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Colegio de Ciencias e Ingeniería Politécnico

**Measurements of ultrasound Fields inside a cylindrical vessel using
a Scanning Vibrometer**

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HOJA DE APROBACIÓN DE PROYECTO

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Quito, 22 de Mayo del 2012

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Francisco Hernández

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Resumen

Se hace un estudio sobre los distintos modos de vibración debido a campos de sonido en un contenedor cilíndrico lleno de agua. Se proponen distintos métodos para medir experimentalmente estos campos de sonido con el objetivo de que los errores experimentales sean mínimos. Los resultados obtenidos se comparan con los resultados teóricos y se observa la exactitud de los métodos propuestos

Abstract

A study of different mode shapes inside a cylindrical vessel filled with water caused by a sound field is done. Some experimental methods to measure these sound fields are proposed in order to avoid experimental mistakes. The results obtained are compared with theoretical simulations and the effectiveness of each method is observed.

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1 Introduction

1.1 Doppler shift due to moving reflector

The aim of the project is to measure the sound field inside a cylindrical vessel filled with water using a Polytec Scanning Vibrometer (PSV). PSV uses classic refracto vibrometry which is a novel non-contact method used for measuring sound fields in transparent media as shown in figure 1. As a first approach we will calculate the Doppler shift due to the geometrical Doppler shift and the Doppler shift due to ultrasound.

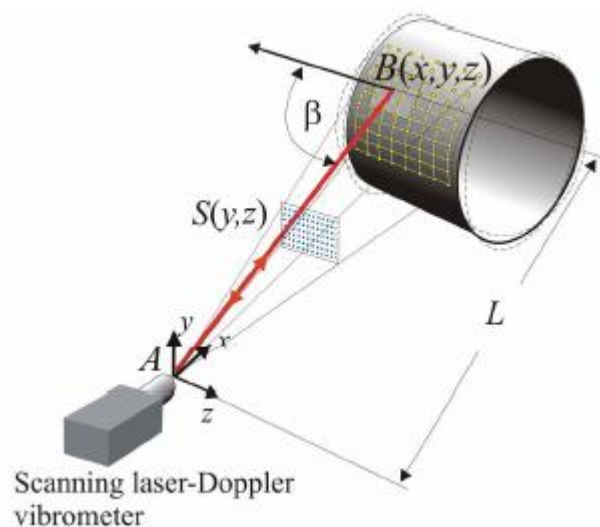


Figure 1 Principle of Classic Vibrometry (Zipser, 2007)

In this method a scanning laser-Doppler vibrometer based on Mach-Zehnder-Doppler interferometer is used as shown in figure 2.

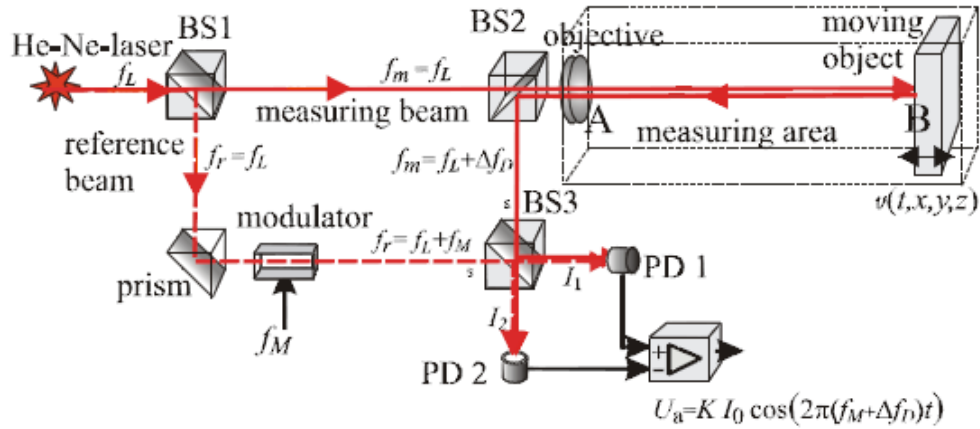


Figure 2. Scheme of Mach-Zehnder-Doppler Interferometer (Zipser, 2007)

The operation of the interferometer is briefly described as follows. The beam from the laser is divided into a reference beam and a measuring beam. The measuring beam hits the moving object (reflector) at the end of measuring area, gets reflected there and is guided from BS2 to BS3. Behind BS3 two beams interfere and the result is a light signal with fluctuating intensities I_1 and I_2 . In case the object is moving along a geometrical distance $\Delta L_g(t)$ with a velocity $v_g(t)$, because of the Doppler effect, the frequency f_m of the reflected measuring beam changes about the (geometrical) Doppler-shift. (Zipser, 2007)

$$\Delta f_{Dg}(t, x, y, z) = \pm \frac{2v_g(t, x, y, z)}{\lambda_m} \quad (1)$$

In order to identify the actual direction of the velocity $v_g(t)$, the reference beam is shifted by a frequency f_M .

Which depends on Δf_{Dg} and therefore on the velocity $v_g(t)$. Also, ultrasound influences the optical path length L_n along the measuring beam.

$$\Delta L_n(t) = 2 \int_A^B \Delta n(t, x, y, z) dl \quad (2)$$

Where n is the optical refractive index of the medium. Sound pressure cause variations of the optical refractive index.

$$\Delta n(t, x, y, z) = \frac{(n_0-1)}{kp_0} \Delta p(t, x, y, z) = \left(\frac{\partial n}{\partial p} \right)_s \Delta p(t, x, y, z) \quad (3)$$

The relationship is given by a constant, which is called piezo-optic coefficient $\left(\frac{\partial n}{\partial p} \right)_s$, the index S indicates adiabatic phase changes.

Consequently, the total Doppler shift results from the superposition of the geometrical and the refractive shares

$$\Delta f_{DSum}(t) = \frac{2}{\lambda_m} (v_g(t) \cos \beta + \left(\frac{\partial n}{\partial p} \right)_s \int_A^B \frac{d}{dt} (\Delta p(t, x, y, z)) dl) \quad (4)$$

Finally, the intensity signal is

$$I(t) = I_0 \cdot \cos (2\pi(f_M \pm \Delta f_{DSum})t) \quad (5)$$

The fast Fourier transform of equation (5) is done, and by doing this the frequency shift due to ultrasound is obtained

1.2 Description of the set up studied by Zipser (Zipser, 2007)

First the set up shown in figure 3 is analyzed.

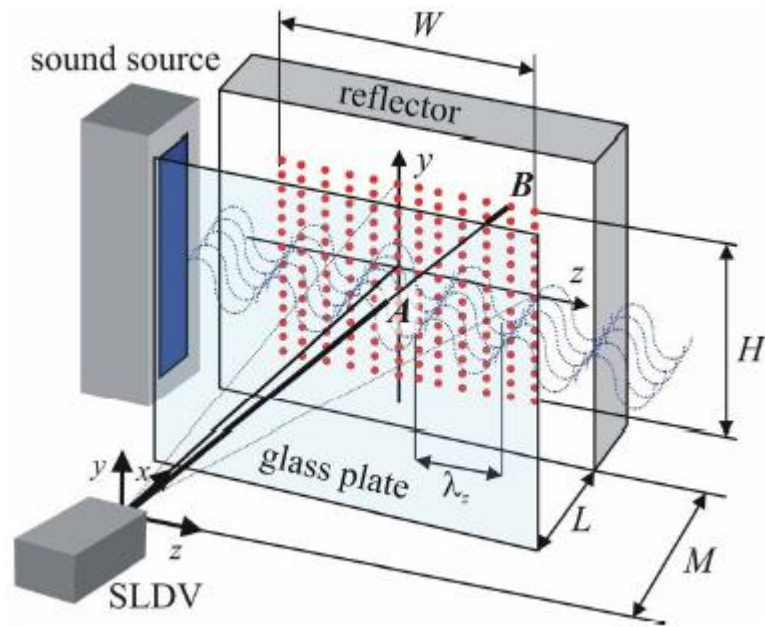


Figure 3. Principle of refracto-vibrometry (Zipser, 2007)

The source of ultrasound is a transducer that runs on its resonance frequency. In order to eliminate the geometrical Doppler shift, a rigid reflector is applied ($v_g = 0$) and a transducer is located in front of the reflector inside the water in order to generate the ultrasound waves (section of length L in figure 3). Laser beam crosses the distance to the reflector and gets reflected. Variations of the optical path length $L_n(t, x, y, z)$ is caused by the variations of pressure due to ultrasound.

$$L(t) = 2 \int_0^X n(x, t) dx = L_o + 2 \int_0^X \left(\frac{dx}{dp} \right)_s p(x, t) dx \quad (6)$$

with $L_o = 2n_o X$, which is the ambient optical path through the medium, and X is distance from the emitting laser to the static reflector.

Even though the reflector is rigid, it seems to move, from the point of view of the PSV (Polytec Scanning vibrometer), with the velocity

$$v_n(t, x, y, z) = \frac{d(2\Delta L_n(t, x, y, z))}{dt} = 2 \left(\frac{\partial n}{\partial p} \right)_s \int_A^B \frac{d}{dt} (\Delta p(t, x, y, z)) dl \quad (7)$$

This indeed recovers the second term in equation (4). The measured virtual velocity is the integral value of the velocities along the measuring beam, because the laser beam goes through all sound field with high and low velocities values.

1.3 Set up using a cylindrical vessel

The set up studied by Zipser (Zipser, 2007) is the base of our study, but it is not useful for our purposes. The set up that will be studied is similar as in figure 3, but instead of locating the sound field in front of the reflector, a cylindrical vessel filled with water is located in front of the reflector. The cylindrical vessel is shown below.

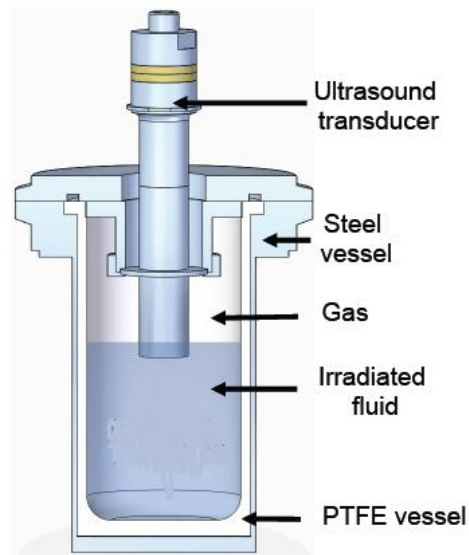


Figure 4. Cylindrical vessel with transducer and water (Bornmann P. , 2011)

In order to recreate the images of the sound field a reconstruction algorithm has to be applied; the most used is the tomography algorithm. The simplest form of

tomography, sometimes referred to as 'step and shoot' tomography, is based on the creation of *parallel* projections (Harvey, 2004).

In this algorithm, the problem is that in a cylindrical vessel, the parallel projections are damaged and therefore, the algorithm applied fail. The work done in this report is about the research on the correction of this problem and the experimental analysis of the sound field inside a cylindrical vessel with glass and metal bottoms.

2 Theoretical research

The first task was to develop a method to make the laser beams parallel inside a cylindrical vessel, in order to minimize errors of the measurements of ultrasound waves inside the vessel.

A simulation was made in order to see the path taken by a laser beam that goes through a cylindrical Plexiglas filled with water.

The result of the beam path was simulated in Matlab using the program written by Martin Klubal (Klubal, Laser beam Path, 2011). A view from above the Bessel is shown in figure five. The blue bar is the reflector and the laser is located in the opposite side of the reflector. Figure 5 describes the path of the laser beam when going through different mediums, in this case, air-glass-water-glass-air.

