Manipulation of microparticles with ultrasound acoustic waves

Lourens van Emmerik
student nr. 0199443
Optical Sciences,
Faculty of Science and Technology,
University of Twente,
Enschede,
The Netherlands,

Supervisors:
Ir. Jorick van 't Oever
Dr. Ir. Herman Offerhaus

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Abstract

The goal of the experiment is to concentrate microparticles and move them to a specific place in water using ultrasound waves. The principle behind this experiment is the difference in compressibility of the microparticles and the water. Due to this difference a radial force drives the particles to a certain position.

Through applying two different, but close, frequencies a kind of travelling standing wave can be produced so that the particles are moved across the flow channel, captured in moving pressure nodes.

Unfortunately it was quit hard to build the flow channel and to find an appropriate way of connecting the piezoelectric elements, such that the goals were not completely met. In the time available it was showed that it was possible to make standing wave patterns in the flow channel. The used 20 μm polystyrene particles would align at the nodes of the waves and form rows of particles.

Possible improvements can be made in the form of a feedback system to be able to make a perfect absorption of the reflected wave. In this report a detailed description of the steps that are taken to achieve the goal of the experiment is included.

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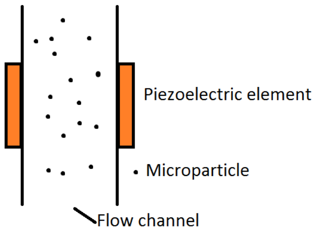
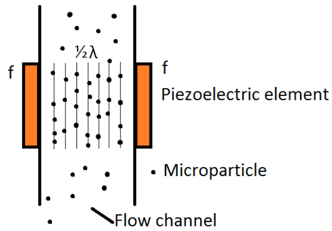
Chapter 1

Introduction

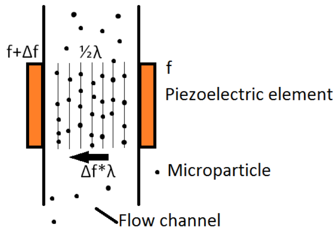
In this report the manipulation of micrometer particles in a fluid with the help of ultrasound acoustic waves is discussed. Also a detailed description of the steps that are taken to try to achieve the goal of the experiment is included.



(a) Both switched off.



(b) Same frequency.



(c) Different frequencies.

Figure 1.1: Schematic drawing of a flow channel with two piezoelectric elements in three different situations. The flow channel is filled with water containing microparticles.

The goal of the experiments is to align the particles within a flow channel and to move them to a specific location with the help of ultrasound acoustic waves. This will be done in the following steps:

- At first a flow cell will be constructed as can be seen in figure 1.1a, which consists of a aluminium flow cell containing two piezoelectric elements. One of these piezoelectric elements can be tilted in 2 dimensions with the help of three spindles. Piezoelectric plates are made of an material that contract or expands if a potential difference over the piezoelectric element is applied.
- The second step will be making a standing wave using one or two of the piezoelectric elements, as can be seen in figure 1.1b. The particles should align on the nodes of the standing wave.
- The last step will be applying two different frequencies that are close to each other. This situation is sketched in figure 1.1c, as can be seen in this figure the particles will start to travel in the direction across the flow channel. In this situation the particles can be moved to a specific location. To be able to do this it is necessary to absorb the waves before they can be reflected. This can be done by both piezoelectric elements.

A final application of this setup is to concentrate microparticles on one side of a fluid stream. This way the particles are easier to measure and the stream of concentrated particles can be separated from the clean stream. This way, for example, small pieces of plastic in water can be filtered out.

Chapter 2

Theoretical aspects

To describe the behaviour of the particles in the fluid stream the perturbation theory of the acoustic fields in fluids is used[1][2][3][4]. In principle this theory describes that particles with a different compressibility react differently on pressure waves. Due to the difference in compressibility a driving force is acting on the particles so that they tend to align on the nodes or anti nodes of an ultrasound acoustic wave. The result for the radiating force can be found in equation 2.3. The complete derivation can be found in Acoustofluidics 1-3,7[1][2][3][4]

In equation 2.4 and 2.5 the Stokes drag and the gravitational force are expressed. They both exert a force on the particle thus influencing the behaviour of the particles. The Stokes drag is the drag that a particle feels when it is moving through a fluid. If the radius of a particle gets really small, say less than 1 μm, the Stokes drag is large compared to the radiating force. This is because $F_{rad} \propto a^3$ and $F_s \propto a$. At this point it will be harder to move the particle. The gravitational force is relatively unimportant as long as the density of the used particles is comparable to the density of the water.

