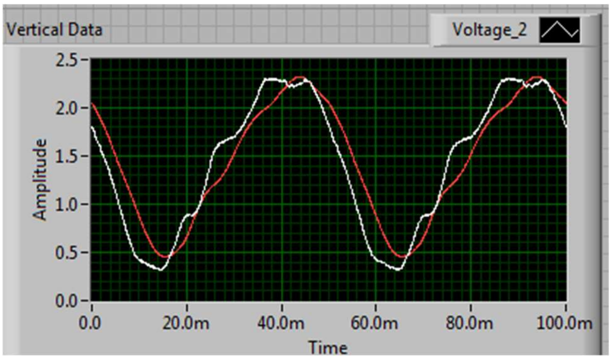

Figure 13 Best result using rubber and disc springs

A lot of the noise is gone, but it is still far from a perfect sine. On top of that, for higher frequencies the noise is still noticeable, since the freedom created to let the shafts align themselves with the bearings, also allows the bouncing behavior to return. This is why I decided to fabricate a whole new bottom bar. Manufacturing the holes exactly in line with the air bearings is impossible. So instead of a tapped hole, I made two slits. This removes all overconstraints and allows the shafts to align themselves with the air bearings before carefully tightening them in this position. Unfortunately, tightening them would still cause friction due to the slightest misalignments. By using two thick pieces of rubber this problem was minimized, while at the same time preventing the bouncing.

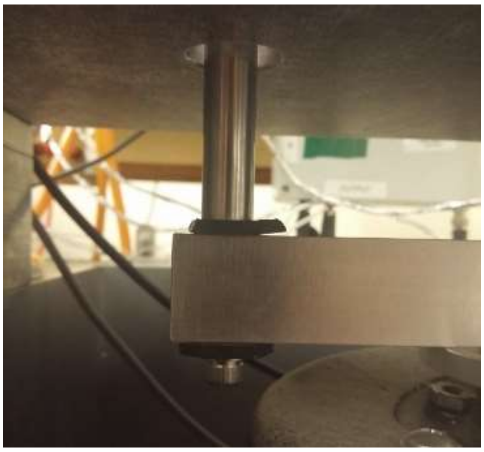

Figure 14 Rubber to prevent bouncing and give some freedom

These rubber pieces make the acceleration profile less precise, but for our research this is not a problem. The shaker output is shown in Figure 151.

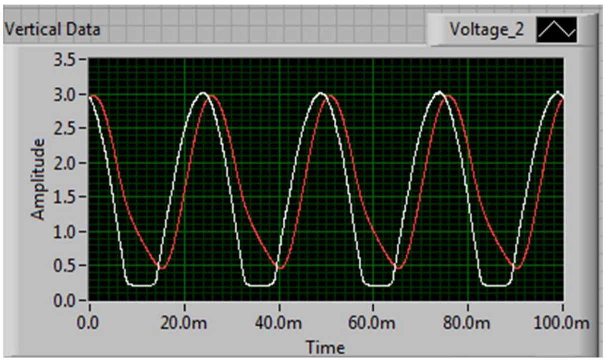

Figure 15 Final shaker output continuous sine

After all these alterations the final shaker output of one sine is as follows.

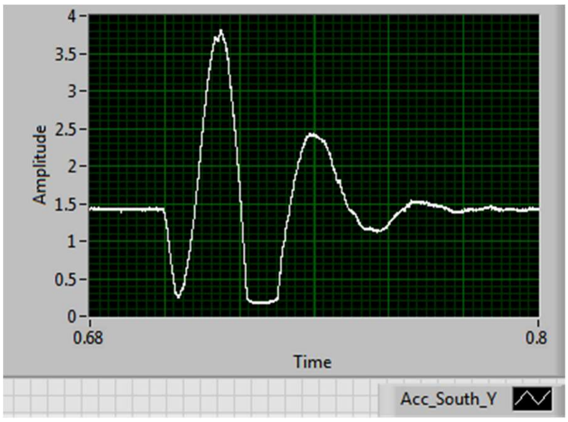

Figure 16 Shaker output of one sine

This is far from a perfect sine, but we are only interested in the first part of the signal. The first half period is almost flawless, which makes this signal very usable.

Microphonics

One of the big problems that I came across when testing the set-up, was noise caused by movement of the piezo wires. Mechanical movement of the wires is transformed into an electrical signal. This is called microphonics. Since the piezo's are resting on top of the particles and the particles have to be unloaded and reloaded, the piezo's cannot be fixed in the set-up. The result is loose wires are hanging over the glass wall, that pick up any vibrations. It would be possible that the measured signal from the piezo's would be some vibration that was transferred through other material than the particles, leading to a wrong measurement. The biggest problem were vibrations that were traveling through the glass walls of the set-up. The way the set-up was designed, the wires had to touch the glass somewhere, so I tried many things to prevent the shaker input to travel into the walls. I redesigned the plastic shaker piece and covered all areas where contact was possible with Teflon tape. I also isolated the wire as much as possible from any contact. When I was sure there was no way the shaker was in contact with the wall in any way and the particles were not touching the piezo's, I would still get a signal as pictured in Figure 177.

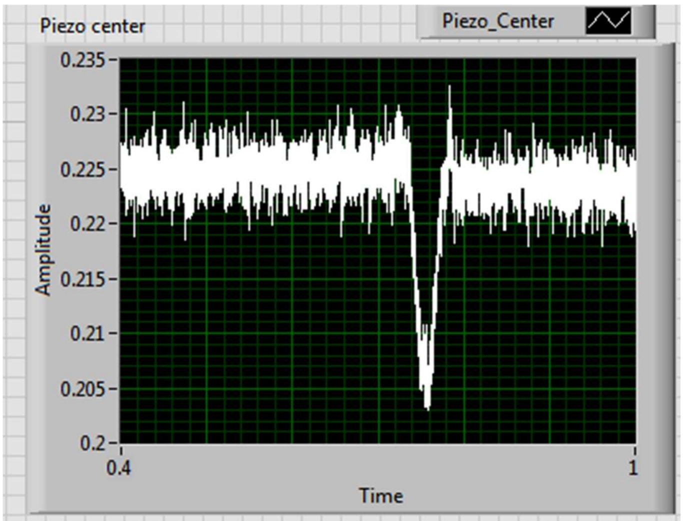

Figure 17 Piezo output when not touching any particles

Somehow, the vibrations were transferred into the wall. I decided to test without any particles in the set-up and, although a small signal was still there, the biggest part of the noise was caused by the particles that transferred the vibrations into the walls. Trying to prevent the vibrations entering the walls was not going to work, so I redesigned the walls in such a way that the wires were not touching the set-up in any way. They would still move when the piezo's moved due to the wave through the particles, but this would not be a problem, since the wave already arrived. So the noise would not be faster than the measurement of the piezo's. The reason this problem has not occurred before is that in other piezo experiments the piezo's are at a fixed location. Hence the wires do not move. For another experiment with moving piezo's I would recommend using prefabricated isolated wires in order to prevent these problems. Redesigning the wall had the added advantaged that I could position the piezo cap much more accurate on the particles and it was now possible to try to position the particles in such a way that they touch the piezo's. In the old set-up I could barely reach the particles.

Piezoelectric sensors

The piezoelectric sensors created many problems in these experiments, both electronically and physically.