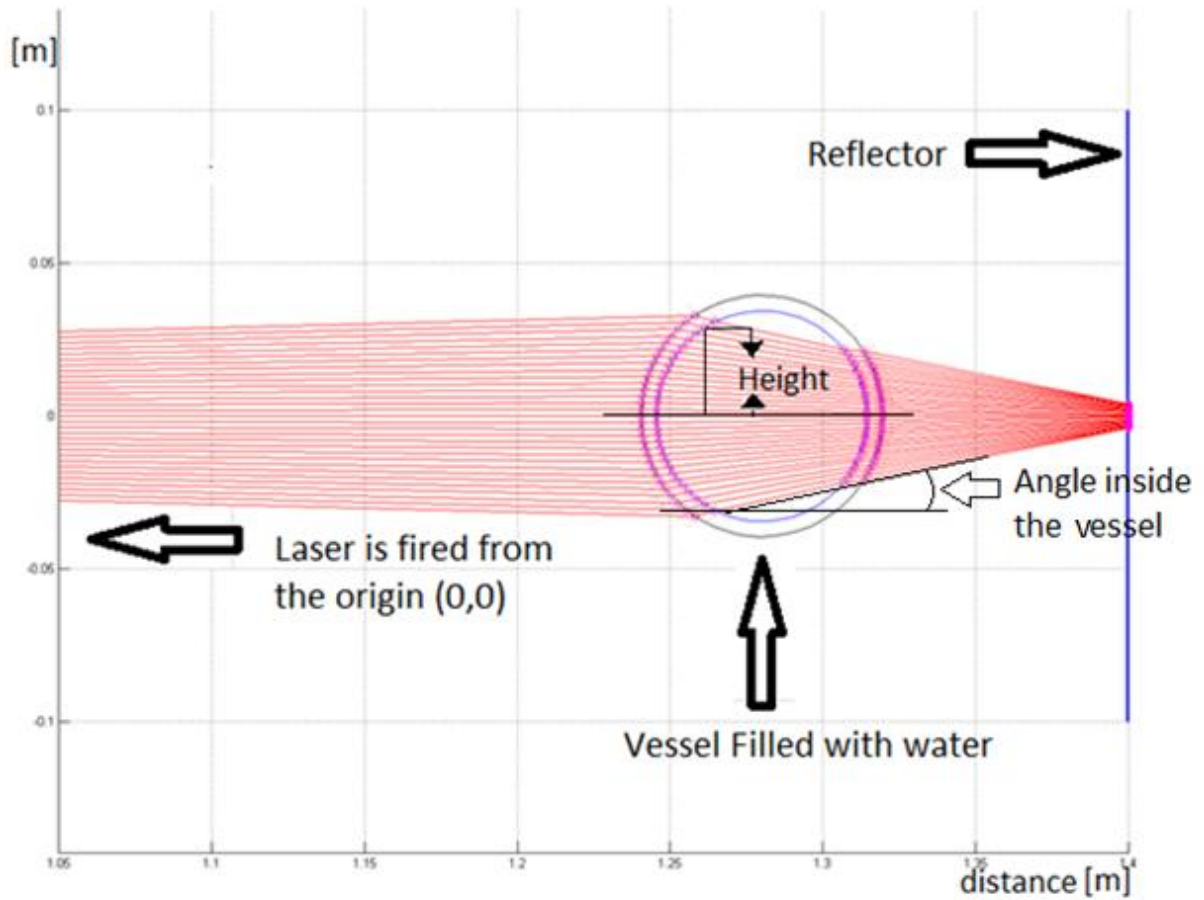


Figure 5. Beam path

The parameters for the simulation were

- Refractive index of water: 1.33
- Refractive index of Plexiglas: 1.49
- Refractive index of air: 1
- Distance from the transducer to source of laser beam: 1.28 m
- Radius of inner glass: 34.5 mm
- Length of Plexiglas: 5 mm

In order for the scanning algorithm to work, it is needed that the laser beams are parallel, but as seen in figure 5, incident lines inside the vessel are not parallel. If considered only the middle of the beams, the laser beams are approximately parallel, so if we measure only in a small part in the center the results may be reliable.

Some calculations were done to see how the angles inside the vessel change when the firing angle is changed (see figure 5). The obtained result was the following

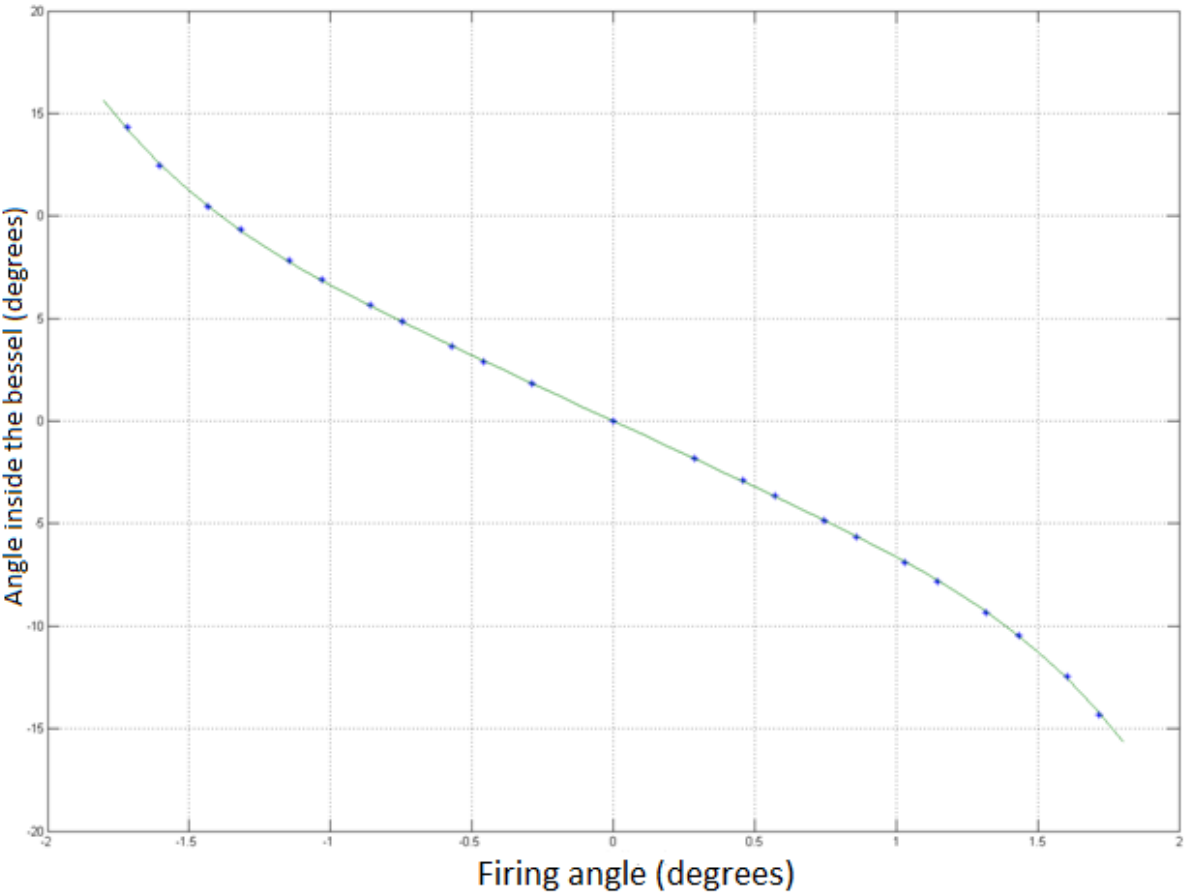


Figure 6. Plot of firing angle versus angle inside the vessel

It can be seen that when one approaches the border of the glass (or when the firing angle increases), the angles become less parallel. It can be seen that the worst angle obtained could be almost 17 degrees.

Another graphic was plotted, this time the firing angle versus the height (see figure 5) of the vessel that is scanned. This was plotted in order to know the area that can be scanned. The graphic is shown below:

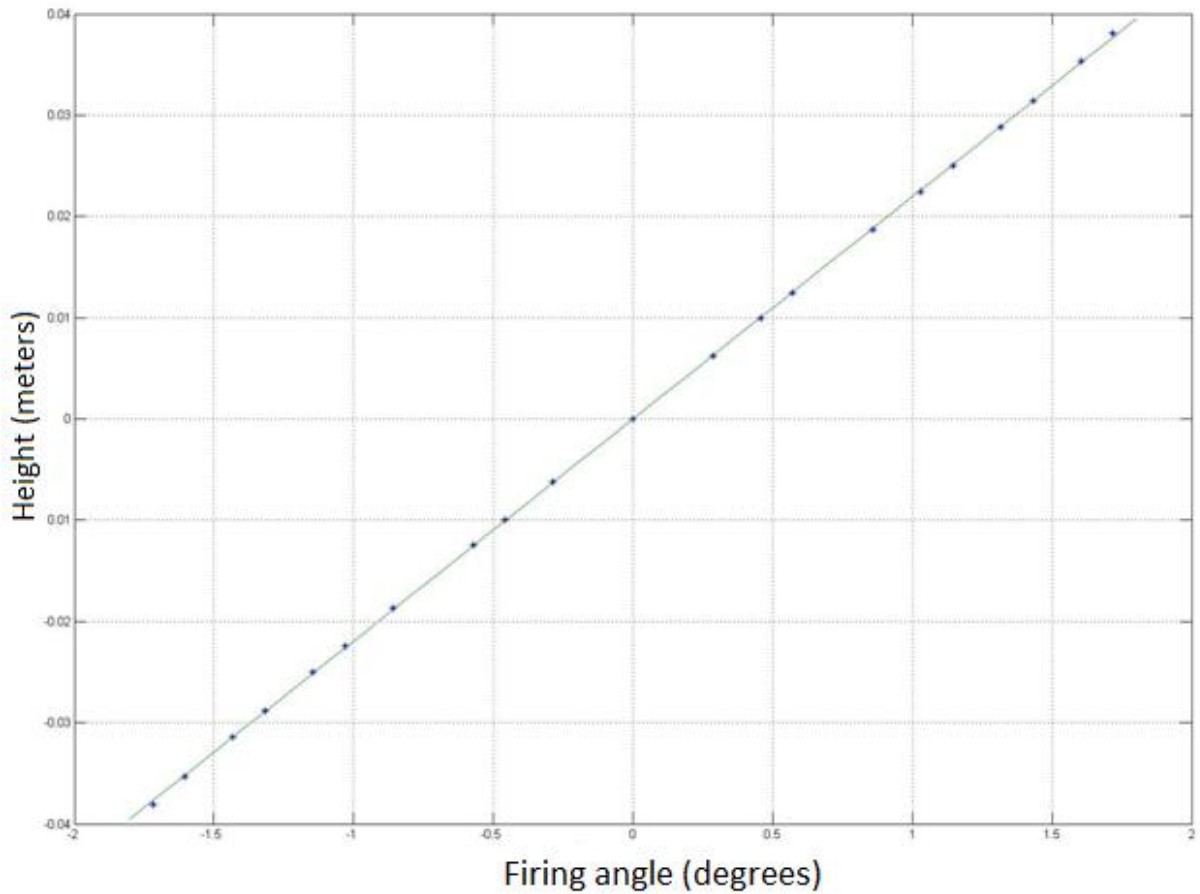


Figure 7. Plot of firing angle versus height

The relation is linear. Now we are interested in which is the area that we can scan, so that we can consider that the lines are almost parallel. The problem here is to determine the limit in which we can say the lines are almost parallel.

The following graphic was plotted to analyze the dependence of the firing angle with the angles inside the vessel and the height.