$$F_{rad} = 4\pi\Phi(\tilde{\kappa},\tilde{\rho})ka^3E_{ac}\sin(2kz) \tag{2.1}$$

$$\Phi(\tilde{\kappa},\tilde{\rho}) = \frac{1}{3}\left[\frac{5\tilde{\rho}-2}{2\tilde{\rho}+1}-\tilde{\kappa}\right] \tag{2.2}$$

$$F_{rad} = \frac{4\pi}{3}\left[\frac{5\tilde{\rho}-2}{2\tilde{\rho}+1}-\tilde{\kappa}\right]ka^3E_{ac}\sin(2kz) \tag{2.3}$$

$$F_{stokes} = \frac{3}{2}\pi\mu Ua \tag{2.4}$$

$$F_z = mg \tag{2.5}$$

Where:
$\Phi(\tilde{\kappa},\tilde{\rho})$ is the acoustophoretic constant factor [-].
a is the radius of the particle [m].
E_{ac} is the acoustic energy density [kg m^{-1} s^{-2}].
$\tilde{\kappa}$ is the relative compressibility [-].
$\tilde{\rho}$ is the relative density [-].
k is the wave number defined as $k = \frac{2\pi}{\lambda}$ with a wavelength λ with λ in [m].
z is a distance from the piezoelectric element [m].
μ is the coefficient of viscosity [kg m^{-1} s^{-1}].
U is the relative velocity of the fluid with respect to the particle [ms^{-1}].
g is the free fall acceleration [ms^{-2}].

Determination of the wavelengths of the used ultrasound acoustics.

$$v = \frac{\lambda}{T} \tag{2.6}$$
$$v = \lambda \cdot f \tag{2.7}$$
$$\lambda = \frac{v}{f} \tag{2.8}$$
$$\lambda = \frac{1,497 * 10^3 m/s}{1,50 * 10^6 Hz} \tag{2.9}$$
$$\lambda = 0,998 * 10^{-3} m \tag{2.10}$$

Values of the speed of sound in water from Table 1 in [2].

As can be seen in equation 2.10 the wavelength of an 1,5 MHz acoustic wave is about 1 mm. This is well observable in the setup used and is easy to produce using commercially available piezoelectric elements. So in the experiments done a 1,5-2,5 MHz acoustic wave is used because this makes the measurements easier.

2.1 Flow cell

The flow cell has got to fulfil the following conditions:

- It got to have a way of connecting some hoses to it to be able to fill the flow cell with water.
- The space between the piezoelectric elements has to be a several wavelengths long so that a few rows of particles can be observed.
- It got to have a window to be able to view the movement of the particles on a (inverted)microscope. This window has to be positioned so that one of the piezoelectric elements can be seen.
- It has to be possible to align one of the piezoelectric elements in 2 dimensions.
- It has to be sectional so that it can be cleaned.

With these conditions in mind a design for the flow cell is designed. The accuracies necessary in this design process are further explained in the next section.

The drawings of the complete flow cell can be found in figure 4.1 in the appendix on page 14.

2.2 Determining the needed accuracy for the flow cell

It is important that both piezoelectric elements send out their waves in the same volume of water between the each other. If this is not the case the waves will not properly overlap and it will not be possible to create an well defined plane wave pattern. To be able to align the piezoelectric elements properly it is necessary to determine the error margins and the accuracy of the used spindles.

If the maximum deviation from the parallel plane of the planer waves is less than $\frac{\lambda}{100}$ the planer waves are overlapping in such a way that they form a standing wave. This deviation is labelled z in fig 2.2. This calculation refers to figure 2.1. The real measurements can be found in figure 2.2.

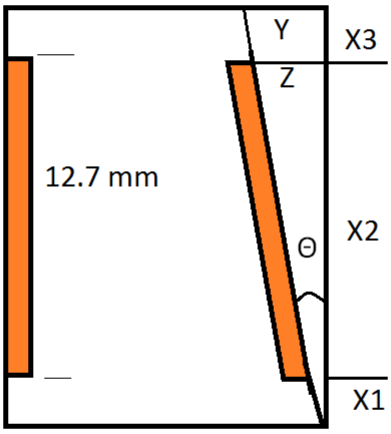


Figure 2.1: Determining the minimal positioning accuracy for the spindles in the setup.

