SOUND OF RAIN

REPORT FOR THE TRAINEESHIP

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SUMMARY

For my traineeship at the Physics of Fluids department at the University of Twente I have made an experimental setup called the sound of the rain, which is a real life example of a liquid drop impact on a liquid surface. When a (rain)droplet is falling on a liquid surface it may happen a sound is being heard. When you hear this sound somehow and measure the frequency, this seems lower than what you would expect with that frequency. Therefore a research is set up to investigate whether frequency of the sound in the air is lower than the frequency measured below water.

It seems when a droplet is falling on the water surface a bubble is entrained when the cavity, created by to the drop impact, closes. When a bubble is entrained it starts oscillating as soon as the bubble is entrained and a sound is created. After measuring the frequency it seems this sound is exactly the same as the Minnaert Frequency.

However bubble entrainment does not happen all the time. A bubble is only entrained when it has the rights size and impact velocity that lies within a certain parameter range. We define different regions where bubbles may be entrained. In the region called the *irregular entrainment* not every impact entrains a bubble and the behaviour is very unpredictable. However, in the region where *regular bubble entrainment* occurs, every drop impact entrains a bubble, which makes this region very predictable.

In our setup a parameter scan, using different impact velocities and drop sizes, was made to investigate what setting should be used to get the same frequency on every drop impact. After taking many measurements it seemed that using a droplet with a diameter of 3.0 mm and an height of 17 cm we obtain a frequency of 7,315 kHz on every drop impact.

After recording the sound above water using an in distance adjustable microphone it was clear that indeed the frequency of the sound was nearly the same above water as below water. However, only a small region was investigated so no hard statement can be made based on this result.

Since the frequency of the sound when traveling from the bubble to the human ear remains the same another possibility is that the pulse length of the sound is related to the perception of frequency. After listening to two artificial sound waves with the same frequency but another pulse length. Surprisingly the sound with the smaller pulse seemed lower in frequency than the one with the longer pulse length.

Assuming that the frequency in the air remains the same, this could be a good explanation why the sound of a bubble seems lower in frequency than you would expect of such a frequency.

INHOUD

1.0 INTRODUCTION

For the master study Science Education and Communication at the University of Twente a traineeship had to be taken which involves some research. The Physics of Fluids department of the University of Twente had some pretty interesting research subjects. Therefore I did my traineeship at the Physics of Fluids department at the University of Twente.

In November 2014 the Physics of Fluids was invited to place some experimental setups in the Science museum NEMO, located in Amsterdam, for the event called 'Night at the Museum'. One of those setups was the sound of rain setup which represents a real life example of a liquid drop impact on a liquid surface.

My assignment for my traineeship was to make the sound of rain setup for the event Night at the Museum and for future open days of the University of Twente. Besides the development of the setup I have also done some experimental research.

The main goal of this research was to investigate whether or not the frequency of the sound is different than the frequency beneath water. This was because the heard sound does not sound like its corresponding frequency, but it sounds lower in frequency. This resulted in the following research question

> *Is the sound above water lower in frequency than its corresponding frequency measured beneath water?*

To answer this question a theoretical background will be given in chapter 1. This chapter describes how the sound is created, what determines its frequency and how the sound propagates from the water into the air and what happens with the sound wave. After the theoretical background the used experimental setup and the performed experiments itself are described in chapter 3. In chapter 4 the results retrieved from the experiments are shown resulting in the conclusions stated in chapter 5.

2.0 THEORETICAL BACKGROUND

2.1 WHAT CREATES THE SOUND OF THE RAIN?

Over the years many have studied the sound created when a raindrop hits a water surface. It is known for some time (Franz, 1959) that a sound is only created when during the impact of a liquid drop on a liquid surface, a bubble is entrained. As can be seen in figure 1, when the liquid drop hits the water a cavity is formed. When in its turn the cavity closes due to surface tension it entrains a bubble. As soon as the bubble is entrained, it radially oscillates (Leighton, 1995) and creates a sound which is being discussed later in this report.

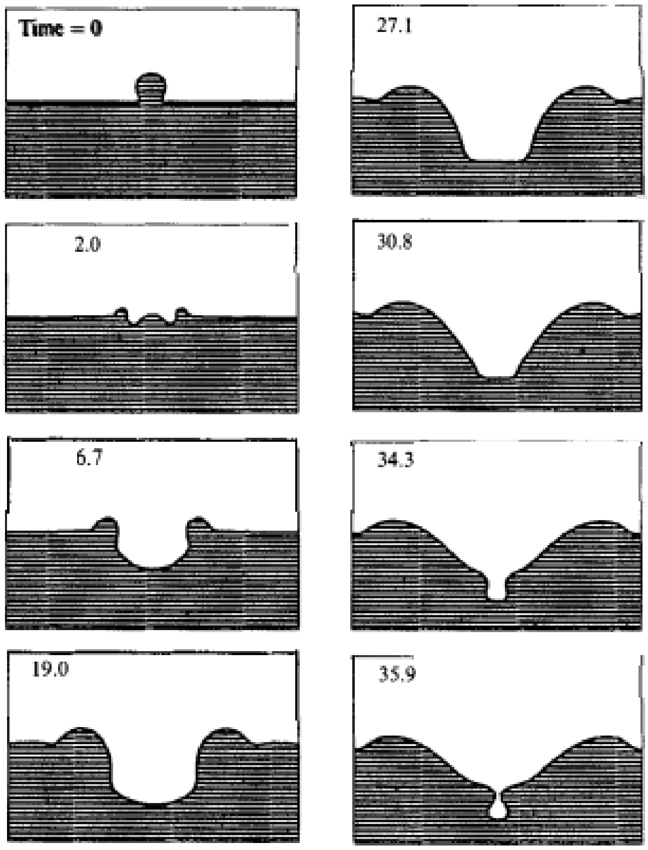

Figure 1 A bubble is entrained when the cavity, produced by a liquid drop impact on a liquid surface, closes. (Oguz & Prosperetti, 1990)

Although this figure gives a good view of how a bubble is formed, it says nothing about the condition in which a bubble is formed. It seems not every drop impact entrains a bubble. Franz, for instance, could not discover a pattern in which a bubble is formed since he was working with what is nowadays know as *irregular bubble entrainment.* As the name suggest the behaviour of the bubble entrainment is irregular and unpredictable.