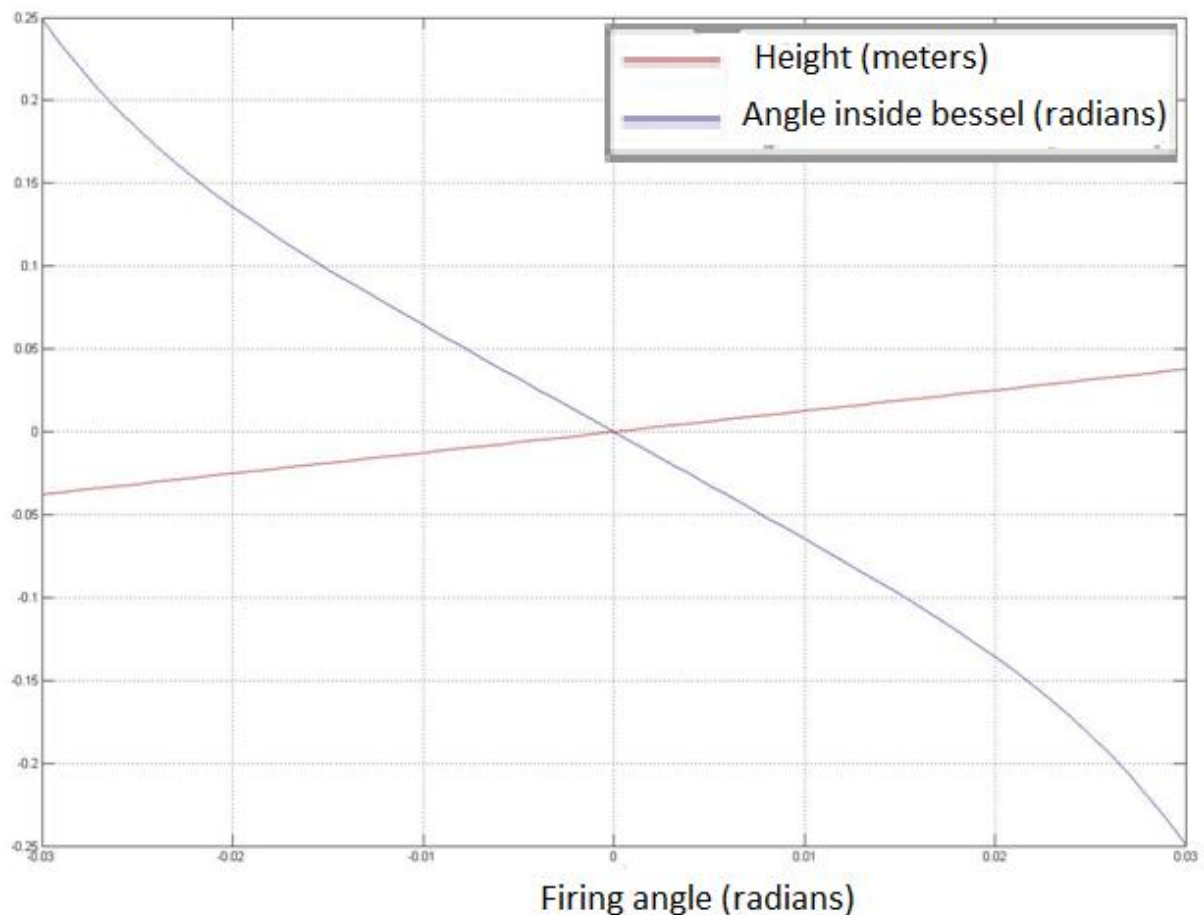


Figure 8. Plot of firing angle versus height and angle inside the vessel

From figure 8 it is concluded that we can scan 2 centimeters of the vessel with a maximum variation of the angle of 4 degrees. But again, the problem is that we

can't say whether if four degrees contribute to a big or a small error. Maybe if we knew which maximum angle we can tolerate, we could know for sure which area is the one we can scan.

Other ideas were proposed to fix the problem of "not parallel lines". The ideas are briefly described as follows:

- The first option was to have the same medium both inside and outside the cylindrical vessel. That means having the vessel inside a rectangular container filled with water. By this way the refractive index would be the same, outside and inside, and the results obtained would be that the lines are "pseudo" parallel.
- The second option was to modify the method described before by changing the firing angle at which the laser beam is fired. By doing so, exact parallel lines may be obtained, though this may take a lot of time and changing the firing angle every time is really a problem and it couldn't be done with exact precision.
- The third method was to put a lens in front of the laser beam. The lens will cause the light to deviate in a way that when it arrives to the vessel's interior part, the beams are parallel. By doing this, there is no need to modify the firing angle of the laser beam because the lens will be able to do it. With this method, the only thing that has to be found is the distance at which the lens is

located. It has to be located in the exact position so that the main objective is obtained.

The last method described was chosen because it was the most achievable of all. In order to make this method work, the specifications of the lens would have to be found. To find the specifications of the lens, the program used to simulate the laser beam path written by Martin Klubal (Klubal, Laser beam Path, 2011) had to be modified, and that's what I did.

Once the program was modified I put a lens in the middle of the beam path in order to change the direction. At the end it wasn't exactly a lens that was chosen for the experiment, instead it was another Plexiglas cylindrical vessel that was used for the simulation in order to simplify the code that had to be written. The parameters that were used for the simulation were:

- Refractive index of water: 1.33
- Refractive index of Plexiglas: 1.49
- Refractive index of air: 1
- Distance from the source of the laser beams to center of the first Plexiglas (lens): 0.63 m
- Distance from the first Plexiglas (lens), to the Plexiglas where the measurement is supposed to be done: 0.32 m
- Radius of both inner glasses: 34.5 mm
- Length of both Plexiglas: 5 mm

With these parameters the obtained result is the following:

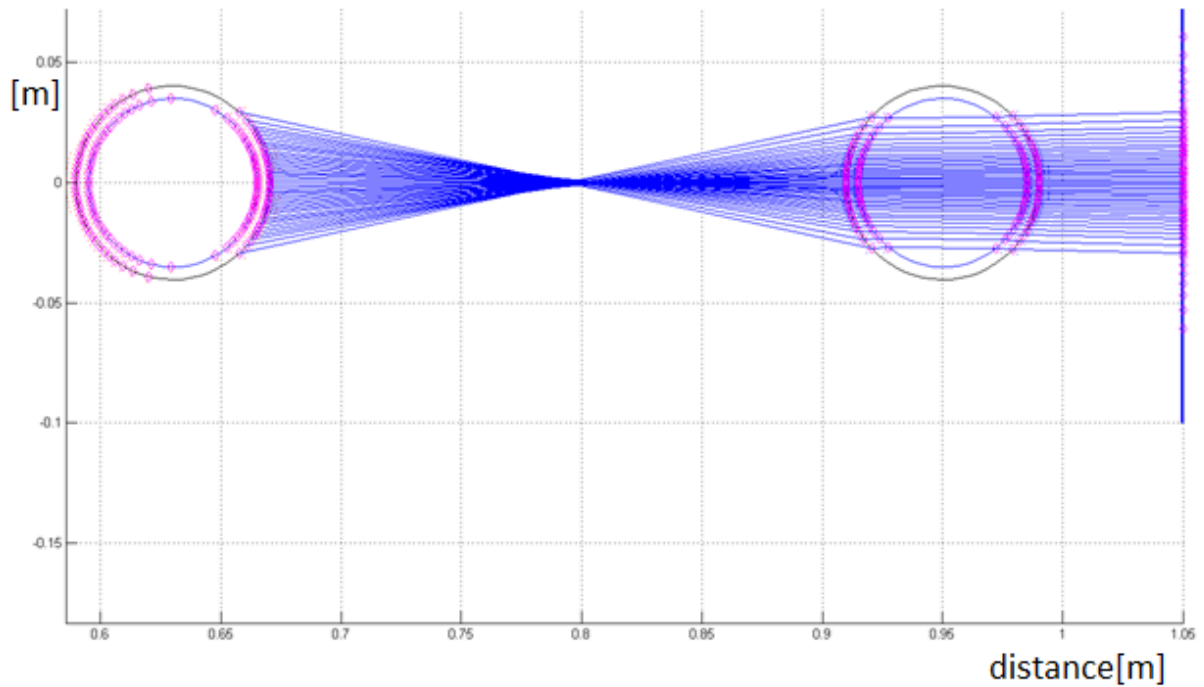


Figure 9. Corrected Beam Path

It can be clearly seen in figure 2 that by doing this modification the laser beams are parallel.

3 Measurements, experimental work

3.1 First Measurements

Some experimental results are shown with different set up arrangements. Below each figure the fast Fourier transform (FFT) of the pressure wave is shown. In the FFT it is

seen that a clear peak near 23 kHz is formed. This is consistent since the pressure waves are being excited by the transducer near this frequency, which is clearly ultrasound. Also it should be noted that the pressure waves are traveling vertically.

3.1.1 Vessel filled with water with glass bottom inside a rectangular

glass:

- Distance from bottom to transducer is 65 mm
- Distance from the source of laser beam to transducer is 1.28 m
- The water filled above the end of the transducer is 16 mm

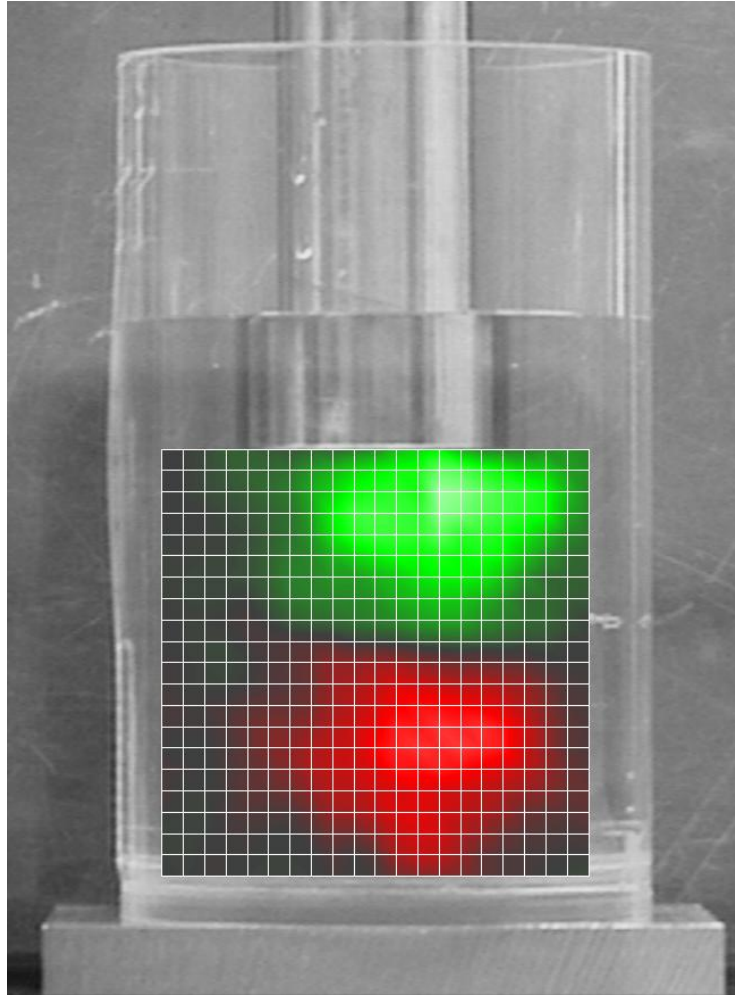


Figure 10. Vessel filled with water with glass bottom inside a rectangular glass

FFT

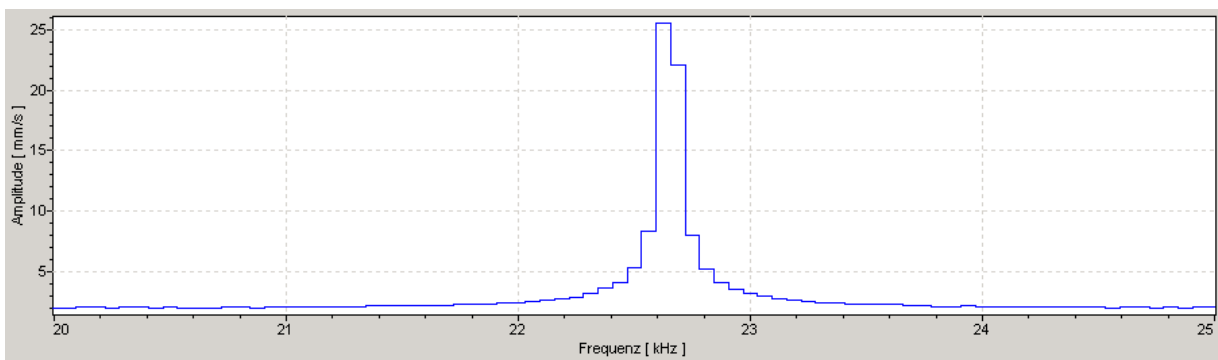


Figure 11. FFT

Comments:

With this arrangement a standing wave is formed inside the vessel. The maximum speed of the wave is 100 mm/s.