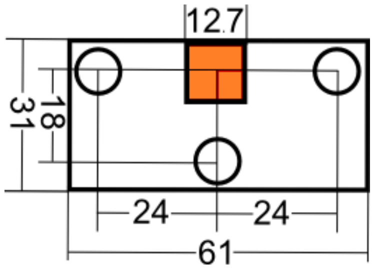


Figure 2.2: The aluminium plate with the piezoelectric element which is movable with the spindles. All measurements are in mm.

$$\tan(\theta) = \frac{z}{x_2} \tag{2.11}$$

$$\tan(\theta) = \frac{y}{x_1 + x_2 + x_3} \tag{2.12}$$

$$\frac{z}{x_2} = \frac{y}{x_1 + x_2 + x_3} \tag{2.13}$$

$$y = \frac{z(x_1 + x_2 + x_3)}{x_2} \tag{2.14}$$

$$y = \frac{0.0100 * 48}{12.7} mm \tag{2.15}$$

$$y = 0.038 mm \tag{2.16}$$

This calculation shows that the spindles need to have a minimum accuracy of 38 μm. The spindles used in the setup have an accuracy of 10 μm so this is accurate enough.

2.3 Determining the best way of connecting the piezoelectric element

As described in section 2.2 it is necessary to have a very flat surface. This issued a problem for the electrical connection of the piezoelectric plates[5]. If a wire is just soldered onto the plate the front of the piezoelectric element isn't flat any more. This problem was solved by introducing an extra plate which is glued onto the piezoelectric plate itself. A schematic drawing of this sandwich is shown in figure 2.3.

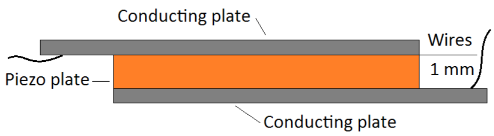


Figure 2.3: Scematical drawing of the piezoelectric sandwich.

The first experiments were done with a combination of copper plates and a conductive silver paint[6], but this combination was too weak. The next step was to add some glue to the edges. In this process two types of glue were used, a fast drying and a slow drying two component glue. After they were done the following test were done:

1. An electrical test to determine the stability and the inductance.
2. A surface scan to determine the front face profile.

Both glue, piezoelectric plate, copper sandwiches were electrically stable after they were switched on for about 90 minutes. The problem was the results from the surface scan which was done using a Dektak 8 profile measurement machine situated in the clean-room of the MESA+ institute at the University of Twente[7]. The results of these scans are shown in figure 2.5. As can be seen in these graphs typically there is a curvature present of around 20-50μm. Compared to the used wavelength λ of 1 mm, this would result in a curvature in the field, so this is too much. So an alternative sandwich connection had to be made.

To make sure that the surface was flat, a glass plate coated with a binding layer of a few nm chrome, 1 μm copper and 100 nm gold glued to the piezoelectric plate with an electro conductive epoxy was tested. The problem with this solution was that the conductive epoxy was too thick so that the glass plates were not parallel. This caused that there was a large tilt in the piezoelectric sandwich. Because of this tilt the alignment in the flow channel would be too large to be compensated.

The next solution was probably the simplest of them all. A glass plate glued directly on the piezoelectric plate with UV-glue. A schematic drawing of this sandwich can be seen in figure 2.4. This solution had a flat surface and was parallel. The only difficulty was the soldering of the contacts because the piezoelectric plate can not handle high temperatures very well. This is because of the so called Curie-temperature T_c. If $T > T_c$ the the piezoelectric element will break down. This is solved by soldering at a low temperature with a short contact time. This is the construction method used in the final setup only with the edges sanded down so that it will not break the film separating the piezoelectric element form the water.