When doing experiments a region is needed where every bubble entrainment is predictable. As we saw, the irregular entrainment region is very unpredictable, however when smaller drops and lower impact velocities are used one could find a region where the bubble entrainment is predictable. In contrary to *irregular entrainment* an entrainment in this region is called *regular bubble entrainment.* As long as the drop size and impact velocity are in range with the regular entrainment region, shown in figure 2, a bubble is entrained on ***every impact*** and the data is very predictable.

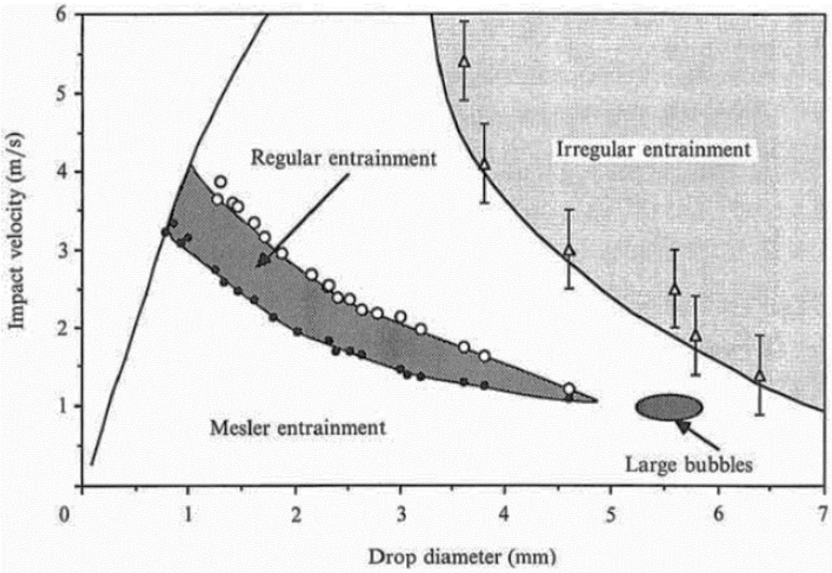

Figure 2 Depending on the drop diameter in mm and the impact velocity in m/s the regions are shown. In the *irregular entrainment* is for greater droplets and mainly higher velocities and the *regular entrainment* occurs with droplets with a diameter between 0.8 and approximately 5 mm. (Pumphrey & Elmorez, 1990)

In addition to the information shown above figure 3 shows a relation between the impact velocities and the frequency of the bubble. Apparently in the edges of the regular entrainment region the frequencies are higher than in the middle of the region.

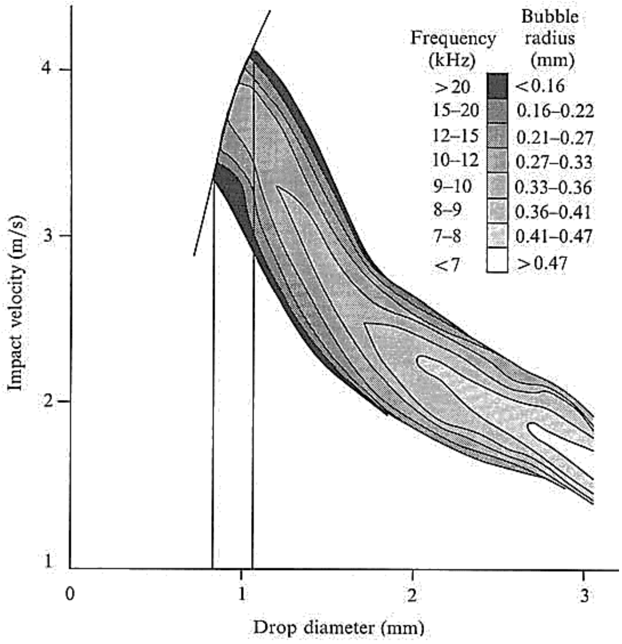

Figure 3 The colour of the contour plot gives information about the bubble size and the frequency of regular entrained bubbles. (Pumphrey & Elmorez, 1990)

2.2 3WHAT DETERMINES THE FREQUENCY?

As mentioned in paragraph 2.1, it is known for a long time, when a bubble is entrained it starts to oscillate. The oscillating bubble in its way created a sound wave which can be best described as a damped sine wave with a certain frequency. As Minnaert suspected this frequency is equal to the resonance frequency given by Minnaert's formula (Pumphrey & Elmorez, 1990)

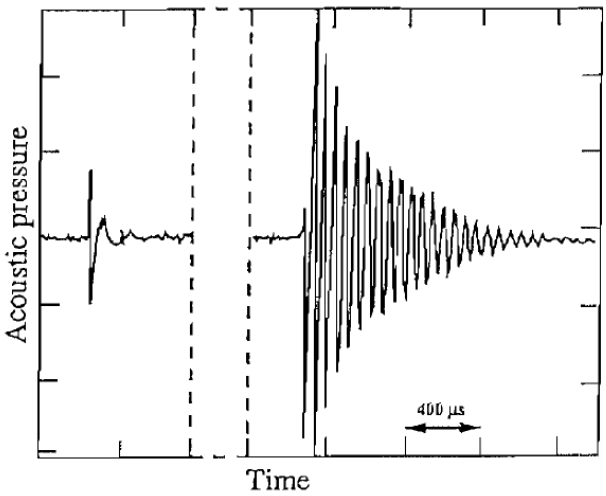

Figure 4 The left part is the pressure signal of a 0.83 mm diameter droplet impact on the surface. The right signal begins after the initial signal, corresponding with the bubble emission. Retrieved from The Acoustic Bubble, pp 223 (Leighton, 1995)

The Minnaert frequency can be calculated as followed (Oguz & Prosperetti, 1993)

$$f_0 = \frac{1}{2\pi R}\sqrt{\frac{3\gamma P_0}{\rho}} \tag{1}$$

with f_0 as the sound frequency in kHz, R as the bubble radius in mm, γ as the ratio of the gas specific heats, P_0 as the ambient pressure and ρ as the liquid density.

According to this formula a 1 mm radius air-filled bubble in water corresponds to approximately 3.3 kHz (Dangla & Poulain, 2010) (Ross, 1976) which leads to the following formula

$$f \cong \frac{3.3}{R} \tag{2}$$

with f as the sound frequency in kHz and R as the bubble radius in mm.