This maximum speed is comparably high if compared with the measurements done with a metallic vessel or Teflon; therefore I may conclude that the measurements done in this arrangement are from the vibrations inside the vessel. In measurements 3.1.10. and 3.1.11. (see below) it is seen that the maximum speed is 5 or 10 mm/s, which is almost 10 to 20 times lower than the velocity in this measurements.

This measurement is consistent with the simulations done by (Bornmann P. , 2011)

3.1.2 Vessel filled with water with glass bottom:

- Distance from bottom to transducer is 65 mm
- Distance from the source of laser beam to transducer is 1.28 m
- The water filled above the end of the transducer is 16 mm

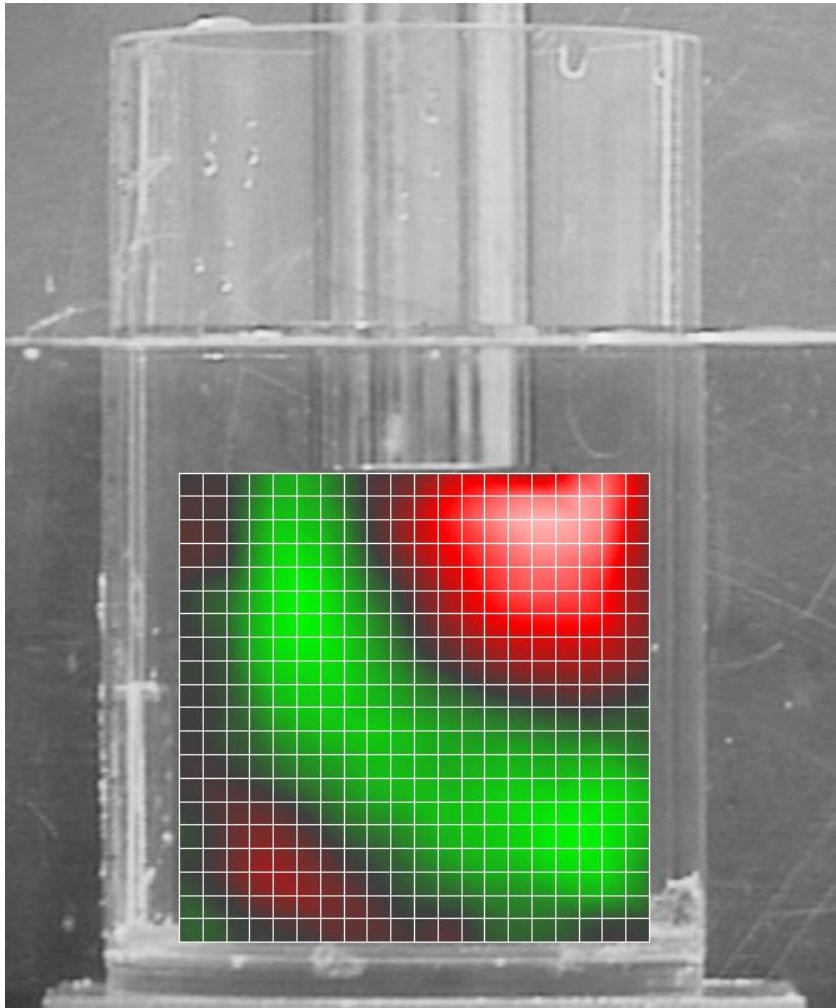


Figure 12. Vessel filled with water with glass bottom, inside a rectangular glass filled with water

FFT

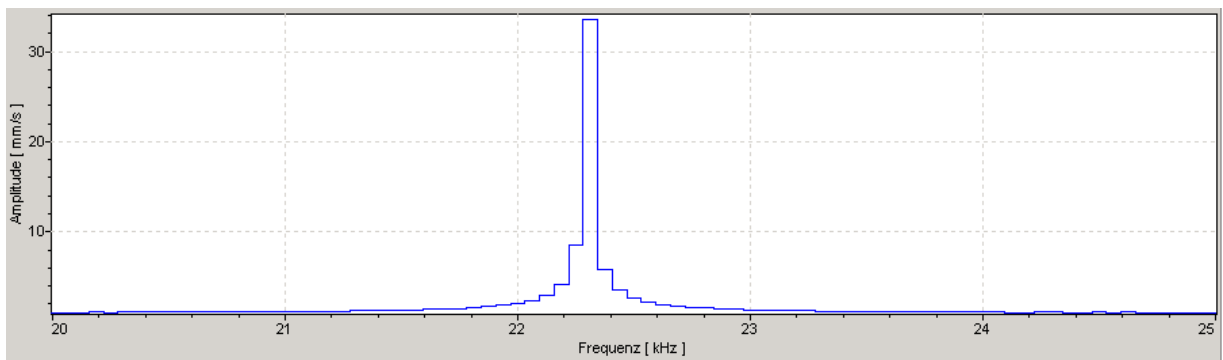


Figure 13. FFT

Comments:

With this set up it can be concluded that the vibrations of the transducer are going through out the cylindrical vessel and therefore the water outside the vessel is affected. It looks like if the measurements are from the vibrations of the water outside the cylindrical vessel because the results obtained are similar to the results obtained by Elena's measurements (Figure 2.1 in Hemsel's report) (Hemsel, E. 2011)

3.1.3 Vessel filled with water with metallic bottom, inside a rectangular glass

- Distance from bottom to transducer is 65 mm
- Distance from the source of laser beam to transducer is 1.28 m
- The water filled above the end of the transducer is 16 mm

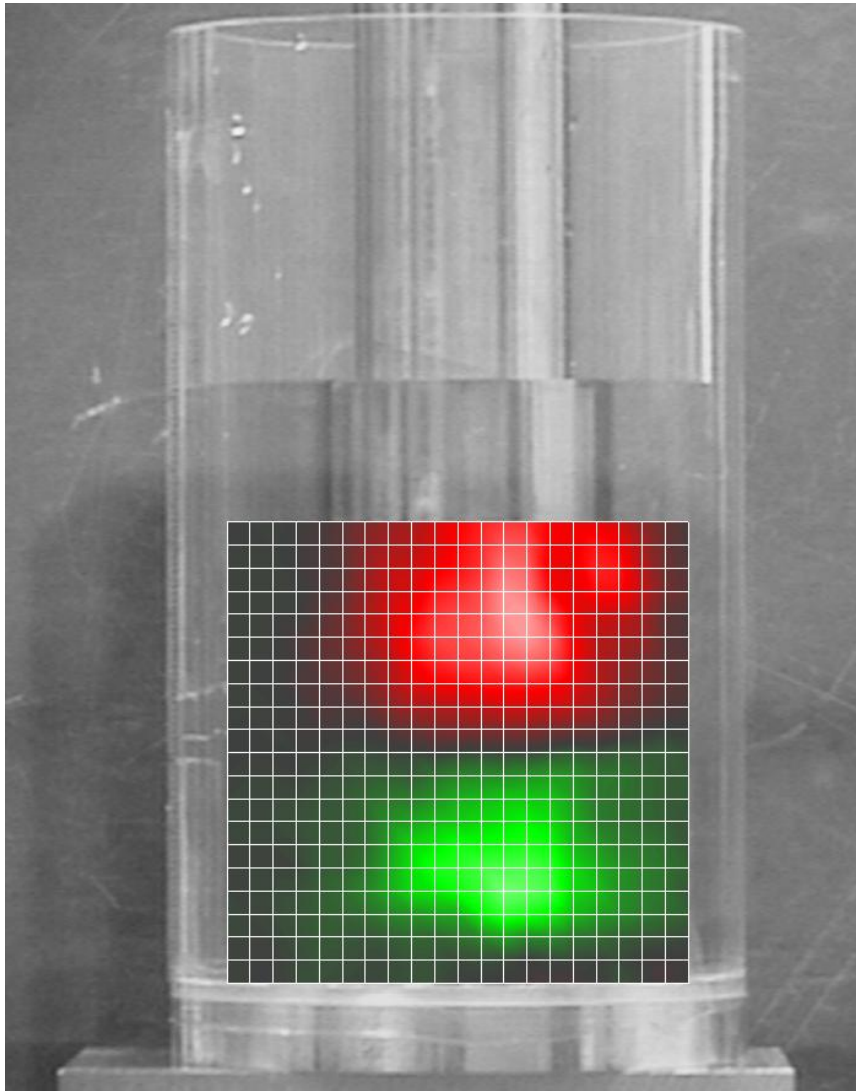


Figure 14. Vessel filled with water with metallic bottom, inside a rectangular glass

FFT graphic

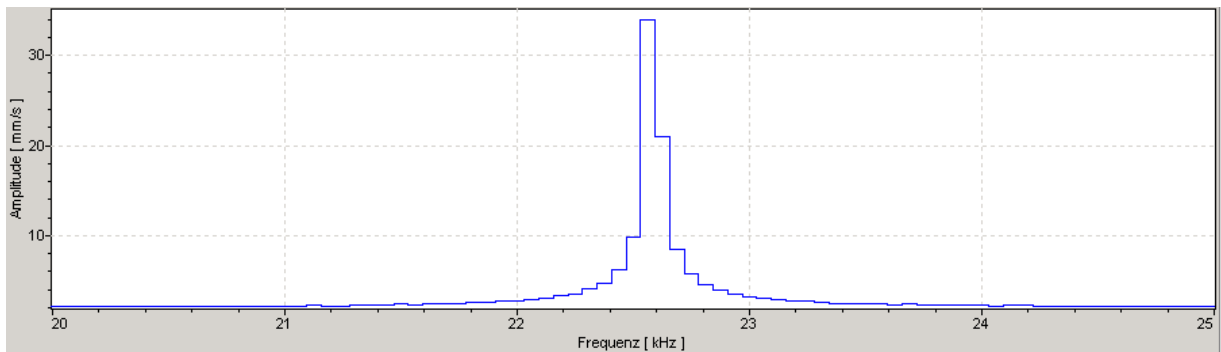


Figure 15. FFT

Comments:

Almost the same result as from the vessel with glass bottom is obtained. The maximum velocity is 100 mm/s. A standing wave is formed. An interesting thing was observed with the metallic bottom. If the video is observed in detail it can be seen that a little portion of the wave is reflected, but with very low speed, around 10 mm/s

3.1.4 Vessel filled with water with metallic bottom inside a cylindrical vessel filled with water

- Distance from bottom to transducer is 65 mm
- Distance from the source of laser beam to transducer is 1.28 m
- The water filled above the end of the transducer is 16 mm