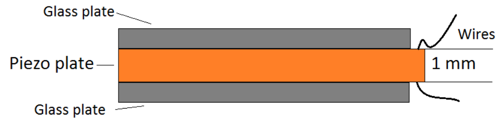
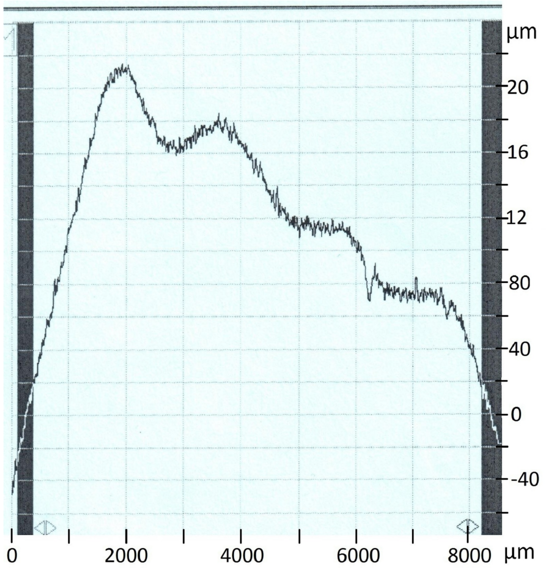
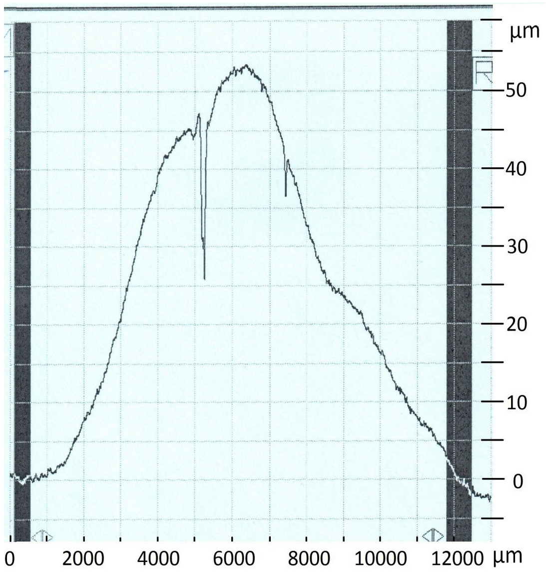


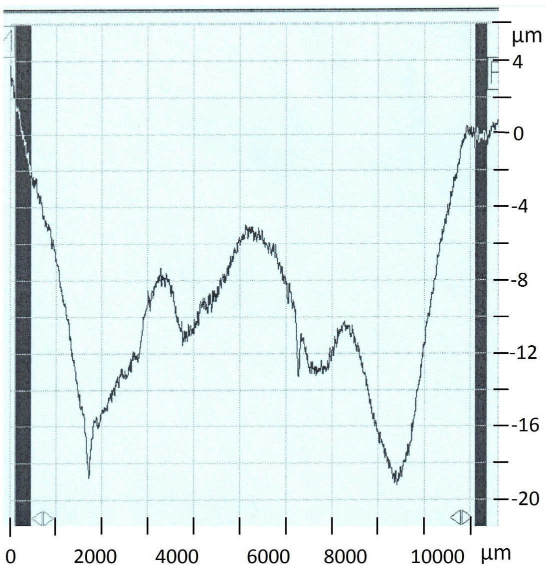
Figure 2.4: Shcematical drawing of the second piezoelectric sandwich.



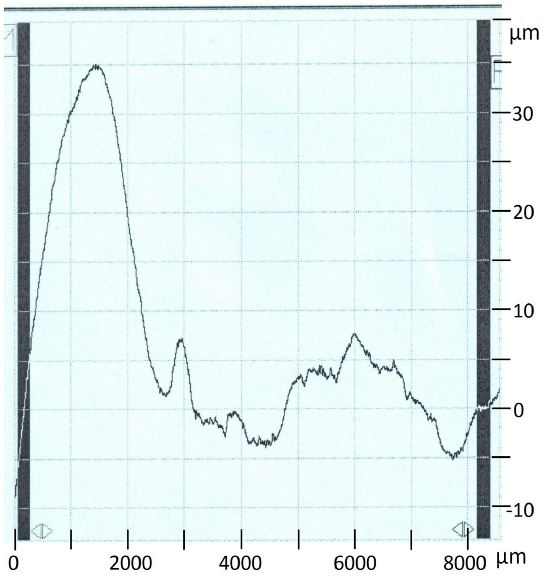
(a) Two component glue in the x direction.



(b) Two component glue in the y direction.



(c) Fast drying glue in the x direction.



(d) Fast drying glue in the y direction.