Electronic problems

The first problem with the piezo's, was the large amount of drift that was present. In Figure 188 this is shown. It is not the biggest problem, since in the drift appears to be linear in this small time step. This can be compensated for in post processing.

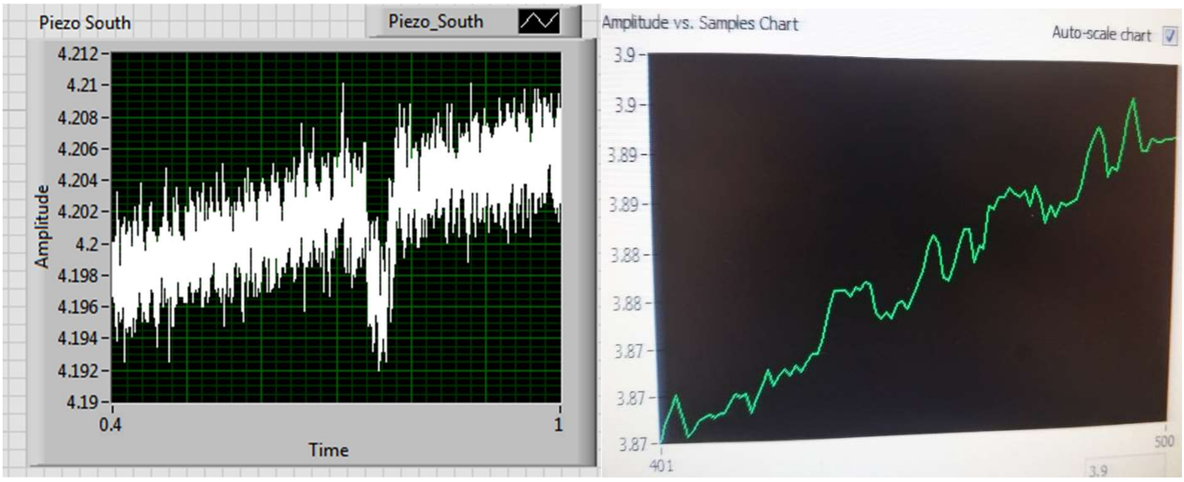

Figure 18 Drift in piezo's. Left a live measurement of a piezo, right a Labview output after sending a wave.

However, as shown in Figure 199, the drift leads to the piezo reaching its maximum output of +10 or -10 V. The oscillations that are visible are of me pinching the piezo, which shows the piezo cannot transmit any output after it reaches its maximum. This is a problem.

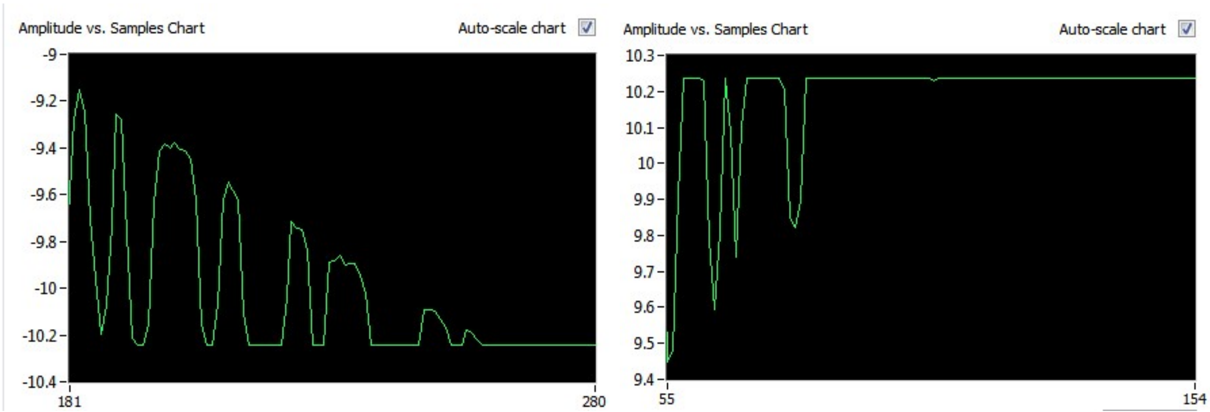

Figure 19 Piezo output reaching max output

Even when no drift is present (Figure 2020), a constant nonzero output generated by the piezo's is still a problem. An amplifier, which was considered a solution for the problem of microphonics, cannot be used in this case. The voltage should stay close to zero in order to be able to use an amplifier.

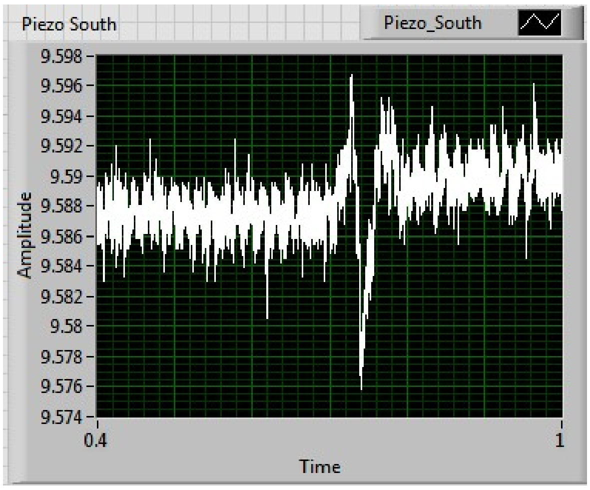

Figure 20 Constant voltage, but big offset from zero

Somehow the piezo's are building up a lot of excess charge. This might be a consequence of the DAQ card not bleeding off excess charges from the measuring capacitor. This should not happen, but testing the piezo's on other DAQ cards resulted in the same problem. When testing the piezo's with an oscilloscope there was no problem. I tried adding ghosting channels to prevent the charge to build up, but this did not work. What did work, was adding a high pass filter to each piezo. I tried different filters, a resistor of 1 MΩ and a capacitor of 100 µF gave the best results. The cutoff frequency becomes $f_c = \frac{1}{2*pi*R*C} = \frac{1}{2*pi*10^6*10^{-4}} = \frac{1}{628} Hz$. This makes the cutoff frequency 24000 times smaller than the input frequency of 40 Hz. With this filter the slow charge build up was no longer possible, as clearly visible in Figure 2121. The signal almost exactly zero, shows no signs of drift and the noise is in the order of single bits.

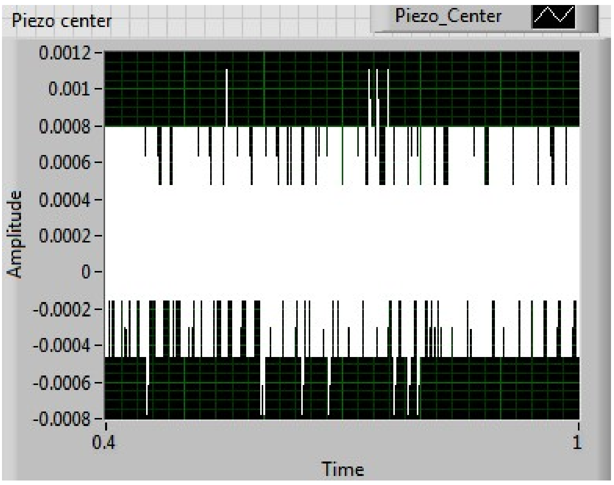

Figure 21 Piezo output with high pass filter, without sending a wave

When a wave is sent through the particles, the output is as is shown in Figure 2222. The output is clearly visible and practically no noise is present.