2.3 SOUND PROPAGATION FROM THE WATER INTO THE AIR

To investigate why the frequency of the sound above water seems lower than its corresponding frequency measured beneath water, research has been made on how the sounds propagates through the different media and what happens with the sound wave..

As we know the sound, created by the oscillating bubble, travels from the water, into the air to the human ear. When the sound wave travels towards the human ear, two different scenarios are present which might influence the sound wave in amplitude or frequency. One of these stages is where the sound goes through a medium (water or air) and the other stage is the transition from the water to the air. Both scenarios will be discussed in the next section.

2.3.1 TRAVELING THROUGH A MEDIUM

When a sound wave travels through a medium it is known that the sound wave experiences some losses in amplitude (Szabo, 2004). These losses called *attenuation* can be described as an exponential decrease as the distance increases. For a single-frequency (*fc)* wave, Szabo gives us the following formula

$$A_{(z)} = A_0 \cdot e^{-\alpha z} \tag{3}$$

with $A_{(z)}$ as the amplitude as function of the depth z in cm and the attenuation coefficient α in nepers per centimetre per megahertz. However since the attenuation confident is mostly written in decibel per centimetre per megahertz [dB cm^{-1} MHz^{-1}].

The amplitude in decibel [dB] can be calculated as the ratio of two amplitudes using the formula

$$Amplitude\ (dB) = 20 \cdot \log \left[{}^{A}\!/_{A_0} \right]$$

The attenuation coefficients (Dendy & Heaton, 1999) of water and air are

$$\alpha_{air} \quad = \ 1.6 \qquad dB\ cm^{-1}\ MHz^{-1}$$

$$\alpha_{water} = \ 0.002 \ \ dB\ cm^{-1}\ MHz^{-1}$$

which represent the ratio in which the amplitude gets lower as it travels through the water or the air. As the amplitude is affected when the sound wave travels, the frequency however remains the same.

2.3.2 MATERIAL TRANSITION

When a sound wave enters a transition between materials a portion of the incident wave is reflected and the other part is transmitted. In figure 5 a transition between water and air is represented.

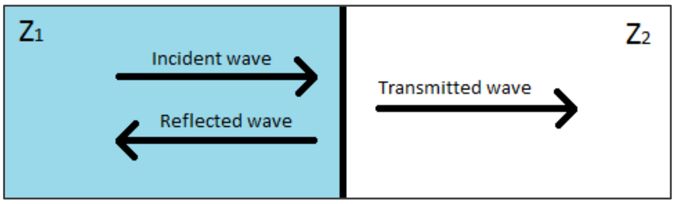

Figure 5 Transition from water to air. In this figure $Z_1$is the acoustic impedance of the water and Z_2 is the acoustic impedance of the air.

The ratio of the amplitude of the reflected and transmitted wave is defined by the combination of acoustic impedances of both materials. These (specific) acoustic impedances can be calculated using the formula

$$Z = {}^{p}/_{c} \tag{3}$$

with *Z* as the specific acoustic impedance in Rayls, *p* as the density of the medium and c as the speed of sound in the medium. For air and water this means they have an acoustic impedance of respectively 0.0004 Mrayls and 1.48 MRayls.

$$Z_{air} = 0.0004\ MRayls$$

$$Z_{water} = 1.48\ MRayls$$

The ratio in which the sound wave is transmitted or reflected can be calculated using the following formulas (Szabo, 2004)

Amplitude reflection coefficient: $$R = \frac{Z_2 - Z_1}{Z_2 + Z_1} \tag{4}$$

Amplitude transmission coefficient: $$T = \frac{2Z_2}{Z_1 + Z_2} \tag{5}$$

As we previously saw only the amplitude is infected while propagating through the medium, which left the frequency as it is. Surprisingly, again, only the amplitude is affected in the transition between the materials. It can be concluded that the frequency remains the same while traveling from the bubble to the human ear.

2.4 SUMMARY

When a (rain)droplet is falling on a liquid surface it may happen a sound is being heard. Apparently this sound is created because a bubble is entrained when the cavity, created due to the drop impact, closes. When a bubble is entrained it starts oscillating as soon as the bubble is entrained. It seems the frequency of the sound is exactly the same as the Minnaert Frequency.

Unfortunately bubble entrainment does not happen all the time. A bubble is only entrained when it has the rights size and impact velocity that it is in a certain region. We define different regions where bubbles may be entrained. In the region called the *irregular entrainment* not every impact entrains a bubble and the behaviour is very unpredictable. However, in the region where *regular bubble entrainment* occurs, every drop impact entrains a bubble, which makes this region very predictable.

As the sound is created the sound propagation from the bubble to the human air is divided in three stages. In two of these stages the sound travels through a media, where losses are present. The ratio in which the material has more or less losses can be seen in the attenuation coefficients of the materials. The attenuation coefficient is expressed in decibel per centimetre per megahertz. As can be seen, the attenuation is only affecting the amplitude of the sound signal.

The other stage is the transition from the water to the air. When the sound wave incidents the layer of air a part of the sound wave is reflected and a part of the sound wave is transmitted into the air. Depending on the materials the ration in which the amplitude of the sound wave is affected, however the frequency of the sound is not affected by the transition of the materials.

2.5 EXPECTATIONS FROM THEORY

Since only the amplitude of sound wave is affected during the propagation of the sound towards the human air, no difference in measured frequency below water and the above water is expected. The way in which the frequency seems lower than its corresponding frequency is probably due to the length of the pulse.

3.0 THE EXPERIMENTS

3.1 EXPERIMENTAL SETUP

To test whether theory is in agreement with the data and to look for parameter settings where the data is most consistent a basic setup has been made. A visualisation of this basic setup is shown below in figure 6. A more detailed description can be found beneath the visualisation.