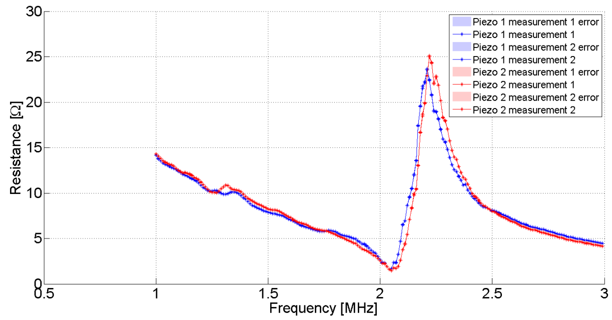
Figure 2.5: Dektak measurement of the piezoelectric sandwich based on copper plates.

Chapter 3

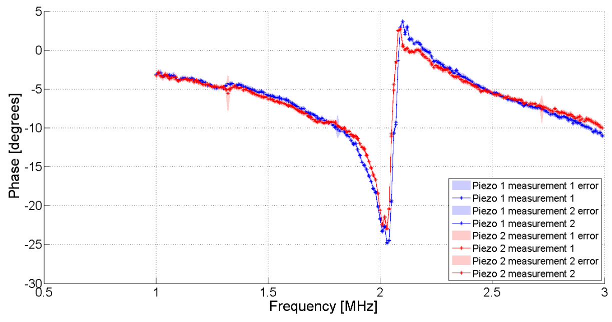
Practical aspects

3.1 Electrical resonance measurements

In figure 3.1a a measurement of the complex impedance of the piezoelectric elements fixed in the complete setup filled with water is shown. These measurements tell something about the electrical behaviour of the flow channel. This information can be used in the design of electrical feedback systems. In figure 3.1b the phase response of the piezoelectric elements fixed in the complete setup filled with water is shown. In these graphs it is clearly visible that the resonance frequency of the setup is around 2.2 MHz. Also these measurements indicate that the setup is electrically working.



(a)



(b)

Figure 3.1: Electrical resonance measurement of the flow channel with water. Measurements done by J.J.F. van 't Oever

3.2 Measurements

For these measurements a 100 times deluded solution of 10 mass% 20 μm polystyrene particle[8] is used. A schematic drawing of the setup is shown in figure 3.2. One of the piezoelectric elements can be tilted in 2 dimensions so that both piezoelectric elements are lined out. At the beginning of each experiment the piezoelectric element that can be tilted is tilted in such a way that the signal measured by this piezoelectric element is maximal. This is done by turning the spindles over a large distance so that the global optimum is found. This means that both piezoelectric elements are optimally aligned. If there is only one piezoelectric element switched on it is always the one that can not be tilted.

A list of the used equipment:

- Amplifiers: home built, amplification 1.5 times at 2.0 MHz
- Function generator: Rigol DG4162
- Oscilloscope: Rigol DS1202CA
- Flow channel with piezoelectric elements: home built. Details can be found in figure 4.1 on page 14.
- Microscope: Olympus SZ60
- Camera: Nikon D3100

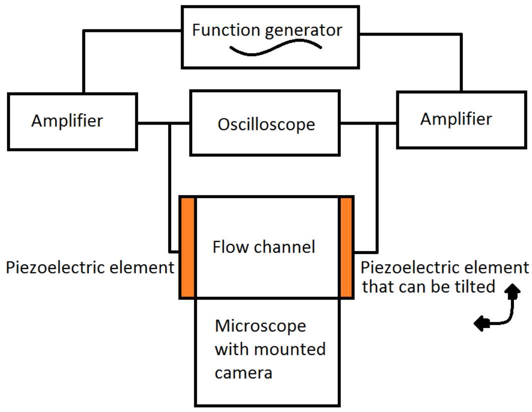


Figure 3.2: A schematic drawing of the setup.