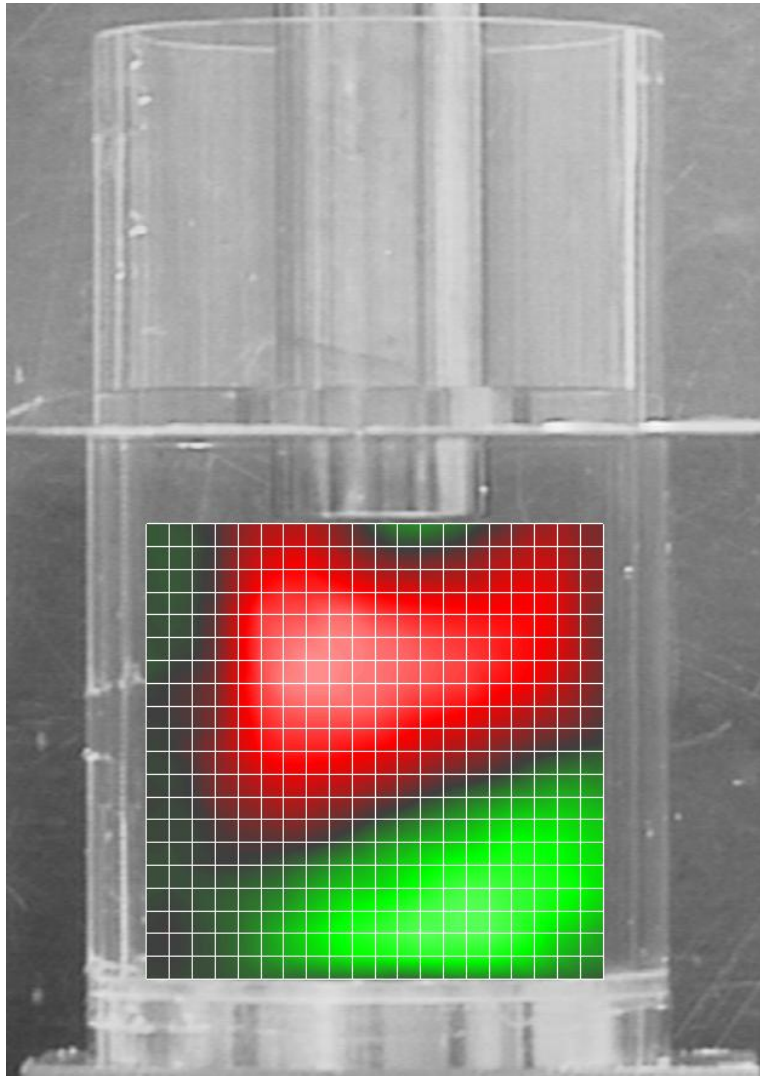


Figure 16. Vessel filled with water with metallic bottom

FFT graphic

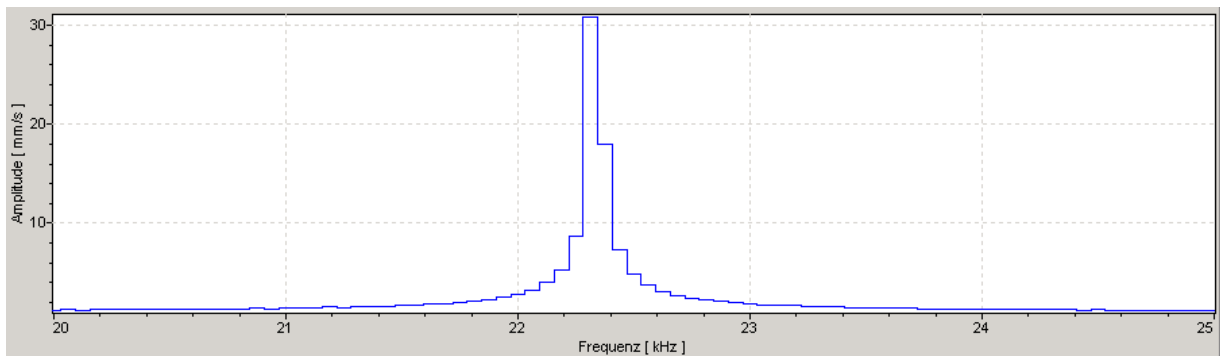


Figure 17. FFT

Comments:

As in the case of the vessel with glass bottom, the water outside the vessel is also affected by the vibrations by the same reasons as in the measurement 3.1.2.

3.1.5 Vessel filled with water with glass bottom, inside a rectangular glass filled with water (measurements are done outside the vessel)

- Distance from bottom to transducer is 65 mm
- Distance from the source of laser beam to transducer is 1.28 m
- The water filled above the end of the transducer is 16 mm

The vessel is now put higher than the measurements done before, in order to see if the wave is transmitted through the glass in the bottom of the vessel. The distance from the bottom of the vessel to the transducer is 65 mm

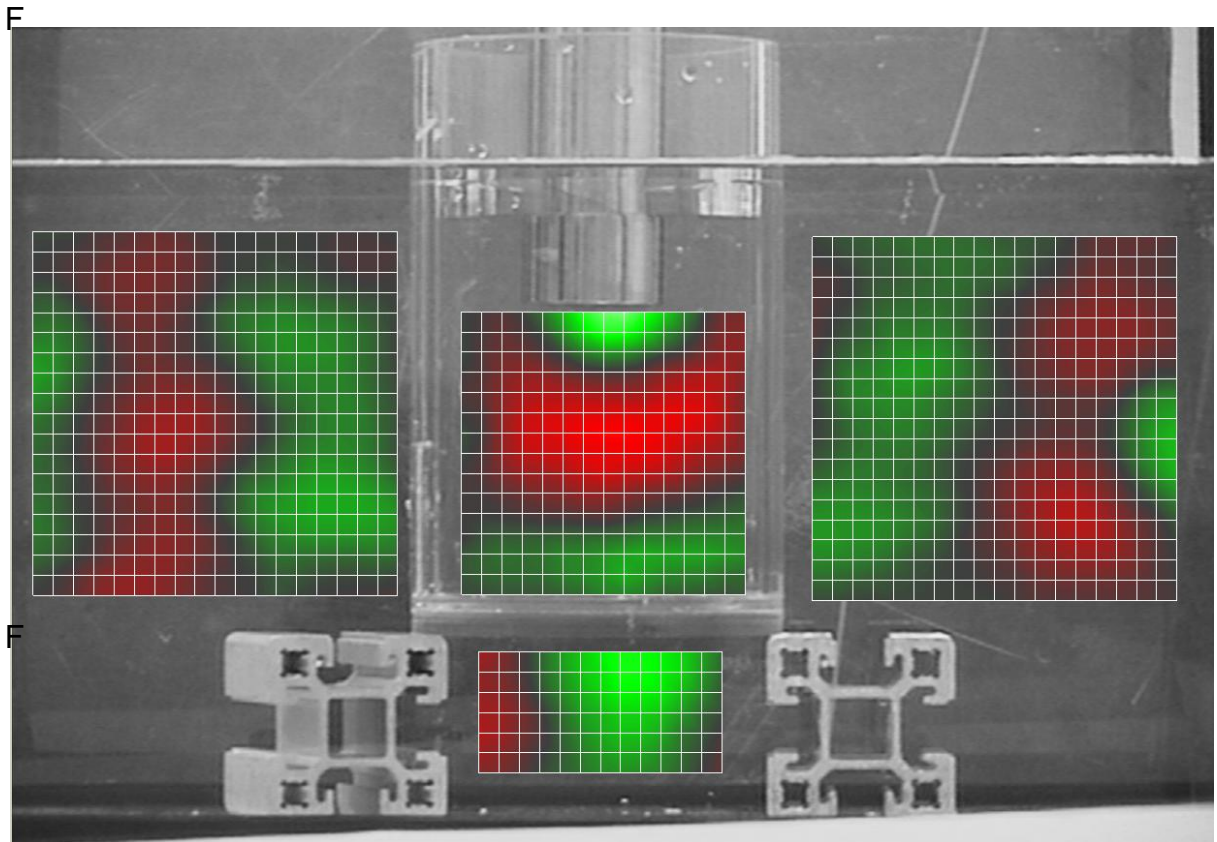


Figure 18. Vessel filled with water with glass bottom, inside a rectangular glass filled with water

FFT graphic

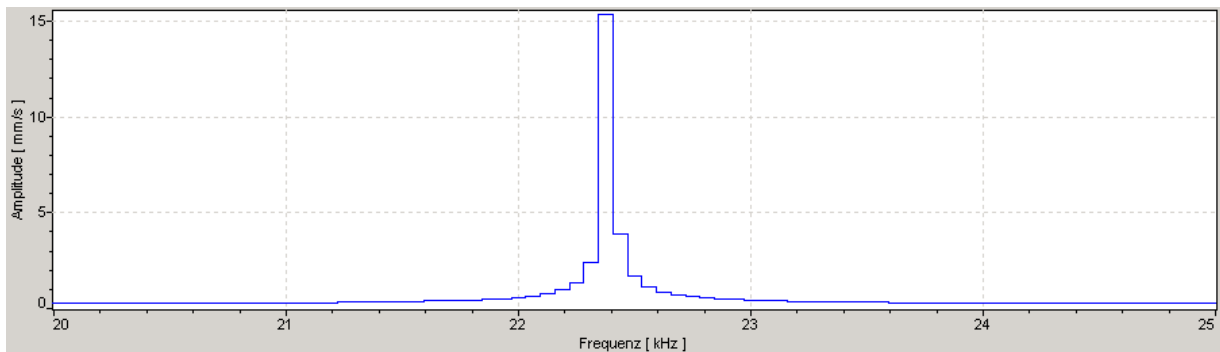


Figure 19. FFT

Comments:

There are two possibilities for this measurement. The first option is that the wave goes through the glass. I would say this is the most logical option.

But the other option is that we are not measuring the wave inside the vessel, and instead we are measuring the vibrations outside the vessel. In that case we wouldn't be able to assure that the wave is going through the glass, because all the measured vibrations are outside the glass.

3.1.6 Vessel filled with water with metallic bottom, inside a rectangular glass filled with water (measurements are done outside the vessel)

- Distance from bottom to transducer is 65 mm
- Distance from the source of laser beam to transducer is 1.28 m
- The water filled above the end of the transducer is 16 mm

The vessel is now put higher than the measurements done before, in order to see if the wave is transmitted through the metal located at the bottom of the vessel.