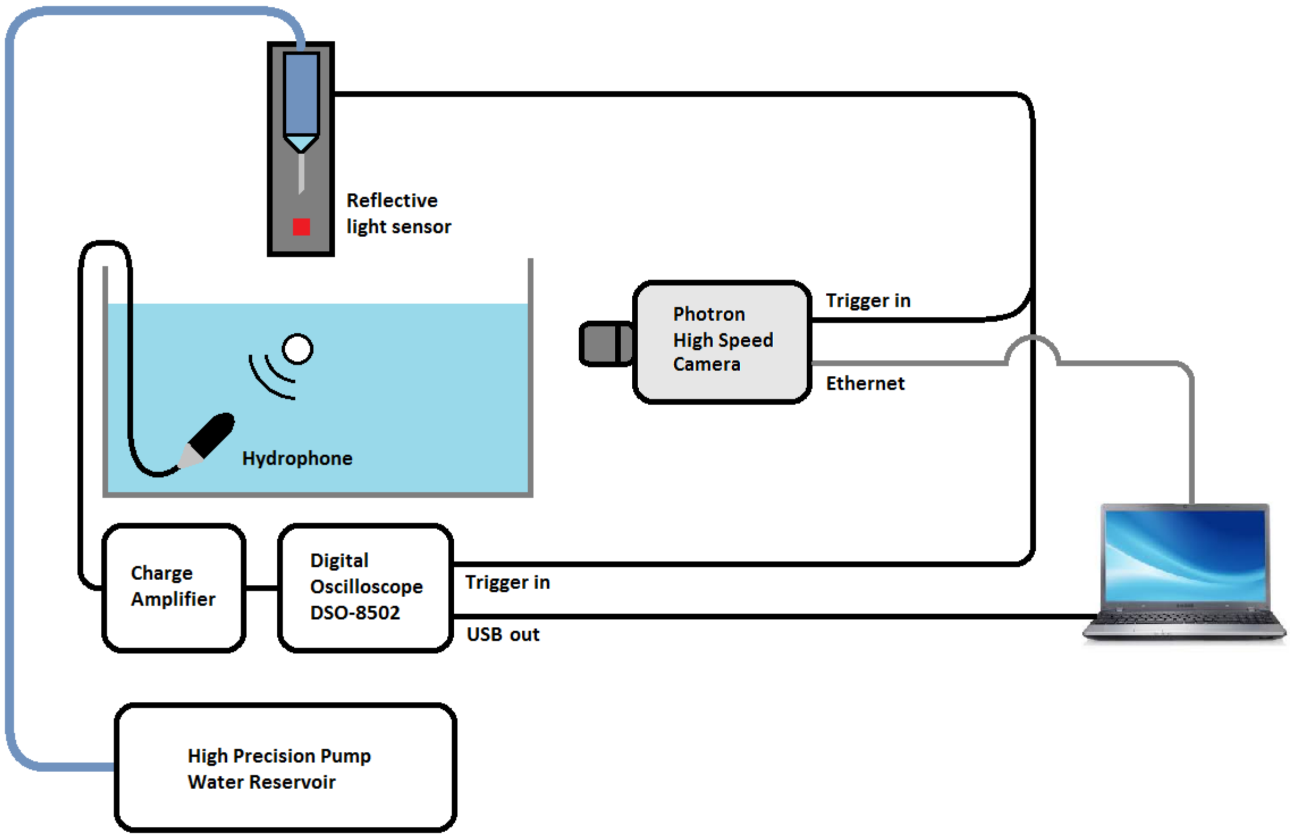

Figure 6 Visualisation of the experimental setup.

DROPLET FORMATION

To realize the droplet formation a syringe is used in combination with a high precision syringe pump. Since a syringe pump is used the diameter of the droplets can be adjusted by switching needle and the number of droplets per second can be easily adjusted. The number of droplets are set in such a way a droplet is not interfering with data from the previous droplet. The chosen time interval between each droplet was about 5 seconds.

SYNCHRONIZING THE SYSTEM

To trigger a reflective light sensor is being used to detect whether a droplet is falling from the syringe towards the water. In this way the digital oscilloscope and the high speed camera can be triggered at the same time to see if the sound is really emitted as soon as the bubble is created. (paragraph 2.1)

CAPTURING BUBBLE ENTRAINMENT

Since we want to measure how the bubble is entrained, a high speed camera of the brand Photron is being used. Since colour is not important in this setup the Photron SA1 which only records black and white videos and the Photron SA2 which records in colour were being used. The advantage of the SA2 compared to the SA1 is the light sensitivity, which is slightly better. Anyways, since extra light sources were needed to capture the bubble entrainment in high speed this was negligible.

Figure 7 Photron SA2, Image retrieved from http://www.wired.com/images_blogs/gadgetlab/2009/05/sa21.jpg

Both cameras make use of an Ethernet connection to stream the video data to the computer. They also have the option to automatically trigger the video recording which comes in handy when synchronizing the sound recorded with the hydrophone and the video.

RECORDING THE SOUND BENEATH WATER

For recording the sound a hydrophone is being used. Since the hydrophones signal was to weak a charge amplifier is used to increase the signal strength. In this way the signal can be recorded using a Texas Instruments DSO-8502 which is a digital oscilloscope including a USB output. Using the supplied software data logging on each trigger signal was possible to automate the measuring process. A representation of the devices in cascade can be seen in figure 8

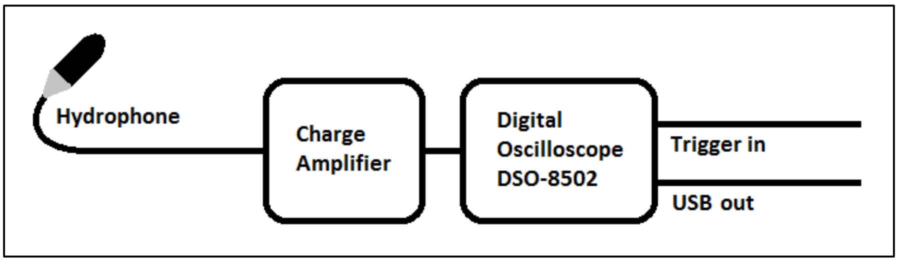

Figure 8 Sound recording part of the setup.

RECORDING THE SOUND ABOVE WATER

When theory has been checked with the data and parameter settings where the frequency of the sound is most consistent have been found, some sound measurements above water have to be made. This is accomplished by using an in distance adjustable microphone. Since this is a rather cheap microphone the sound emitted by the bubble was very weak. Therefore an amplification is realized using a Realtek High Definition sound card.

3.2 PERFORMED EXPERIMENTS

3.2.1 REGULAR BUBBLE ENTRAINMENT

The first performed experiment was to see whether the regular bubble entrainment behaves as the theory describes. This experiment is purpose is mainly to define whether there is really *regular bubble entrainment* and to calculate the size of the bubble and the frequency of the sound. This has been done by recording the bubble entrainment of a droplet with a diameter of 2.5 mm.