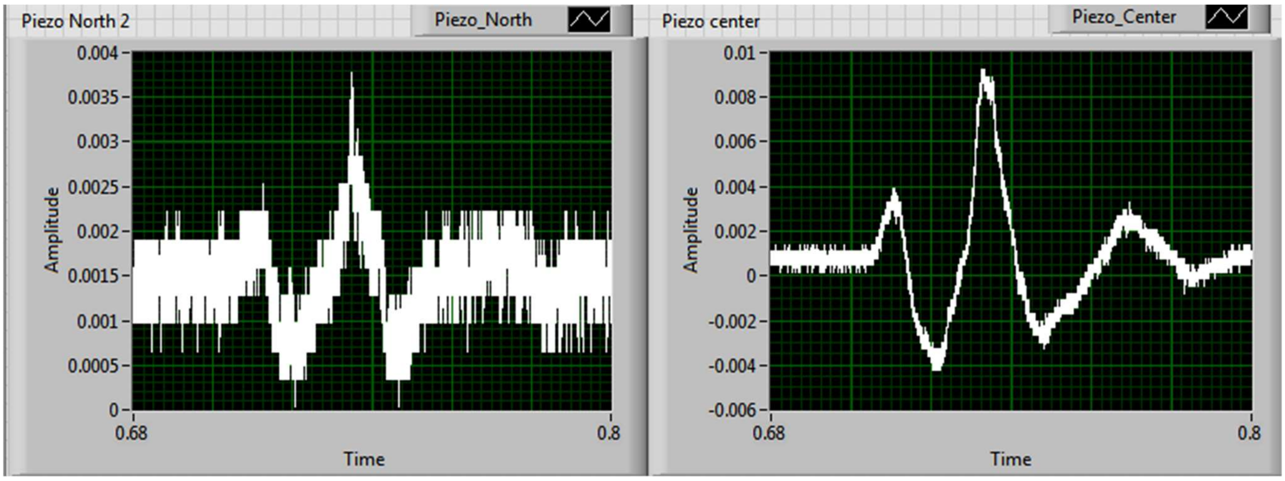

Figure 22 Piezo output with high pass filter after sending a wave

Physical problems

After all the electrical problems were solved, it was finally possible to measure real signals from the particle mixes. It turned out that the location of the piezo's was far from ideal. It was very hard to position the particles in such a way that they made a horizontal line. The piezo cap would often tilt, so that one of the corners touched the wall (Figure 2323Figure 25). This would lead to unwanted noise picked up through the wall. Also the particles that are touching both the wall and the piezo (as in the upper right corner of Figure 2323), the vibrations of the wall might be transferred to the piezo. Placing the piezo's further away from the wall would decrease the chances of this noise being picked up. However, not enough time was left to design and fabricate a complete new piezo cap.

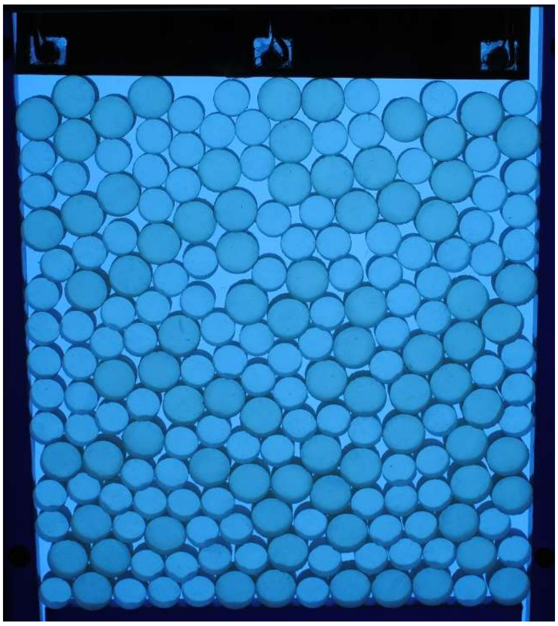

Figure 23 Line particles up horizontally

Another challenge was making sure the particles were touching the piezo's. In the left image of Figure 2424 a perfect configuration is visible, on the right a situation is pictured where no particles touch the piezo's directly. The results of the left picture are obviously much more useful. When using random configurations of the particles, only a limited amount of networks would have particles that touch piezo's. This would be a waste of time, so I would use a small stick to try to line up the particles in such a way that:

- They were lined up horizontally
- No particles would be in the upper corners touching wall and piezo
- All three piezo's have a particle touching them

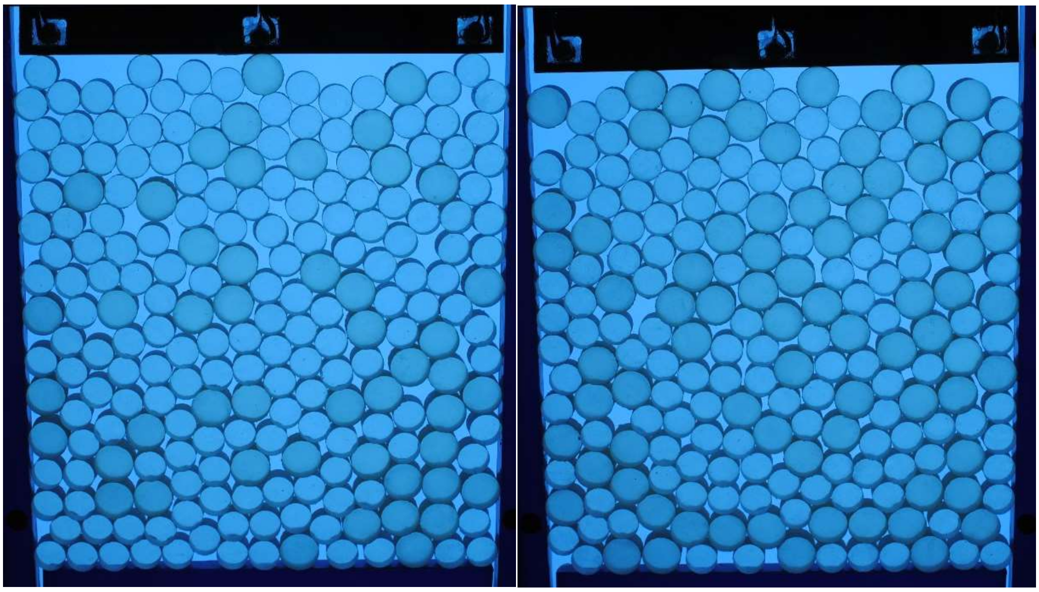

Figure 24 Particles touching piezo's

In theory, this seem a good idea. In reality, this is really, really hard. Using a stick to place three particles in certain spots and trying to keep everything horizontal while leaning across a table is nearly impossible and very frustrating. I would compare is to trying to push three footballs under water, using only one hand. Every time I get one particle at the right position, the other two particles will move. Also, when I load the cap on top of the particles, they will sometimes change position and loose contact, making me start over again. Furthermore, when I start sending waves in order to settle the network, the particles will shift to a more favorable position, causing the piezo cap to tilt after all.