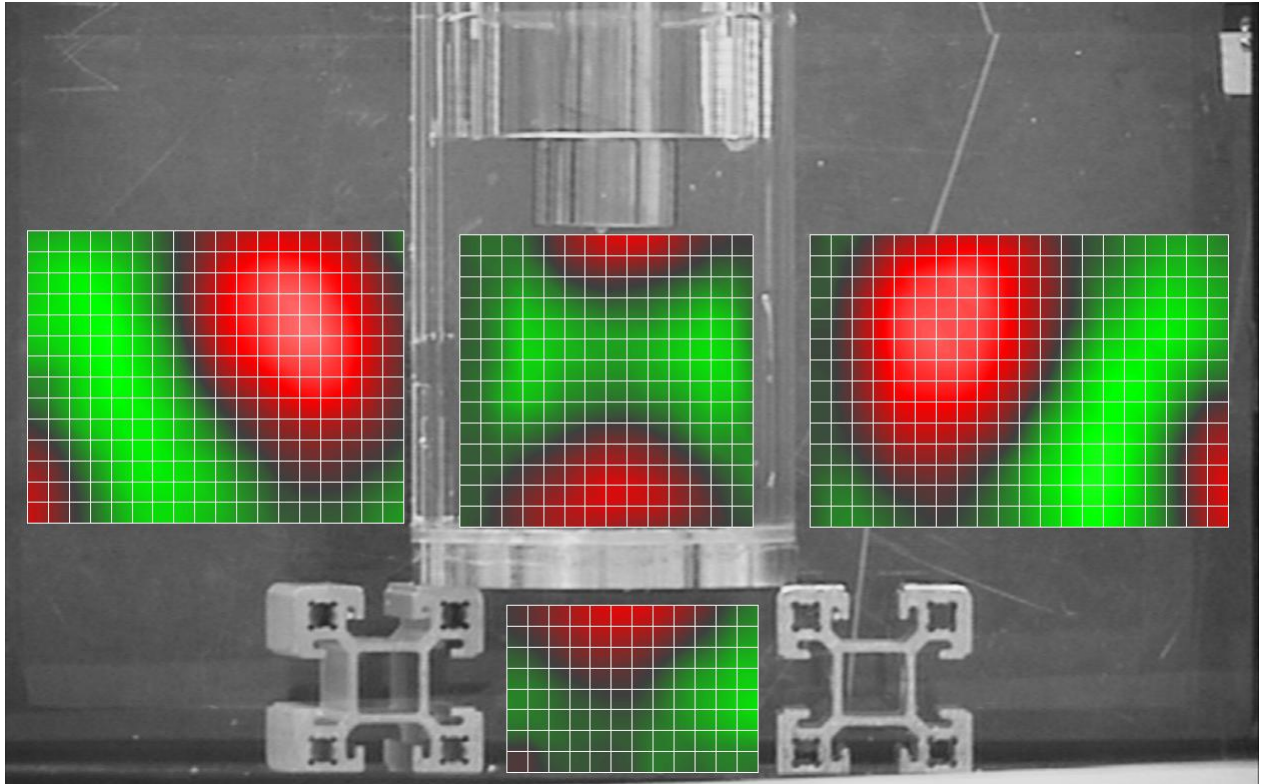


Figure 20. Vessel filled with water with metallic bottom, inside a rectangular glass filled with water

FFT graphic

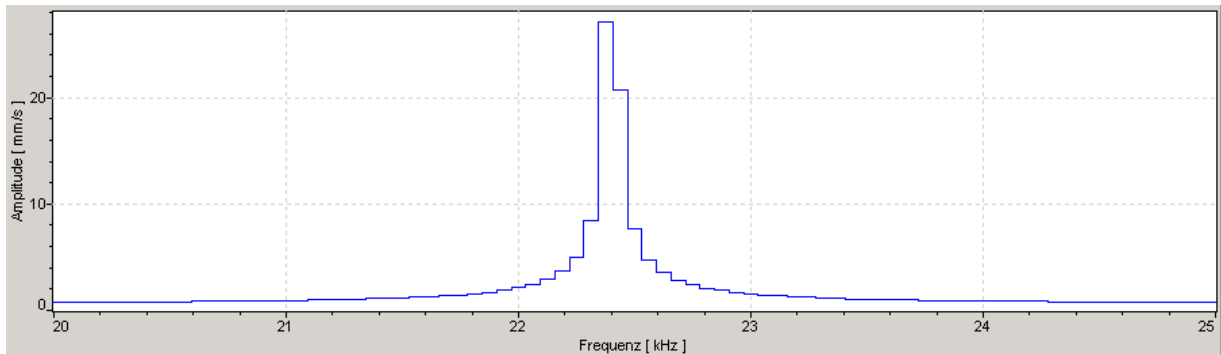


Figure 21. FFT

Comments:

The same conclusion as the measurement in 3.1.5.

**3.1.7 Complete metallic vessel filled with water, inside a rectangular glass
filled with water**

- Distance from bottom to transducer is 65 mm
- Distance from the source of laser beam to transducer is 1.28 m
- The water filled above the end of the transducer is 16 mm

The vessel is put higher than the measurements done before, in order to see if the wave is transmitted through the metal located at the bottom of the vessel.

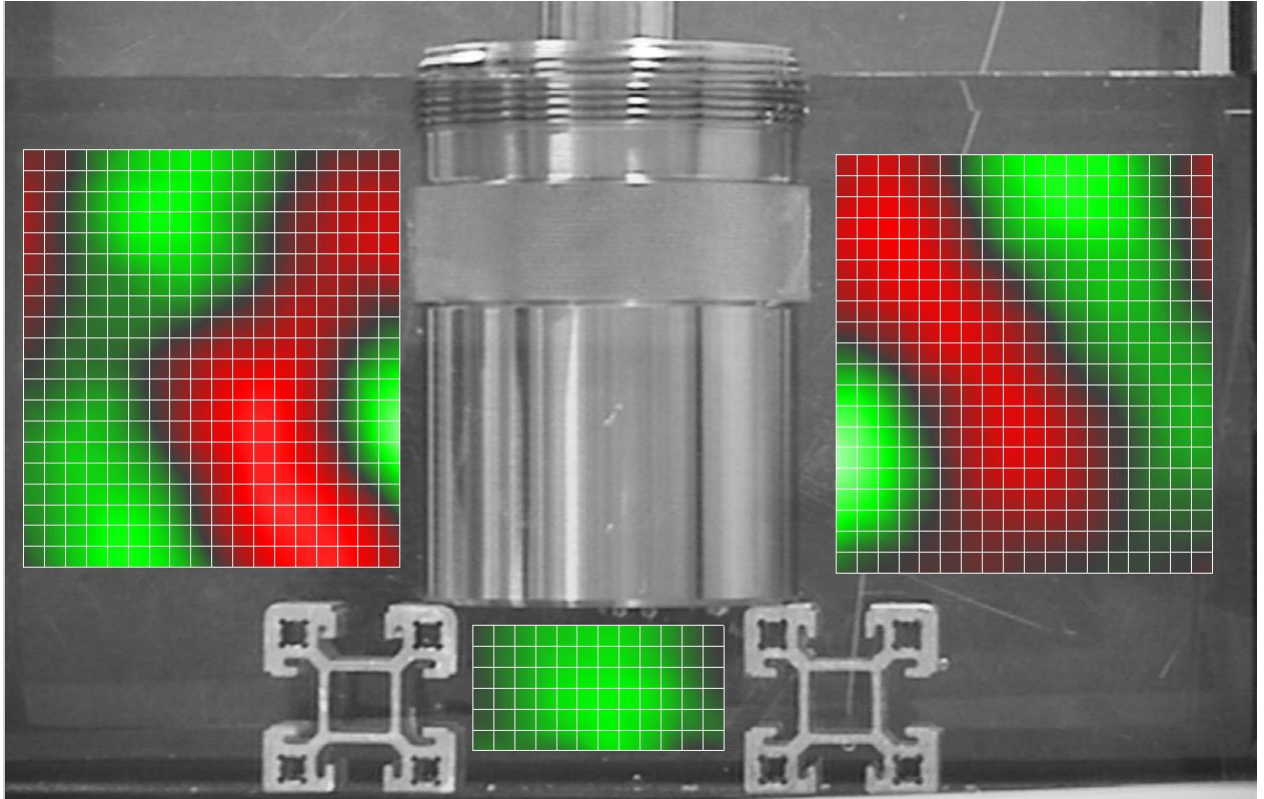


Figure 22. Complete metallic vessel filled with water, inside a rectangular glass filled with water

FFT graphic

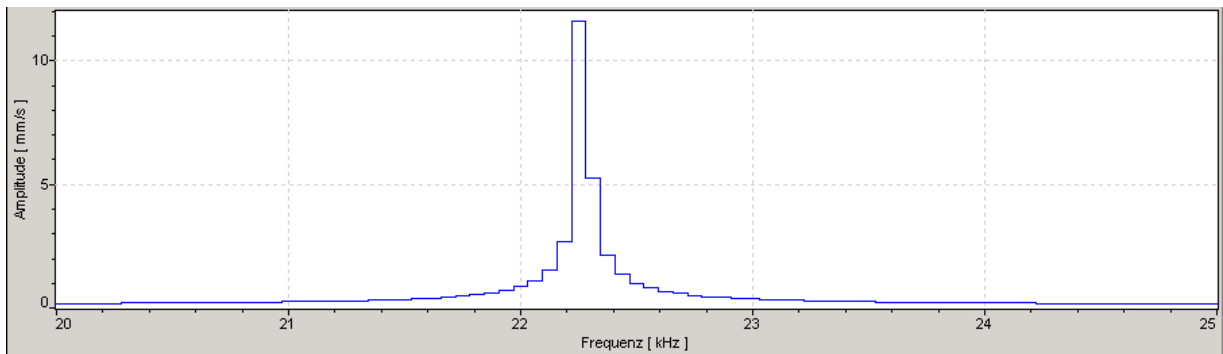


Figure 23. FFT

Comments:

Something unexpected seems to happen in this experiment. Under the bottom of the vessel the wave is travelling horizontally. I would have expected that, if the wave is going through the bottom of the cylindrical vessel, the wave measured under this vessel would have to travel vertically, but this is not seen in the experiment. Because of this reason, it can be concluded that the wave doesn't go through the bottom of the metallic vessel, but it does go through the sides of the vessel.

A reasonable conclusion of why the wave is travelling horizontally under the metallic vessel is because the water that has been excited in the right and left side of the vessel affects all the water in the rectangular container, and therefore the area under the metallic vessel also vibrates.

The maximum velocity is 20 mm/s

3.1.8 Teflon inside a rectangular glass filled with water

- Distance from bottom to transducer is 60 mm
- Distance from the source of laser beam to transducer is 1.28 m
- The water filled above the end of the transducer is 16 mm