3.2.2 PARAMETER SCAN

The second experiment also was to check whether the region and frequencies shown in figure 3 are correct. Another goal of this experiment is to look for an "ideal" drop impact, where the frequency of the sound is the same on every impact. To do so the underwater sounds of bubbles has been recorded for different impact velocities. For each measurement 50 sounds have been recorded every cm using different drop sizes. The used drop sizes are 3.0 and 3.5 mm.

3.2.3 SOUND PROPAGATION THROUGH THE AIR

As we have found a good setting for our setup, where every drop impact creates nearly the same frequency, now multiple records have been made from the sound above water. The purpose of this goal is to see what happens with the frequency when the sound wave propagates in the air. Therefore an in distance adjustable microphone has been used.

3.2.4 PULSE LENGTH

To test whether the pulse length of the sound makes the sound seems lower in frequency than its corresponding frequency two artificial sound waves with the same frequency are made. However both pulses have another pulse length to hear the difference in the perception of the frequency.

4.0 RESULTS

4.1 REGULAR BUBBLE ENTRAINMENT

As described in paragraph 2.1 the regular bubble entrainment is where data should be most predictable. Using a high speed camera the bubble entrainment we encounter in this region is compared to the described behaviour. A selection of frames from the movie is shown below.

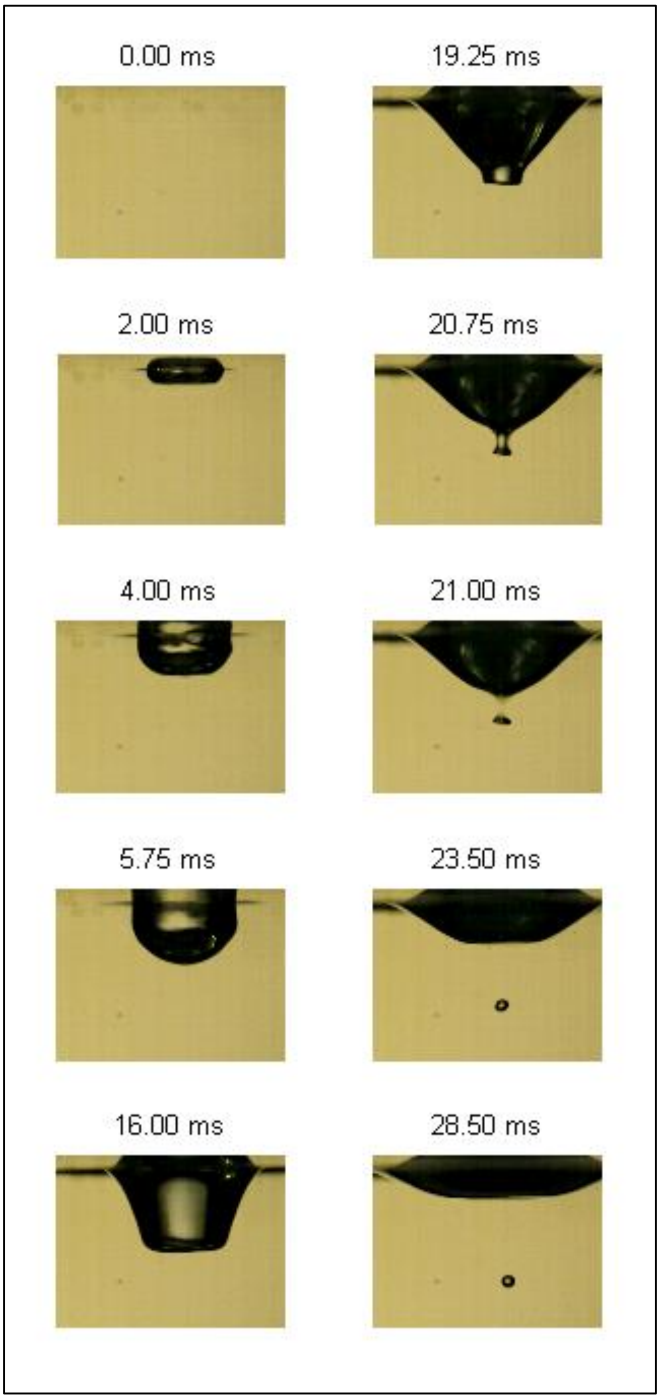

Figure 9 Regular bubble entrainment of an 2.5 mm droplet and an impact velocity of about 1,8 m/s. Recorded using the Photron SA1 at 4000fps. Width of the image corresponds to 13.65 mm. The black line next to the cavities corresponds with the level of the water surface. The depth measured from the water surface is approximately 9,4 mm.

Using the last timeframe from figure 9 the bubble size can be measured. The measured diameter of the bubble is about 62 pixels corresponding to 0.83 mm. This gives a bubble radius of about 0.415 mm.

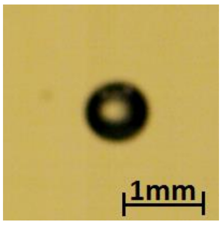

Figure 10 Zoomed image of the bubble where 75 pixels correspond to 1mm. The size of the bubble is measured at approximately 62 pixels or 0.83 mm.

Calculating the Minnaert frequency for this bubble radius gives a frequency of about 8 kHz.

$$f_M \cong \frac{3.3}{R} = \frac{3.3}{0.415} = 7.95\ kHz$$

The sound recorded with the hydrophone is shown in the left frame of figure 11 . The sound starts at 21.1 ms which corresponds well with the emission of the bubble.

On the right a plot of the frequency domain of the sound sample is shown where the location of the highest peak corresponds to the frequency of the sound wave. This peak lies at 8008 kHz.