When I managed to load the cap in the right position, the next problem arises. All piezo's are touched be particles, but are these particles part of force chains? In Figure 255 an example is shown, where the three main force chains do not (or barely) touch any piezo's. We want to measure the first arrival of the wave through the particles, this wave is supposed to travel fastest through the strongest force chains. When these force chains do not end up on a piezo, are we measuring the first arrival or peak response? If sometimes the first arrival is measured and sometimes it is not, this can lead to a high STD. Although this is inherent to granular research, the aim is to prevent it as much as possible.

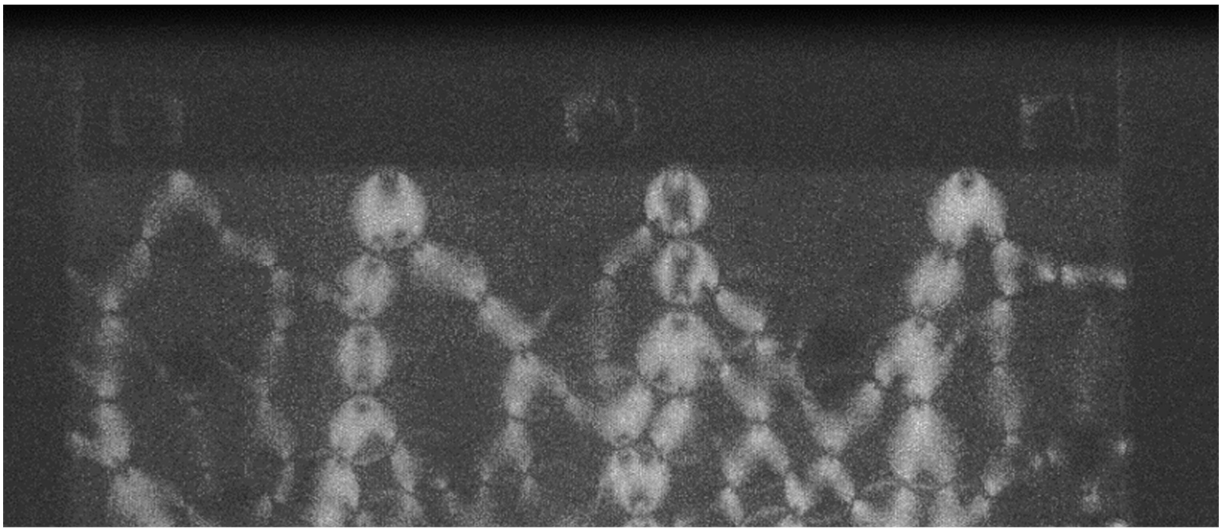

Figure 25 Force chains not touching piezo's

The best solution would be to have more piezo's in the cap, so that first arrivals on any location in the cap would be measured instantly. But when reading the output of the situation of Figure 255, it seems that the piezo's do pick up the first arrival of the wave. The signals of a force chain touching a piezo and no force chains touching any piezo's look the same, which is promising. However, post processing should tell us if there really is no difference in these situations, by comparing piezo output with the videos.

Boundaries

The first idea was to use smooth walls (boundaries) to keep the particles in the set-up. This way the boundaries would not interfere with the wave that was sent through the particles. However, in order to prevent the particles to move as a bulk and disturb the formation of a lattice in the particles, we considered using rough boundaries, as pictured in Figure 266. The holes are the size of an 11 mm particle and they are unevenly spaced, to prevent the formation of a lattice.

Figure 26 Rough boundaries

This did slightly prevent the formation of crystals, but it led to another problem. As shown in Figure 277, the rough boundaries will carry the weight placed on top of the particles, and force chains will form between the boundaries and the piezo cap.

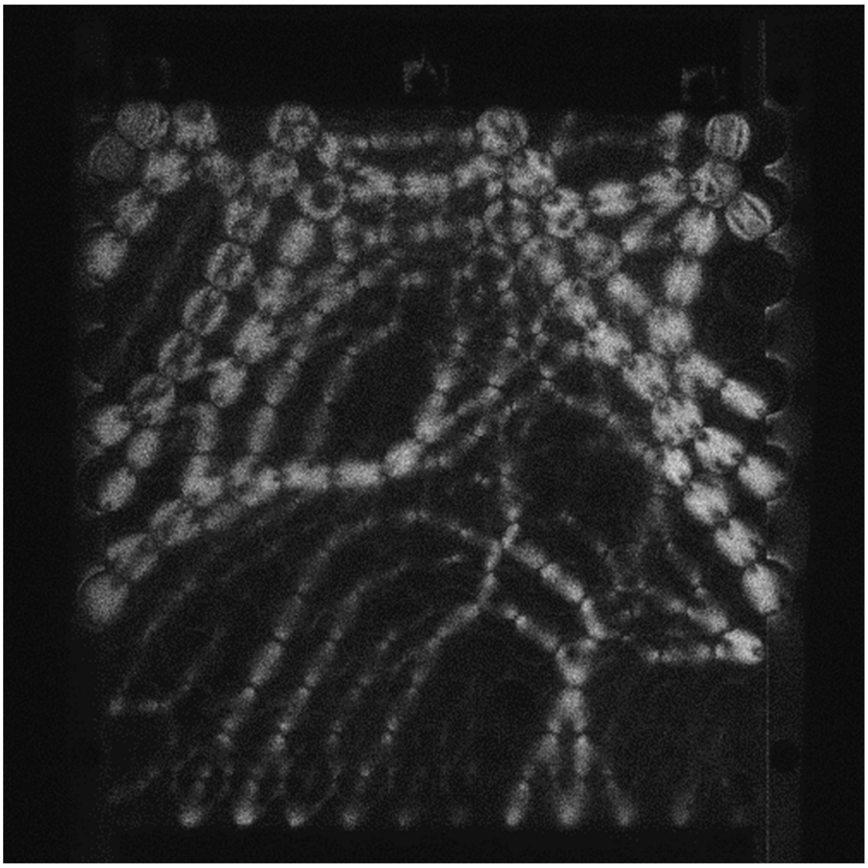

Figure 27 Force chains into boundaries (extreme case)

It is not known what the effect of these preformed force chains is and furthermore these chains increase the risk that vibrations are transferred from the walls to the piezo's. Also, due to the placement of the piezo's, the piezo's close to the wall will be almost useless, since the force chains in the upper corners transfer directly into the walls. This is why the choice was made to use the smooth boundaries after all. How the problem of the formation of a lattice was solved is discussed next.

Lattice forming

In the left image of Figure 288 a configuration of 100% 11mm particles is shown. Even with the rough boundaries, the particles form a lattice in certain parts of the network. In order to solve this problem, it was decided to use a bi-disperse mix for both the 100% soft and the 100% hard networks. This was done by using 11 mm particles for the first half of the total volume and using 9 mm particles for the other half. This results in the network on the right in Figure 288. Now no crystals are formed anymore.