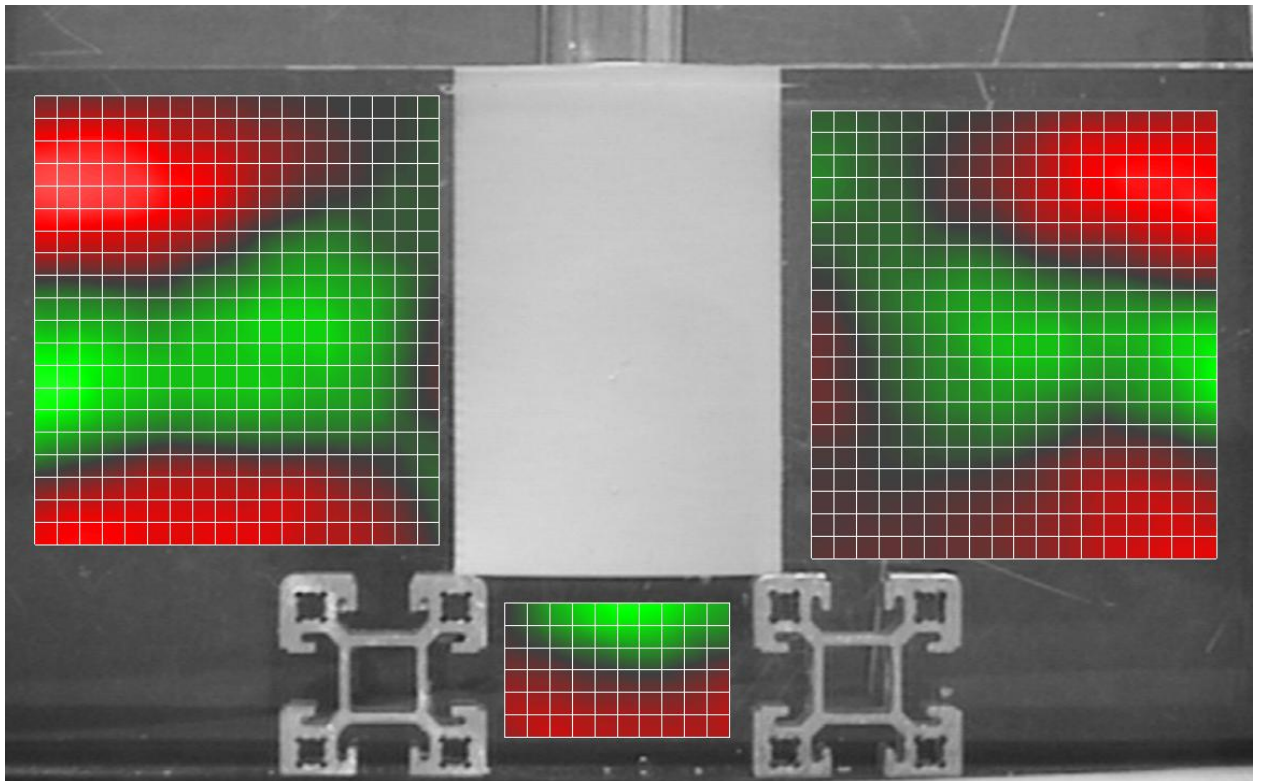


Figure 24. Teflon inside a rectangular glass filled with water

FFT graphic

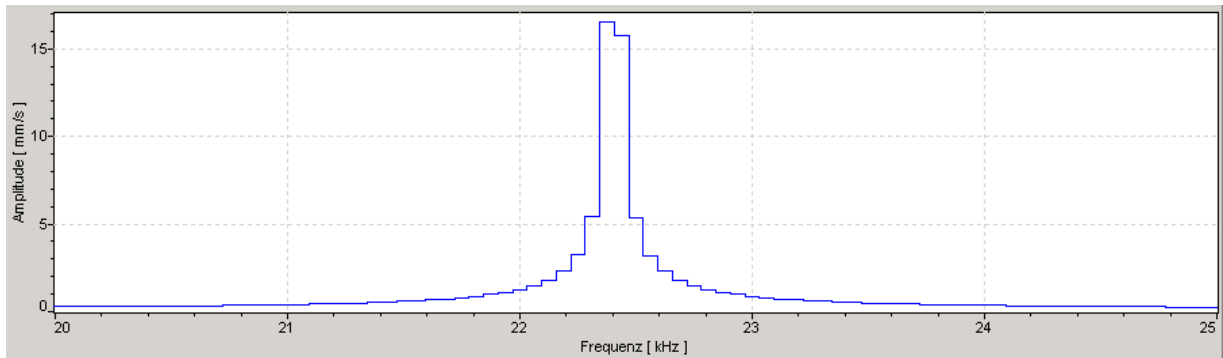


Figure 25. FFT

Comments:

It can be seen that the wave goes through the bottom and the sides of the cylindrical vessel.

The maximum velocity is 40 mm/s. If we compare the velocity of measurement 3.1.7. with the velocity of this measurement, it can be noticed that the maximum speed outside the vessel with Teflon is half the maximum speed of the measurement done with the metallic vessel, which is something coherent since the wave is reflected when the boundary is metallic, and the wave is absorbed when the boundary is made of Teflon.

3.1.9 Complete metallic vessel with Teflon inside a rectangular glass filled with water

- Distance from bottom to transducer is 60 mm
- Distance from the source of laser beam to transducer is 1.28 m
- The water filled above the end of the transducer is 16 mm

The vessel is put higher, in order to see if the wave is transmitted through the metal located at the bottom of the vessel.

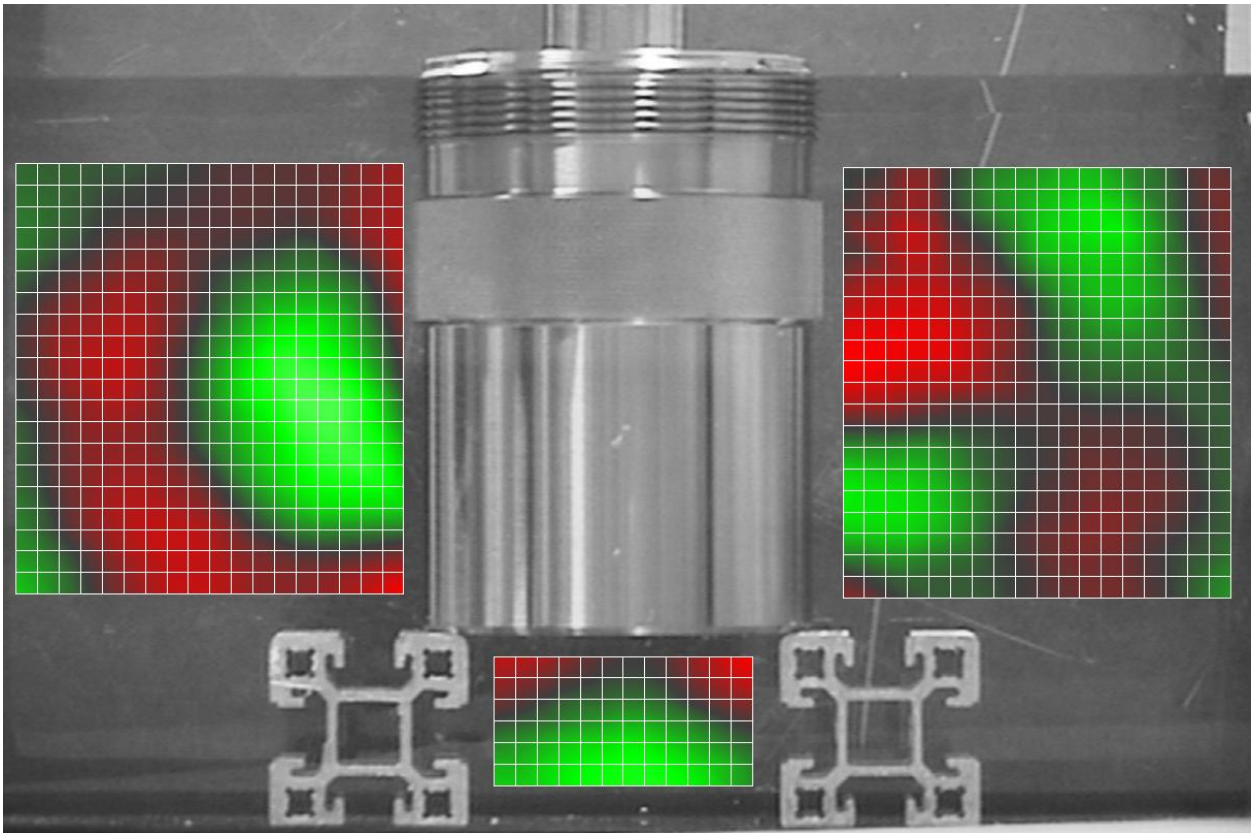


Figure 26. Complete metallic vessel with Teflon inside a rectangular glass filled with water

FFT graphic

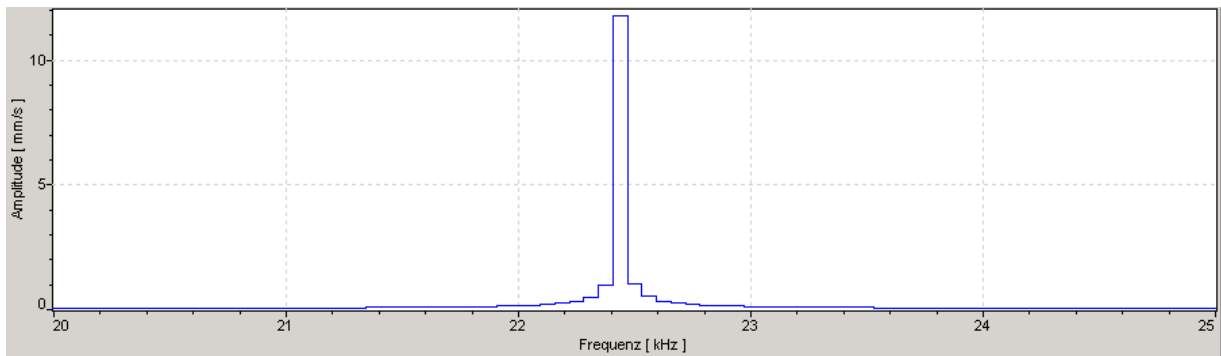


Figure 27. FFT

Comments:

It is very strange to see that below the cylindrical vessel it looks like the wave is going from the bottom to the top outside the vessel. Again, this experiment demonstrates that the wave is not transmitted through the bottom of the cylindrical vessel, like the measurement 3.1.7. and the reason why the wave is going from the bottom to the top under the metallic vessel is because that wave is only a consequence of the vibrations of the water that has been excited on the left and right of the cylindrical vessel.

3.1.10 Metallic cylindrical vessel filled with water

- Distance from bottom to transducer is 60 mm
- Distance from the source of laser beam to transducer is 1.28 m
- The water filled above the end of the transducer is near 16 mm. The 16 mm distance is not very precise since the measurement of that distance was difficult to achieve.
- A reflective tape was used in order to improve the laser signal.
- The maximum velocity is 4mm/s

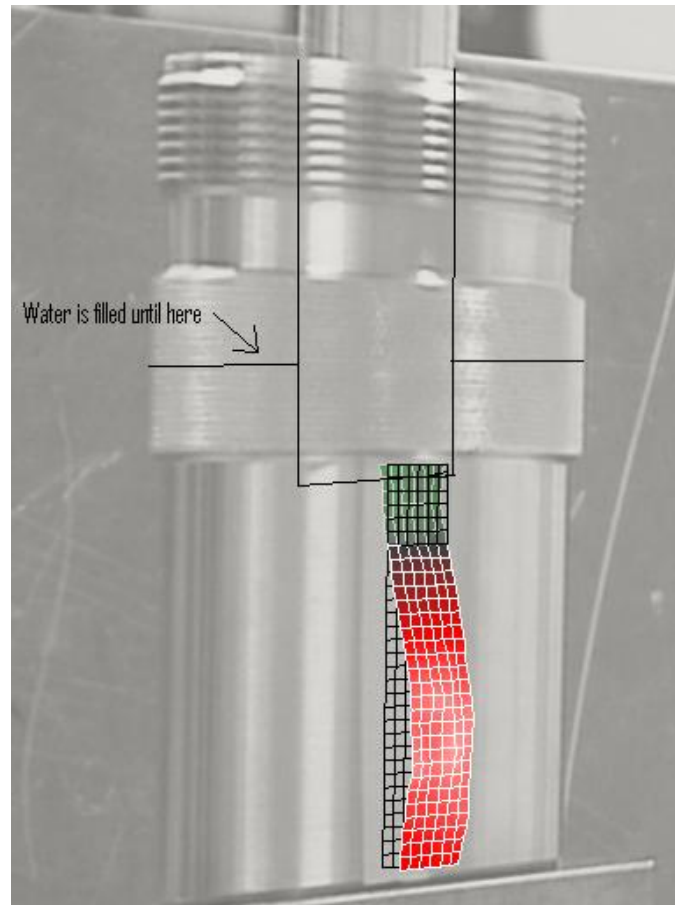


Figure 28. Metallic cylindrical vessel filled with water

FFT graphic:

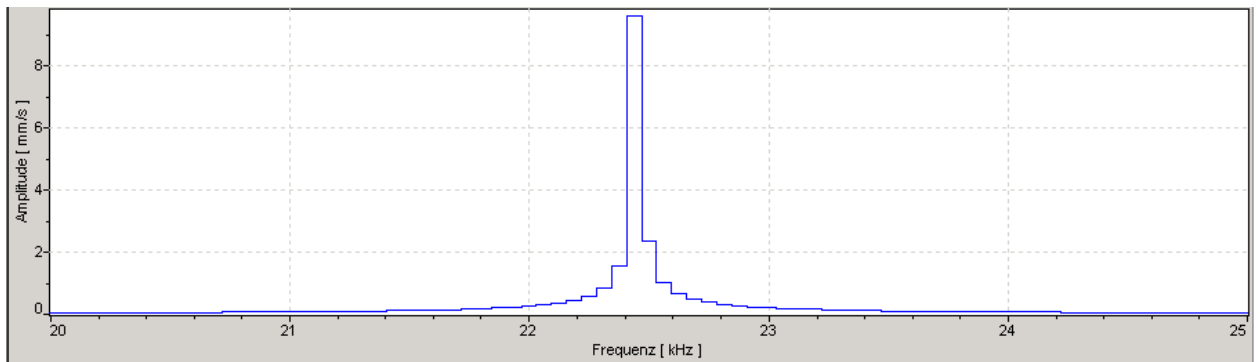


Figure 29. FFT

Comments:

It is seen that a standing wave is formed in the vessel, the speed of the wave is just 4 mm/s, but this proves that the vibrations of the vessel also may affect in the measurements. The water filled above the end of the transducer is 16 mm. A perfect standing wave is formed. This measurement demonstrates that the vibrations of the vessel may interfere in the measurements of water.