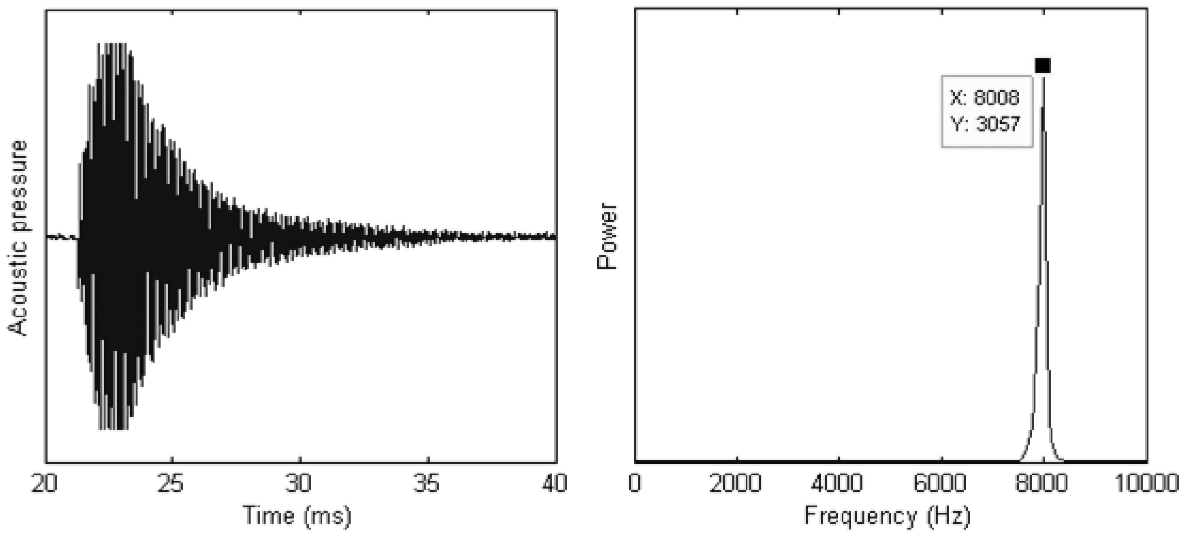

Figure 11 On the left the sound wave recorded with the hydrophone is shown. The frequency domain of the sound wave is plotted. The highest peak corresponds to the frequency of the sound wave which lies at 8008 kHz.

4.2 PARAMETER SCAN

PREVIOUS RESULTS

Using the previous results the following conclusions can be made which all correspond well with the theory stated in paragraph 2.1 and 2.2.

- There is regular bubble entrainment in the region of interest,
- The frequency of the sound indeed corresponds to the Minnaert frequency
- As soon as the bubble is created it starts oscillating

CURRENT RESULTS

To see how the frequency of the sound behaves in the air a parameter scan has been made to look for a place where the frequency is most consistent. The measured frequencies of the 3.0 mm bubble can be seen in figure 12.

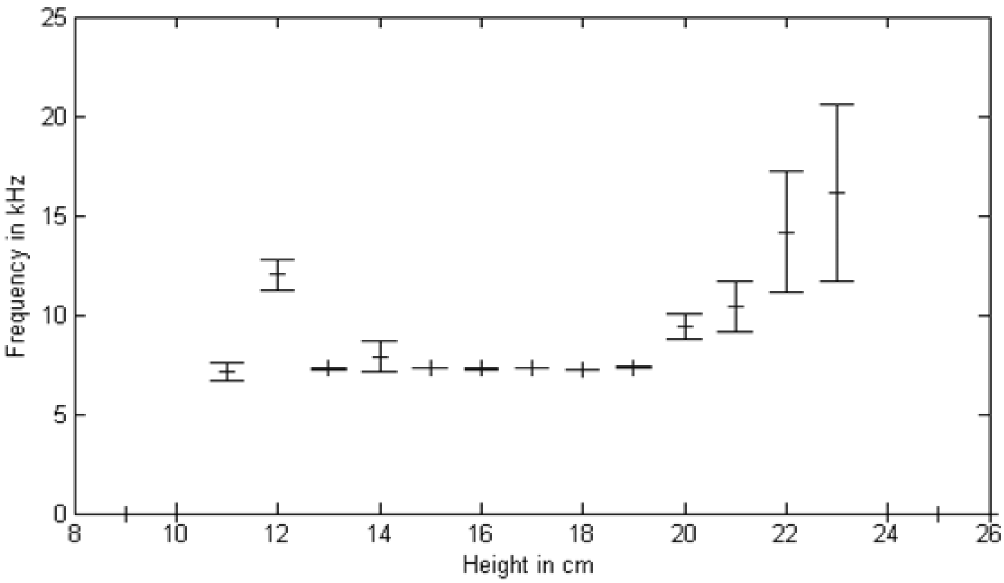

Figure 12 Using a 3.0 mm droplet and different heights the mean frequency and the mean frequency error has been measured. The mean frequency in the area of 15 – 19 cm is 7.3145 kHz For every cm 50 bubble sounds have been used.

The region in which regular bubble entrainment occurs lies between 11 and 21 cm or to verify with theory better represented as 1,46 – 2,1 m/s. At a distance of 22 and 23 cm also 50 measurements have been made, however not every drop impact entrained a bubble.

As can be seen the more the impact velocity reaches the upper border, the higher the frequency and the greater the error. The frequencies of the bubble between 15 and 19 cm lie at 7.315 Hz with a negligible frequency error. At 20, 21 and 22 cm the frequencies lie respectively around 8, 10 and 14 kHz with greater frequency errors.

The mean frequency in the most steady region, using a 3.0mm droplet, was 7135 Hz. In the most steady region with a droplet of 3.5mm the mean frequency is now 7202 Hz. Unlike the small error using a 3.0mm droplet it can be seen the error in the most steady region of the 3.5 mm region much higher.