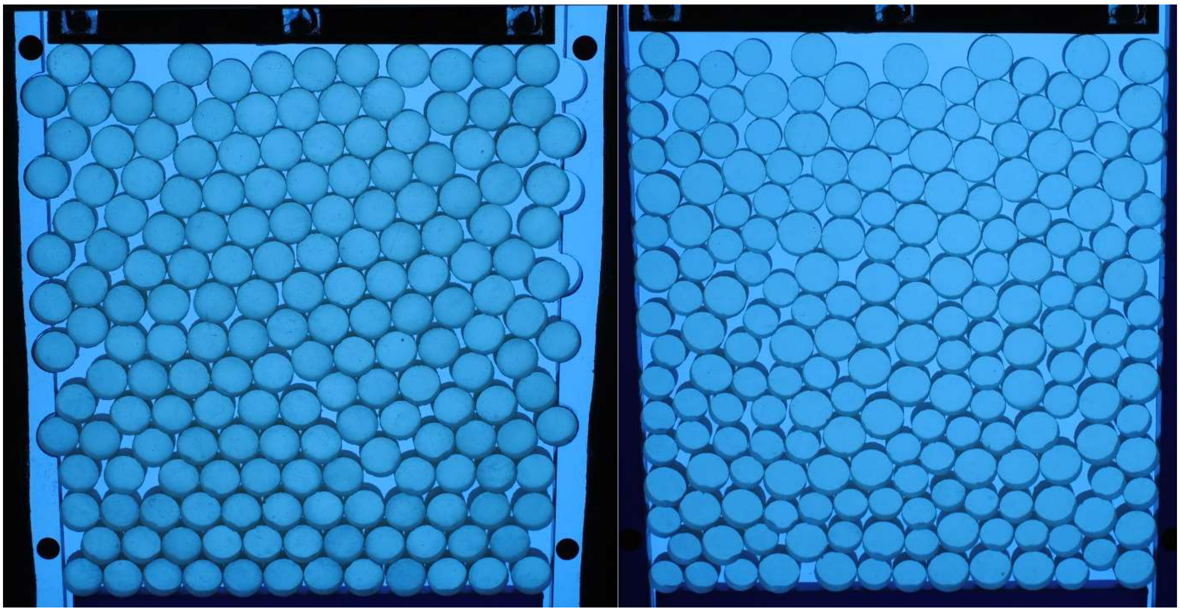

Figure 28 Mono-disperse and bi-disperse particle mixes

For the mixes of hard and soft particles the forming of a lattice was not a problem, since these mixes already consist of 9 mm and 11 mm particles. Only for the cases of 10 % soft and 85 % soft it might be a problem. In Figure 299 it is clear that some small crystals are formed in the 10 % soft mix, but not enough to be worried about. In the 85 % soft mix no problems are present whatsoever. The big difference is caused by the fact that a small volume % of small particles still consists of a significant number of particles (36). The 10 % large particles consists of only 16 particles.

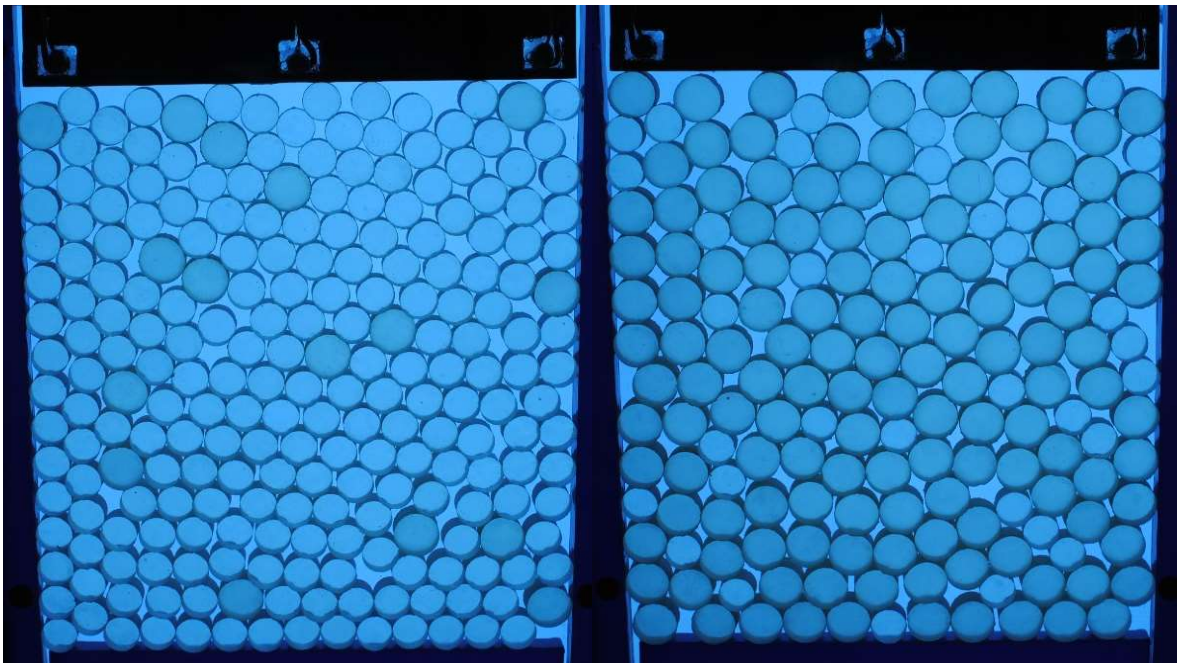

Figure 29 Left: 10% soft, 90% hard particles. Right: 85 % soft, 15 % hard particles

General problems

The high speed camera maximum resolution (1024x1024) is too low for force calculation. In order to calculate the force, software must be able to recognize the number of fringes in each particle. The absolute minimum of pixels needed is 60 pixels. With the camera the number of pixels for the 11 mm particles is just over 60, for the 9 mm particles it is below 60. It might be possible to get some results, but a camera with a higher resolution would have made sure this would be possible.

The maximum frame rate of the camera (when using the maximum resolution) is 1200 frames per second. This means that is will be very inaccurate to estimate the wave speed based on the frames of the video. It is hard to estimate in which frame the wave exactly arrives at the piezo's and the difference in one frame is enormous. Since the distance that the wave has to travel (height of particle mix) is around 0.140 meters, the difference the number of frames makes is as follows:

$$\text{4 frames: } \frac{0.140}{\frac{4}{1200}} = 42.0\ m/s$$
$$\text{5 frames: } \frac{0.140}{\frac{5}{1200}} = 33.6\ m/s$$
$$\text{6 frames: } \frac{0.140}{\frac{6}{1200}} = 28.0\ m/s$$

Hence getting the time of flight from the video will be very hard and inaccurate.

To determine what frequency was best to use for the wave that the shaker sent, many testing has been done. However, most of the tests were conducted with a dysfunctional shaker, which was not known at the time. We don't want to have any near field effects, to the wavelength should be large compared to the size of the particles. It was calculated that the frequency should be below 70 Hz. The shaker only produces perfect sines for frequencies higher than 50 Hz. It seems that 60 Hz would be a good frequency to use, but this is exactly the frequency of all the electronic noise. So this is not a great idea. Since the only important part of the wave is the first half of the sine, lower frequencies were tested. 40 Hz, as shown before in the shaker chapter, has a very smooth first half of a sine. Also, the output from the piezo's was clear for this frequency. So 40 Hz is used as the excitation frequency.

Finding the leading edge of the wave that arrives at the piezo's in Matlab is a hard task. Many different parameters influence the location. And how accurate the location is found has a large effect on the calculated wave speed. From the data I have taken, there are several things to look out for.