3.2.1 One piezoelectric element switched on

In figure 3.3 a photograph of the fluid channel with one of the piezoelectric elements switched on at 2 MHz. Figure 3.4 is a intensity plot of a cross section of figure 3.3. In figure 3.4 there are 10 lines of captured particles observed. The line numbered with the number 2 has a length of 5.0 ± 0.5 mm this is the width of the viewing window. This error is due to the difference in focus, due to this focus it is hard to see what the edges of the window are. The distance between the particle lines, for example line number 1, is $420 \pm 42 \mu$m. This is also the average distance d between the peaks in figure 3.4, the deviation from this length is about 20 μm. Considering that the particles are 20 μm in diameter and sometimes tend to stick together, this is not very strange. According to equation 2.10 the theoretical wavelength of the used frequency is about 750μm. So the half wavelength distance between the rows of particles should be about 375μm. Because the reference point is not very clear and out of focus the difference of 25 μm between the measured distance and the theoretical distance can be explained by the error of 42 μm. In future measurements there should be a clear reference length in the picture to be able to calibrate the measurement. The drop in each dip in figure 3.4 is much steeper than the rise. This is possibly due to the large amount of reflected waves in the flow channel because only one piezoelectric element is emitting causing asymmetrical pressure nodes.

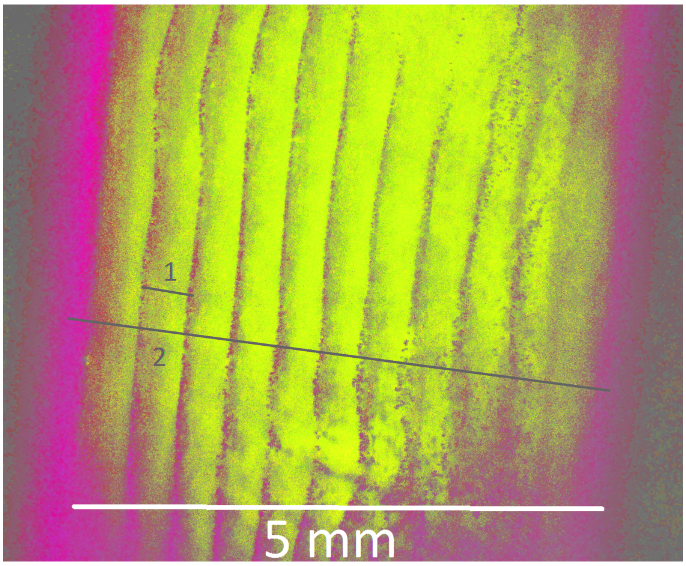


Figure 3.3: A photograph of the fluid channel with one of the piezoelectric elements switched on at 2 MHz. The colours are altered for maximum contrast.

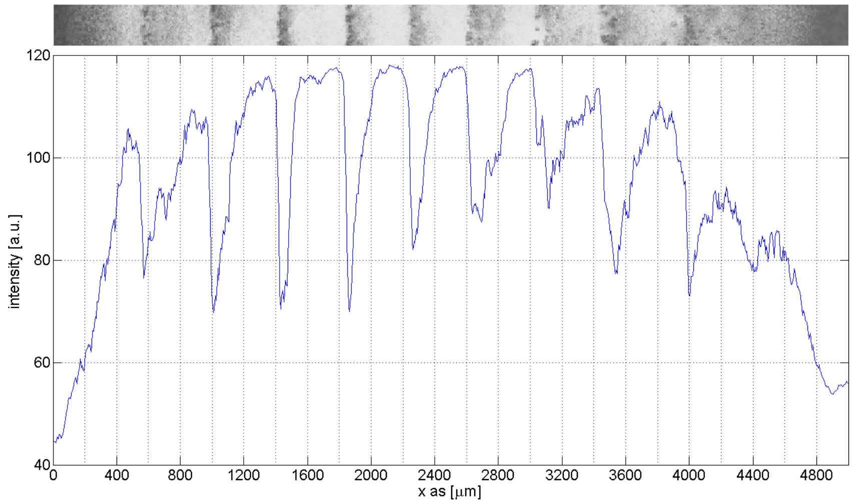


Figure 3.4: A plot of the intensity of the summation of all the horizontal lines in the picture above.