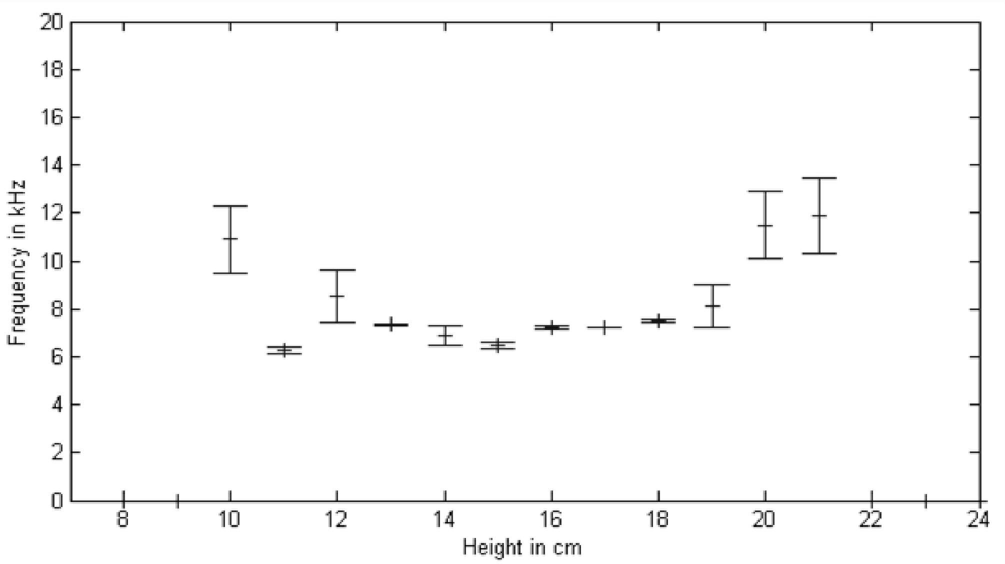

Figure 13 Using a 3.5 mm droplet and different heights the mean frequency and the mean frequency error has been measured. The mean frequency in the area of 13 – 18 cm is 7.202 kHz. For every cm 50 bubble sounds have been used.

An important thing to notice here is the measurements from 19-21 cm. With regular bubble entrainment you can see a bubble floating on the surface for a certain time. However in the region from 19-21 cm two bubbles were seen. The size of the bubbles itself were also smaller as could be seen by eye. However due to the lack of time no high speed recording of this area are made to confirm the observation and to describe this region. Therefore it is recommended to further investigate this observation.

4.3 SOUND PROPAGATION THROUGH THE AIR

FREQUENCY PROPAGATION

Since in the previous results show that the most predictable frequency can be achieved using a 3.0 mm droplet and with an height between 15-19 cm. To see what happens with the frequency as the sound propagates through the air a 3.0mm droplet which falls from a height of 17cm is being used.

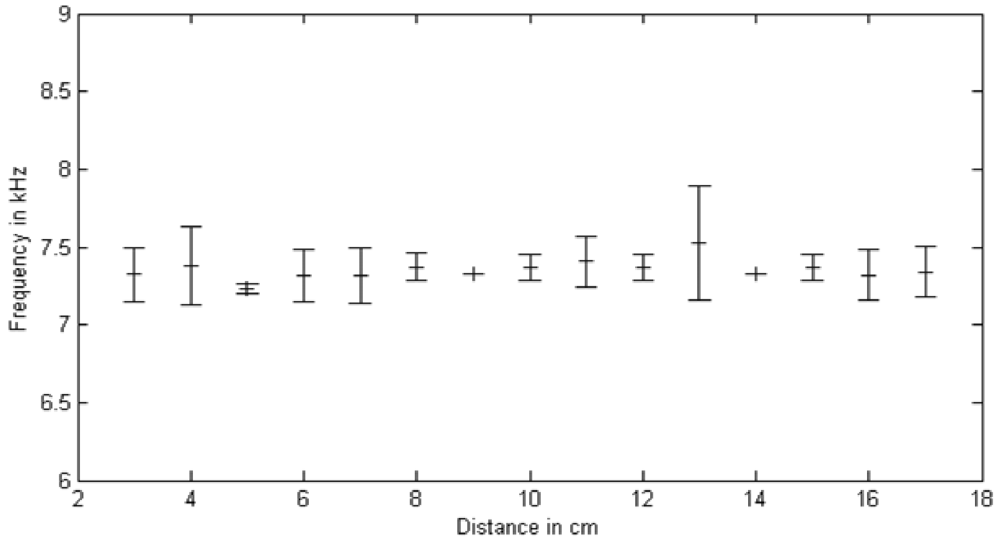

Figure 14 Using a 3.0 mm droplet and a distance between the water surface and the microphone of 17 cm, the mean frequency and the mean frequency error has been measured. For every increasing distance in cm again 50 bubble sounds have been recorded. As can be seen the frequency is the same nearly the same every time

Above the results show a good steady frequency as the distance between the water and the microphone is increased. Since there was no better microphone only a small region of the sound propagation in the air was possible to make.

4.3.1 TIME DIFFERENCE

Another important fact to measure is to calculate the time between the sound beneath water and the sound below water as the distance between the water and the microphone is increasing. A plot of the time difference is shown in figure 15.

Since the sound is amplified with the sound card a time delay from the amplification is included in the time difference between the sound underwater and the sound beneath water.

$$v^{-1} = \frac{dt}{ds} \approx 0.03\ ms/cm$$

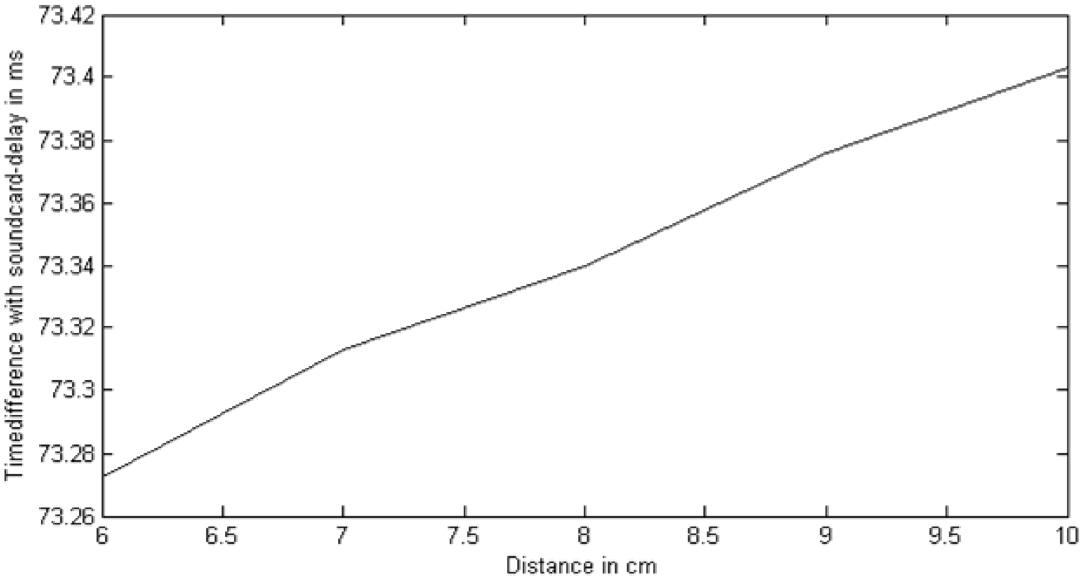

Figure 15 Time difference of the sound under and above water as a function of the distance in cm. Important is to notice that the delay of the soundcard is included in this figure. Every cm 50 measurements have been made.