- Sometimes piezo's might have picked up some vibrations through the glass (e.g. when the particles are pressed against the glass due to high weights on top of the particles). These fast and very small peaks should be filtered out.
- Some piezo's might not touch any particles, but still pick up some small noise. This noise should not be considered as an arriving wave by Matlab.
- The 20 waves for each network should have all a similar shape. When they do not, that means the network is still rearranging when the waves are sent, leading to bad results.

One of the earliest problems that I encountered was the phenomenon "ghosting". The output of the piezo's in Labview would be very clear and very consistent. However, no difference in speed could be detected in the different particle mixes and the shape of the output was too similar to the input acceleration. It turned out that the current of the input acceleration somehow reached the output channels. By insulating all wires with aluminum foil and adding ghosting channels in the DAQ card this problem was solved.

Experimental plan

The experimental plan is as follows. The particles 30A and 50A are used to make the particle mixes. Due to time constraints a limited number of 10 mixes could be tested. For each mix, 10 different networks are tested. For each network, 5 different loads are used (0, 100, 200, 300 and 500 grams). For each load, 20 separate waves are sent. For each wave the acceleration of the shaker and the output of the three piezo's is saved. The number of particles in each mix is as follows (with the exception of the 0 % and the 100 % soft content, where a bi-disperse mix is used as explained earlier).

11 mm (30A)		**9 mm (50A)**	
Percentage	***# particles***	***# particles***	*Percentage*
0%	***0***	***120+80***	*100%*
10%	***16***	***215***	*90%*
20%	***32***	***191***	*80%*
30%	***48***	***167***	*70%*
40%	***64***	***143***	*60%*
50%	***80***	***120***	*50%*
60%	***96***	***96***	*40%*
70%	***112***	***72***	*30%*
85%	***136***	***36***	*15%*
100%	***80+120***	***0***	*0%*

Data collection

Step-by-step description of the data collection:

- Create the particle mix by carefully counting the right number of particles.
  - Mix the particles thoroughly.
  - Load the mix in the set-up.
  - Send 4 series of 20 sines waves of 20 Hz in order to settle the network.
  - Carefully position the upper particles in such a way that they are horizontally and touch the three piezo's as good as possible.
  - Load the piezo cap. If particles do not touch well, return to the previous step.
    - Load the weight (except when testing the network without load). If loading the weight causes the particles to rearrange and not touch the piezo's anymore, return to positioning the particles. Distribute the weight in such a way, that the piezo cap stays horizontal.
    - Send 10 single waves of 40 Hz to make sure the weight dropped to its final position.
    - Check whether the piezo's have a clear signal in Labview. If the piezo's do not have a clear signal, unload the piezo's and go back to the 4 series of 20 sines step.
    - Send 19 separate waves and save the piezo output

        - Trigger the high speed camera and send the 20^{th} wave. Save both the piezo output and the video.
        - Take a picture of the network with the photo camera and save it.
        - Measure the height of the network and save it.
        - Unload the weight from the piezo cap.
        - Go back to the first step or loading the next weight.
    - After all five loads have been tested, unload the piezo cap and unmount the set-up
    - Go back to the particle mixing step.
- After ten networks have been tested, go back to the first step and create the next mix of particles.

Camera settings

To preserve the linear mapping from light intensity to pixel brightness, the gamma is set to 1. In order to be able to see what is happening on the computer screen, the brightness and gain are set to the maximum values. I made sure that when the system was as heavily-loaded as it would be during testing, the histogram fits inside the range of pixel values without clipping at the top and bottom.

Saved data

The data is saved in the following way:

Each mix has its own folder (e.g. 50%). In this folder, each load has its own folder. In this folder, the 200 files of the 10 networks with each 20 waves are saved. Each file has the accelerometer and piezo data in it. The first 20 files numbered 1 to 20 are from network one. The next 20 files numbered 21 to 40 are from network two etcetera.

So the 20 data files of the 6^{th} network of the mix with 50 % soft (30A) content and a load of 300 gram are found in the folder Real_Data_Piezos\50%\50%_300gr and numbered 101 to 120. The movie and photo of this network are found in Real_movies_and_photos\50% and are both named 50%_300gr_6.

Results

Analyzing the data collected was not part of this project. However, for the sake of completeness, a short summary of the analysis conducted by Giorgio Oliveri as part of his master thesis will be presented. First the procedure to pick up the velocity of each wave is explained and next the most important results are presented. All the following data is taken straight from this thesis (Oliveri, 2016). More data and results can be found there as well.

The wave speed is computed considering the vertical distance between the upper cap and the piston and the time of flight measured from the signals, L/ToF. For the latter one two different definitions were considered, namely the time difference between the first peaks of piezoelectric and accelerometer signal was used to compute (so-called peak velocity) and the time difference between the deviation of the signals respect to a reference value (rising velocity). The first peak was intended as the first local maximum or minimum far from the resting value.

The working principle of the automated measurement tools is shown in Figure 30. All the signals, both from accelerometer and piezos, had similar features so it was possible to define signal portions. The data between the Lower Bound (LB) and Upper Bound (UB) were taken as reference part; the signals' minimum value of this portion determines the threshold line number 1. A sensible deviation from the standard condition with presence of the fist peak is expected to be between UB and Upper Bound 2 (UB2): in this section the minimum value is considered to compute the peak velocity (defining the threshold line 3). The deviation of the signals with respect to the resting position was set to 15% the distance between the two threshold lines 1 and 3 (Δ in Figure 30): the time of arrival associated with the signals rising can be defined. The two time references are circled in red in Figure 30. This procedure performed to each averaged piezoelectric and accelerometer signals was used to determine the time difference between them determining the wave speed in function of the distance between sender and receiver.

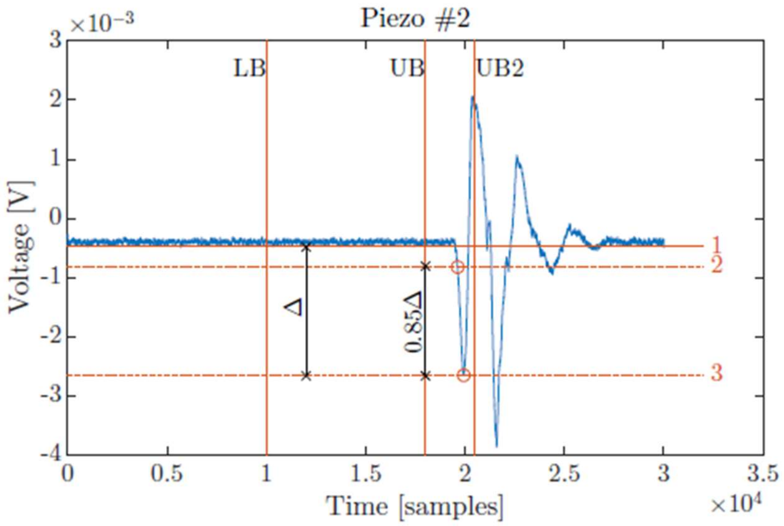

Figure 30 Peak and rising velocity definitions. (Oliveri, 2016)