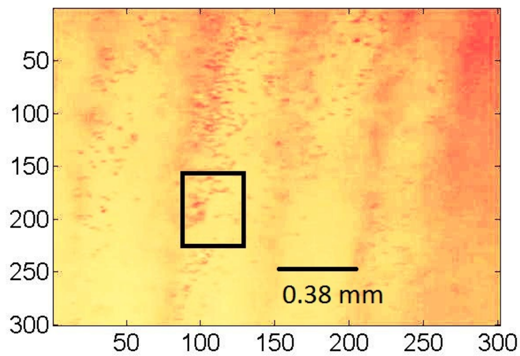
3.2.2 Two piezoelectric elements switched on

In other measurements the second piezoelectric element was also switched on at 2 MHz so that both piezoelectric elements were switched on at 2 MHz. In these measurements the relative phase between the two piezoelectric elements and the amplitude of the two piezoelectric elements were modified. When the amplitude was tuned such that both piezoelectric elements had a same amplitude, the relative phase was adjusted. In all experiments the changes made on the function generator were done by hand. When the phase was changed 90 degrees the lines of particles almost disappeared. This means that there is destructive interference in the flow channel. This was probably due to the waves reflecting at both sides. Because if there would be only two oppositely travelling waves, only the nodes would shift, not cancel. After the phase change there were vortexes visible which are explainable by reflecting waves which are reflected at an angle, this would mean that the piezoelectric elements are not perfectly aligned. A possible way of preventing this is to actively absorb the incoming waves.

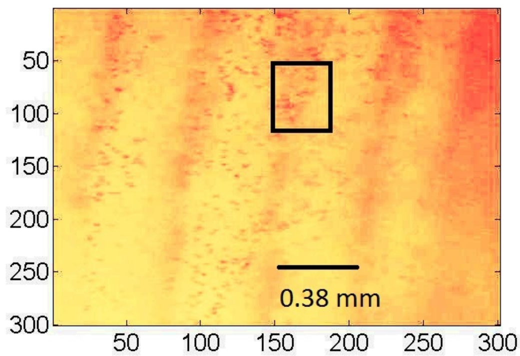
In another experiment the frequency of both piezoelectric elements was changed. In these experiment it was not possible to make a standing wave with only one piezoelectric element switched on. But when the other piezoelectric element was switched on at the same frequency and the relative phase was adjusted, it was possible to observe a standing wave. These experiments would be more accurate and reliable with active absorption of the reflected waves mentioned above.

3.2.3 Particle flow

In some of the experiments were only one piezoelectric element was switched on at 2 MHz, there was a flow of particles in the fluid. This flow did not always have the same direction of flow but still it is interesting to know what the amplitude of this flow speed is. With the help of figure 3.5a and 3.5b the speed of a group of particles is determined. Both pictures are 72 frames apart so the time difference is 3 seconds. Because the wavelength is known the distance between the vague lines of particles is 375μm. With the help of some mathematics the flow rate can be calculated. The flow speed for this set of particles $\approx 250\frac{\mu m}{s}$. The fact that there is a flow of particles is a bit strange because there should only be a standing wave. Some possible explanations are for example there are some effects from the edges of the piezoelectric elements, heating or an imperfect alignment that cause flow in the water. It is also possible that the particles only travel in a circular motion. But this is hard to determine because the view is blurred by the particles if the view is focused deeper in the water.



(a)



(b)

Figure 3.5: Determining the speed of the particles in the flow canal. Axis are in pixels. Because of the zooming it is very hard to see make the particles visible in this report. The colours are altered.

Chapter 4

Conclusion and recommendations

The preparations described in sections 2.1, 2.2 and 2.3 were very time consuming but also very important to do. Thanks to these thorough preparations it was possible to make a standing wave pattern with 20 μm particles in the flow cell. This means that it was possible to make standing waves using one or two piezoelectric elements at the same frequency. Unfortunately, due to time constraints, it was not possible to make the particles move in a controlled way.

In the experiment where one piezoelectric element was switched on the particles were trapped in the nodes of the standing wave. In this experiment, there were also a few problems in measuring dimensions due to the lack of good reference lengths. However the result of $420 \pm 50 \mu$m is comparable to the theory as described in section 2. Unfortunately there were some particles moving in these experiments, this may be due to misalignment, of the counter propagating waves or heating of the piezoelectric elements or liquid.