4.4 PULSE LENGTH

Since no change in frequency is detected it might be possible that even when the frequency of the sound is the same, the sound seems lower in frequency due to the pulse length. Therefore two artificial sound waves are made with the same frequency but with another pulse length. Both sound waves and its frequency domain can be seen in figure …

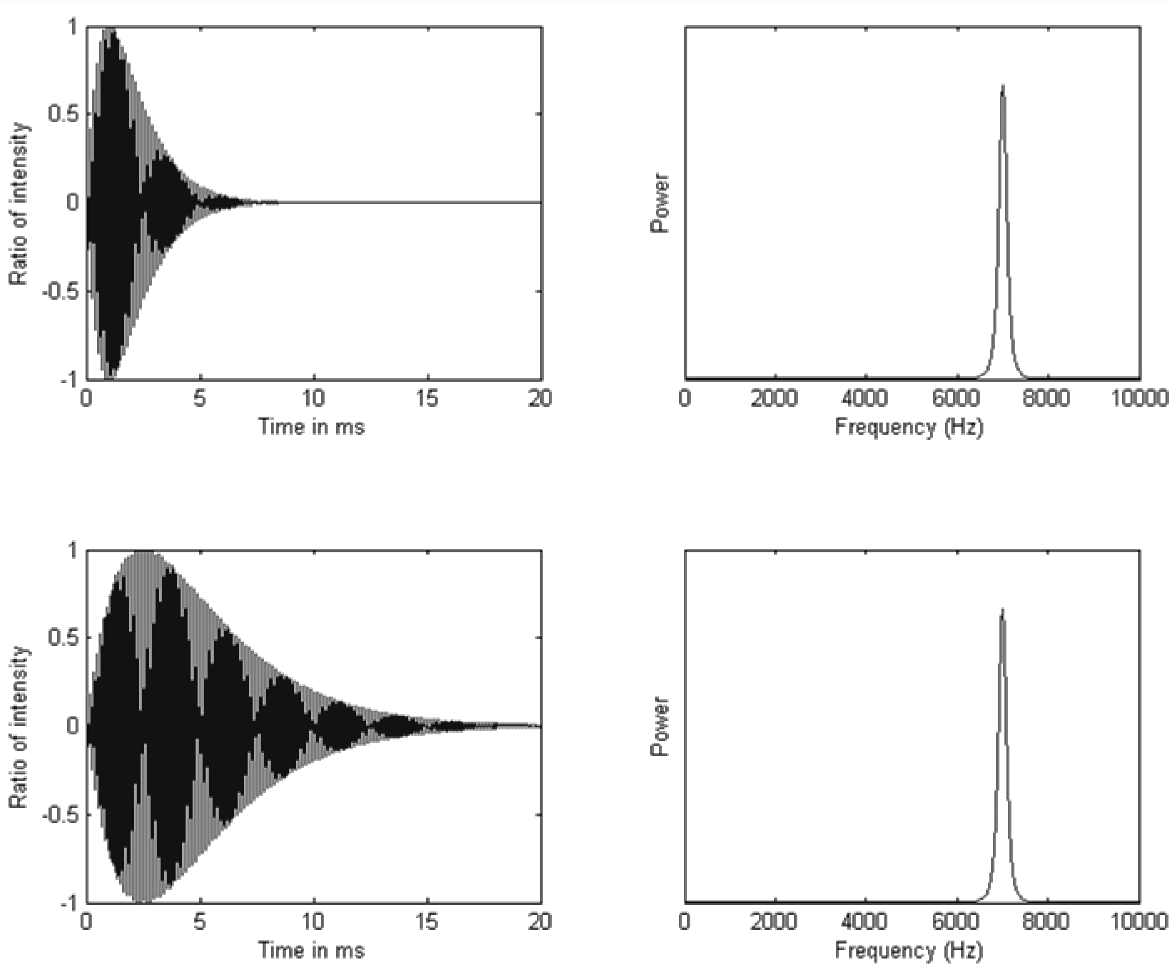

Figure 16 Artificial sound waves on the left and the corresponding frequency plot on the right. Highest peaks lie at 7 kHz for both sound waves.

Both sounds have been heard by some observers who got the instruction to distinguish the high and the low frequency. Observers say the wave with the longest wavelength has the highest frequency.

5.0 CONCLUSIONS AND DISCUSSION

As can be seen the high speed footage of the regular bubble entrainment corresponds well to the theory described in paragraph 1. The bubble also behaves as expected since the frequency of the recorded sound was the same as the Minnaert Frequency for this bubble radius. It is no coincidence the sound was produced at the same time the bubble got free from the cavity. Therefore it can be said that the sound is created by the bubble, to be more specific due to the bubble oscillations.

Since theory says the regular entrainment is very predictable this is tested using a parameter scan. Surprisingly this was indeed correct, for regular entrainment was indeed measured in the same regions as figure 3 shows.

The frequencies measured in the regular entrainment region using a 3.0mm droplet corresponds also very well with theory. Nearly the same results as figure 3 were measured. When looking at the frequency error it can be concluded that the behaviour in the regular entrainment region is very predictable which made a very good setting for recording the sound above water, since we knew the frequency was nearly the same on each drop impact.

The main goal of this report was to see whether or not the frequency measured above water was indeed lower than the frequency measured below water another experiment has been made using the predictability of the frequency of the 3.0 mm droplet. As the distance of the microphone was increased from 3 to 18 cm no noticeable difference in frequency was measured between the sound recorded above and below water.

Even when no noticeable difference in frequency was measured between the sound recorded above and below water, it might be even possible that at a greater distance (for example 1 meter) it might be possible to get a lower frequency since the used distance was not a very long distance. Unfortunately no better microphone was available which made it impossible to record a sound with a greater distance.

Even if the experiments were repeated using a better microphone, based on the theory and the last performed experiment (see paragraph 4.4) it is more likely the frequency seems lower in frequency than a standard tone with a certain frequency due to short pulse length of the sound waves created by bubbles.

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