In Figure 31 and 32 the data is collected and the rising and peak velocity are plotted versus the soft particle content for all the external weights. The box height represent the interquartile (IQR) value whereas the horizontal line contained in it is the median value. The horizontal limits outside each box are determine the maximum whisker length defined as

$$max = q_3 + 1.5(q_3 - q_1)$$

$$min = q_1 - 1.5(q_3 - q_1)$$

where q_3 and q_1 are the 75_{th} and 25_{th} percentiles of the data. A value is beyond these threshold is considered as an outlier. Figure 31 shows a change in propagation speed with a change in soft particles inclusions in agreement with past research. The highest velocity is registered for the lowest soft particles content: this is true for all the external weights apart from the higher most. This is visible for both averaged piezos and fastest piezo definitions. There is no overlap between the IQRs of 0% and 100% SPC this implies that the difference between the two situations is marked. Sharper change in velocity seems to occur beyond the 30-50% soft particle content (SPC) again for all the confining weight but the highest. It is important to notice that the last soft particles content shown cover a range of [70-100%]. There is no change in velocity between the 85% and 100% SPC: this is also valid, increase of 0g and 100g external weight, for 75%. In Figure 32 along with the peak velocity data a reference curve, specifically the rising velocity calculated considering all the piezo, is plotted. It can be seen that the global trend is more flat if compared with the rising velocity data. The velocity gap between 0% and 100% SCP is noticeable (with no IQRs overlap) but less marked than the rising velocity plot. For all the external weights and soft particles content the measured velocities are smaller, this might be related to wave broadening. The p-wave velocity is calculated according to

$$M = v_p^2 \rho = v_p^2 (\rho^{soft} \phi^{soft} + \rho^{hard} \phi^{hard})$$

with ϕ the volume fraction of the mixture component and ρ the particle material density. The behaviour of p-wave modulus M, as a function of the soft particle content for all the external weights was obtained and reported in Figure 33. In Figure 34 the median values for different external weights extracted from Figure 32 and shown together. At SPC 0% the p-wave modulus increases with the increase in external weight. This behaviour is maintained for the full range 0-100% of SPC for external load from 0 to 300g. From SCP = 70% and up all the curves collapse together to the same value where the dependency on SCP and external load is lost. It seem that a sharp drop occurs around SPC=40-50%. In general scaling with the external load is followed for external weights up to 200 beyond which the dependency start to vanish as it does for the higher most weight. With the some knowledge on the dynamic elastic properties of the materials a comparison with the Effective Medium Theory can be done. (Oliveri, 2016)

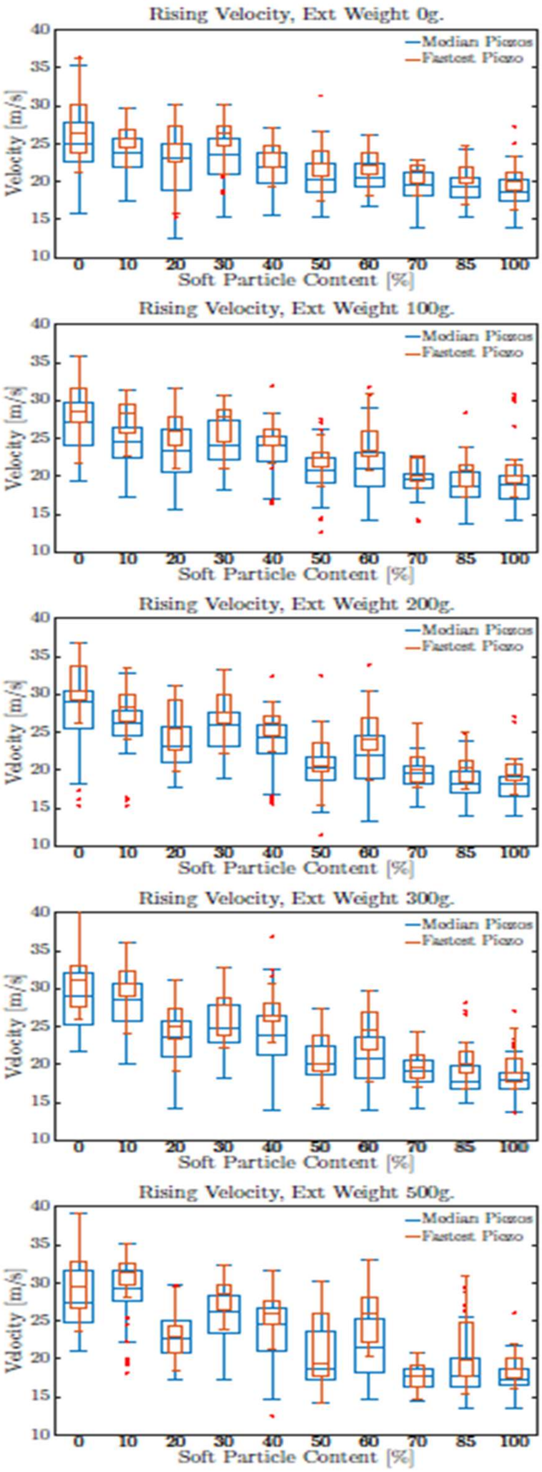

Figure 31 Propagation rising velocity in function of Soft Particle Content for all the external weights. The blue plots consider all the measured velocities from every piezoelectric sensor. The red plots only consider the fastest piezo among the three per each group are marked as red dots. (Oliveri, 2016)

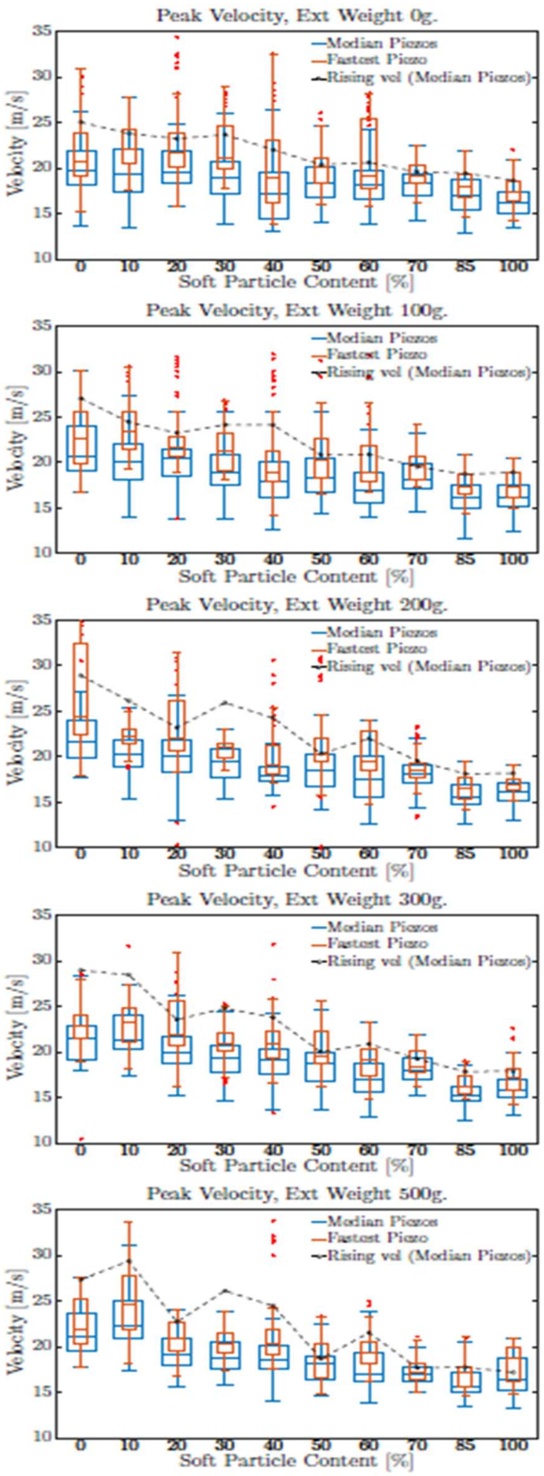

Figure 32 Propagation peak velocity in function of Soft Particle Content for all the external weights. The black dashed line is the rising velocity (median piezo) taken as a reference. (Oliveri, 2016)