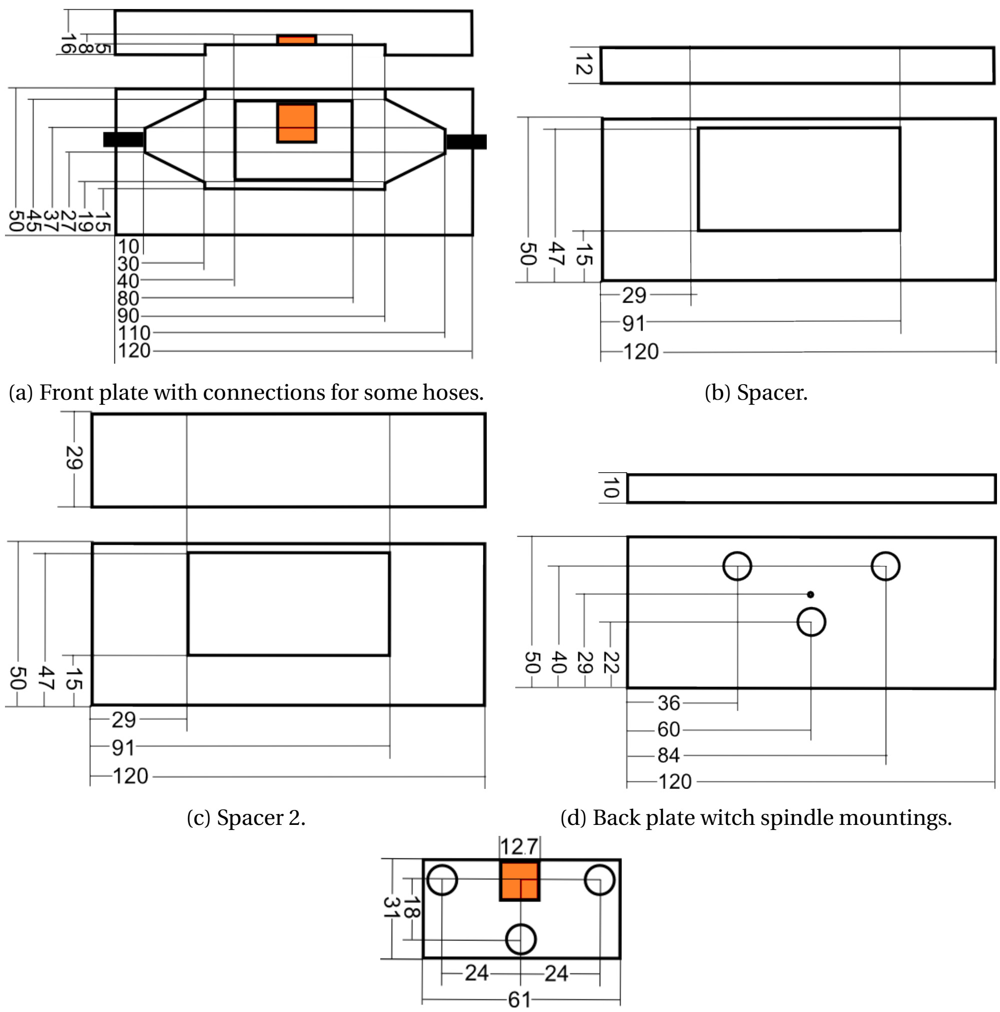
Also some experiments were conducted involving two emitting piezoelectric elements. In these experiments it was visible that there has to be done something about the reflecting waves. These reflecting waves are causing problems by making streams in de water. This can be solves by active absorption by both of the piezoelectric elements. This is also important to be able to make a moving standing wave with two different, but close, frequencies.

A possible solution to determine if the absorbing piezoelectric element absorbs all the incoming waves, which are send out at the emitting piezoelectric element, is to measure the current through the absorbing piezoelectric element. If the current through the absorbing piezoelectric element is small the work done by the absorbing element is also small. In this situation the absorbing piezoelectric element is adsorbing the incoming waves sent out at the emitting piezoelectric element. Because the amplifiers that are used have an I monitor port this can be done without making rigorous changes to the setup.

Another possible experiment to to switch on one piezoelectric element and sweep the frequency. In this way it is possible to determine at which frequencies the system can produce standing waves. Possibly a frequency that has a moving standing wave pattern can be found. If this is the case, there is no need for a second piezoelectric element which makes the setup easier and possibly more reliable.

A possible improvement point is the reliability and robustness of the electric connections on the setup. At the time of writing these connections are quit fragile. This can cause problems if it is used more often.

Appendix



(a) Front plate with connections for some hoses.

(b) Spacer.

(c) Spacer 2.

(d) Back plate witch spindle mountings.

(e) Piezoelectric element holder.

Figure 4.1: Construction drawings of all the separate plates used for the flow cell. All measurements are in mm. All drawings contain a top and a front view. The Piezoelectric plate holder is attached witch a spring to the backplate.

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