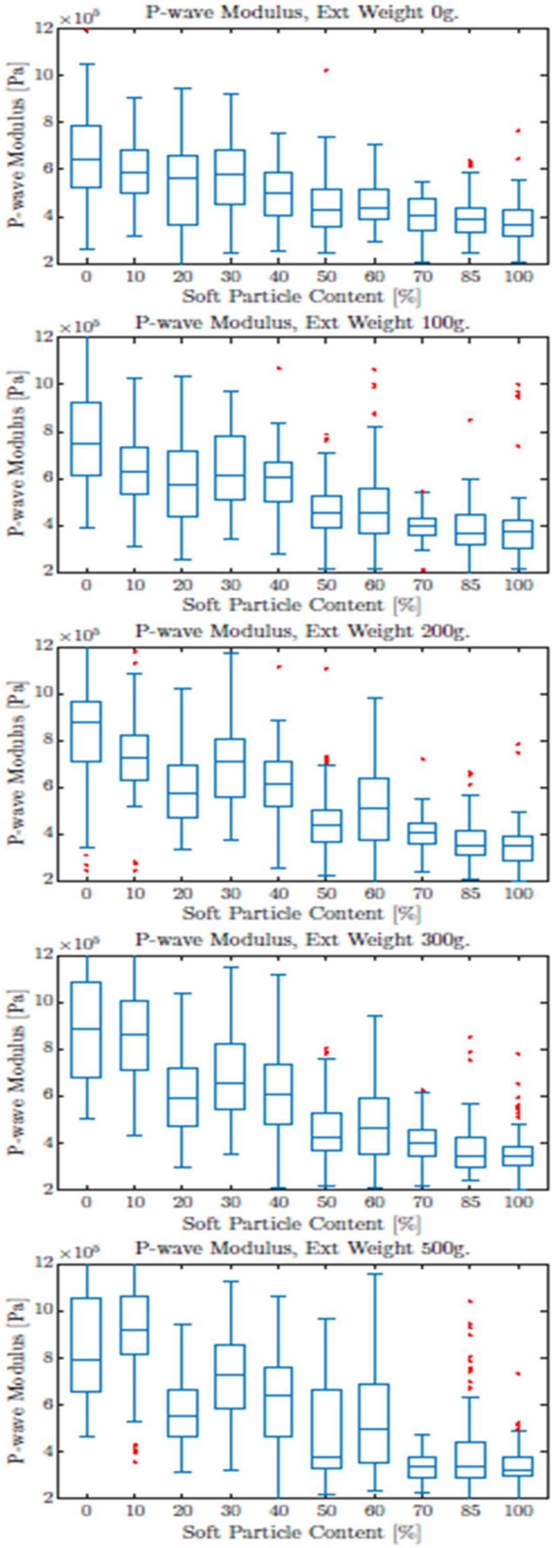

Figure 33 P-wave Moduli in function of the soft particles content calculated from all the rising velocity values. (Oliveri, 2016)

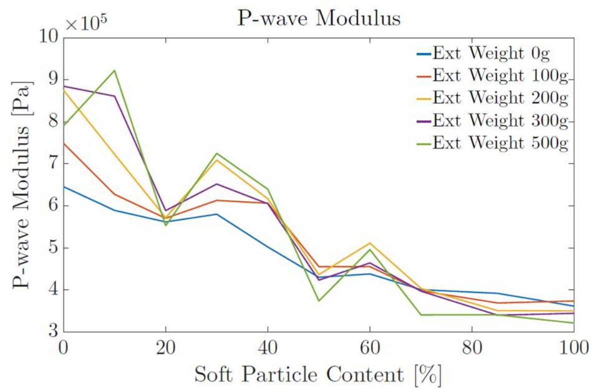

Figure 34 Comparison of the p-wave moduli in function of the soft particle content calculated from the measured velocities for the different external weights. (Oliveri, 2016)

Summary of conclusions and recommendations

In this chapter a summary of the most important problems and recommendations for future research will be given.

When designing the set-up, quite a few different aspects that influence the results should be taken into account. For starters, one must make sure that the signal of the shaker will never be detected in the output. This means in both the mechanical and electronical domains the input signal must be isolated from the output. In this research this was a big problem during the testing stage, where vibration of the shaker were transferred through the walls (mostly due to the particles that touched the walls). These vibrations were picked up by both the piezo's and the wires connected to the piezo's. This led to a lot of noise in the output signal. It would be best to use prefabricated wires to minimize the noise that will be picked up.

The shaker itself should be suitable for sending short pulses. The shaker in this research was designed for sending pulses continuously and had a transient start-up region, which made it hard to use for sending one wave with specific properties.

In order to prevent the forming of a lattice in the particle mix, a combination of larger and smaller particles was used. Larger particles for the softer and smaller particles for the harder particles. This worked really well in preventing the lattice to form. Mixing larger with smaller particles did not seem to have an effect on the wave speed, however this should be checked more extensively.

The system of placing the cap with the piezo's was very sensitive to how it was inserted. It was impossible to do this in the same manner every time, the piezo's could touch the wall (and pick up more noise), the cap would move to an unfavorable position due to the waves and during data collection the cap moves due to the waves which sent extra noise through the piezo's wires. It would be better to have the piezo's fixed in place in the set-up and find another way to unload and reload the particles. This improves the uniformity of the measurement and at the same time reduces the noise, created by a moving piezo cap and wires.

However, this amplifies the problem of the piezo's not touching any particles. With the piezo's fixed in the set-up, this is even harder to manipulate. This problem could be solved by using a higher number of piezo's, so that no matter where an upper particle is positioned, it will always be in contact with a piezo. In this set-up three piezo's were used, so too often in would happen that the 2 or 3 particles that supported the cap did not touch a piezo. Moreover, two of the piezo's were positioned close to the wall, which increased the noise that was transferred through the walls. With more piezo's the measurements can be made a lot more precise.

When high-speed analysis of the force chains is one of the goals of the research, a high speed camera with a sufficiently high resolution should be used. The software used in this research needed a minimum of 60 pixels per particle in order to identify the fringes and thus the stresses in the particles. The camera in this research was just short of this resolution, but for good results a camera with sufficiently more than 60 pixels per particles would be recommended. For calculating the wave speed a camera with more than 1200 fps is suggested. With 1200 fps only 4 to 5 frames are recorded per wave. This is just enough to calculate the time of flight (ToF), but a higher framerate would lead to a more precise calculation.

One of the smaller but still significant problems was the fact that the particles would stick, especially after the weight on top increased. This led to bulk behaviour, which should be prevented. Baking power was used in this research, with the drawback of the particles being somewhat less clear. This did not lead to problems with the imaging.

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