3.1.11 Teflon vessel filled with water

- Distance from bottom to transducer is 60 mm
- Distance from the source of laser beam to transducer is 1.28 m.
- The water filled above the end of the transducer is near 16 mm. The 16 mm distance is not very precise since the measurement of that distance was difficult to achieve, but this shouldn't affect considerably the measurements

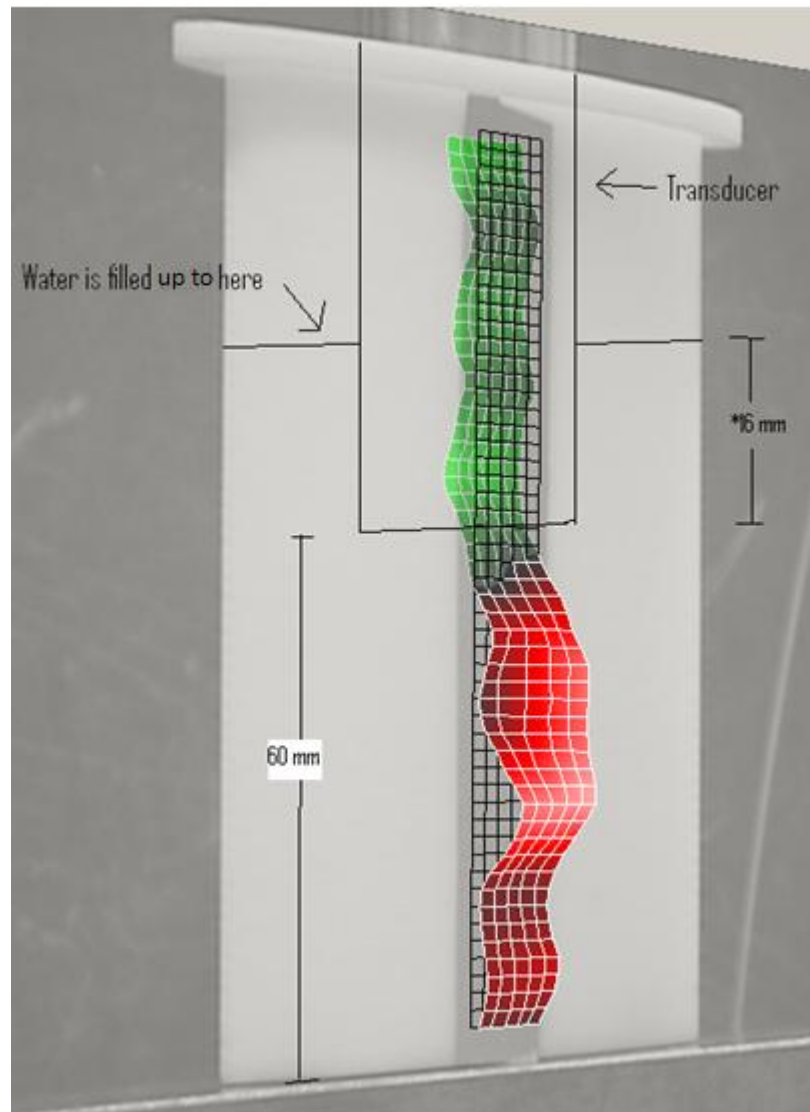


Figure 30. Teflon vessel filled with water

FFT graphic:

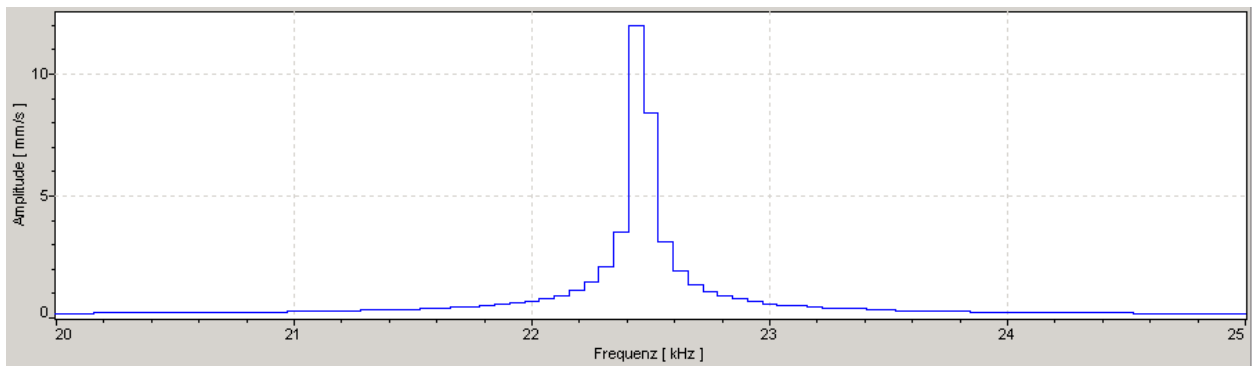


Figure 31. FFT

Comments:

The amplitude of the wave is bigger in the lower part of the vessel than in the top. The maximum velocity is 20 mm/s, which is 5 times higher than the velocity of measurement 3.1.10. A refractive tape was used to improve the signal.

The shape of the wave is not uniform everywhere as in the case of the measurement 3.1.10.

This also proves that the vibration of the vessel also may affect the results obtained when measuring the sound field in the water.

3.2 *Very precise measurements*

After the first experiments were done and some experience was gained, the measurements with water inside a cylindrical vessel with glass and metal bottoms were repeated. This time the height where the laser vibrometer was located was taken into consideration and it was fixed in order to be at the same height as the bottom of the vessels.

Also, the distance from the laser vibrometer to the transducer was larger than the first measurements, this time the distance was 2.26 m. The reason why we increased the distance was to have less variation of the angle than the measurements done with 1.28 m.

3.2.1 Metal bottom

- Distance from the transducer to the laser vibrometer is 2.26 m
- Distance from bottom to transducer is 65 mm
- The water filled above the end of the transducer is 16 mm

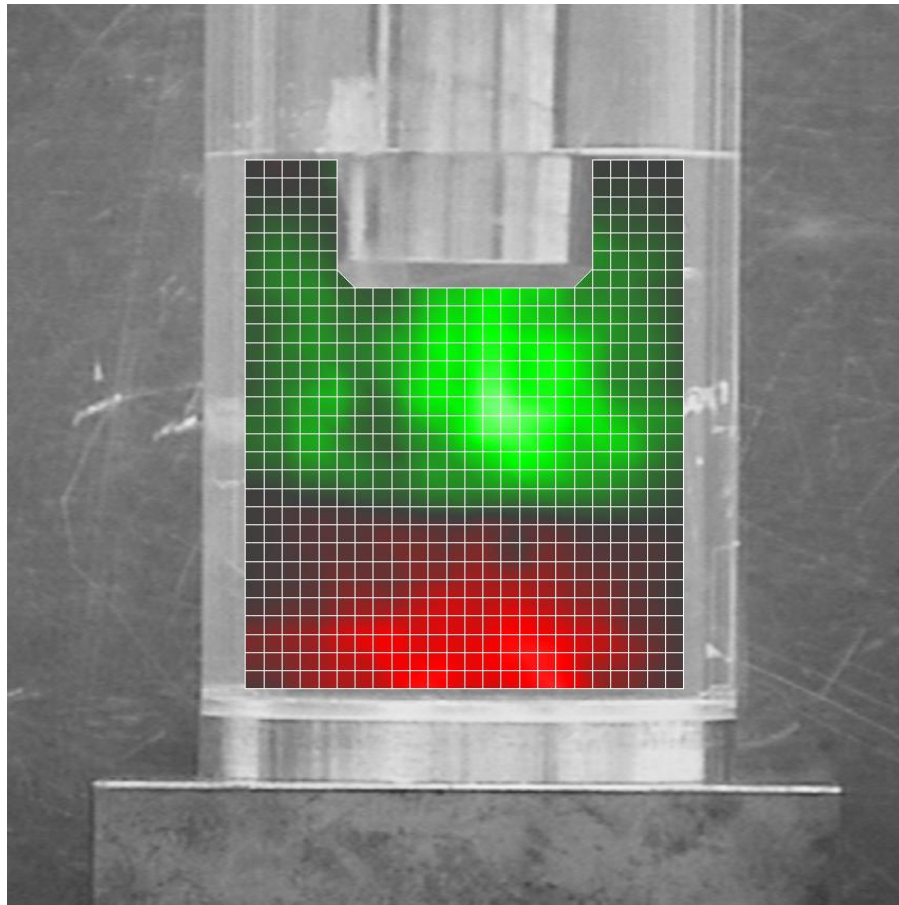
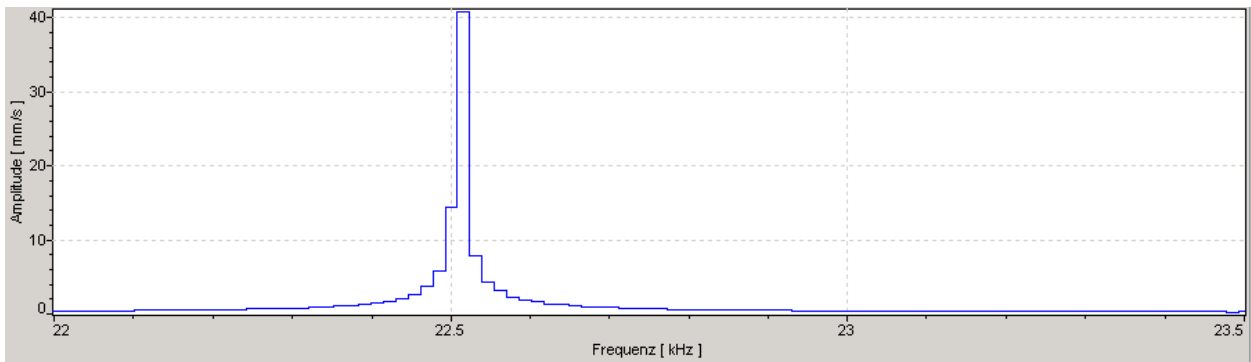


Figure 32. Metal bottom

FFT graphic:**Figure 33. FFT****Comments:**

The maximum velocity is at the end of the vessel. This result agrees with theory so it can be concluded that the measurement was done successfully.

3.2.2 Glass bottom

- Distance from the transducer to the laser vibrometer is 2.26 m
- Distance from bottom to transducer is 65 mm
- The water filled above the end of the transducer is 16 mm

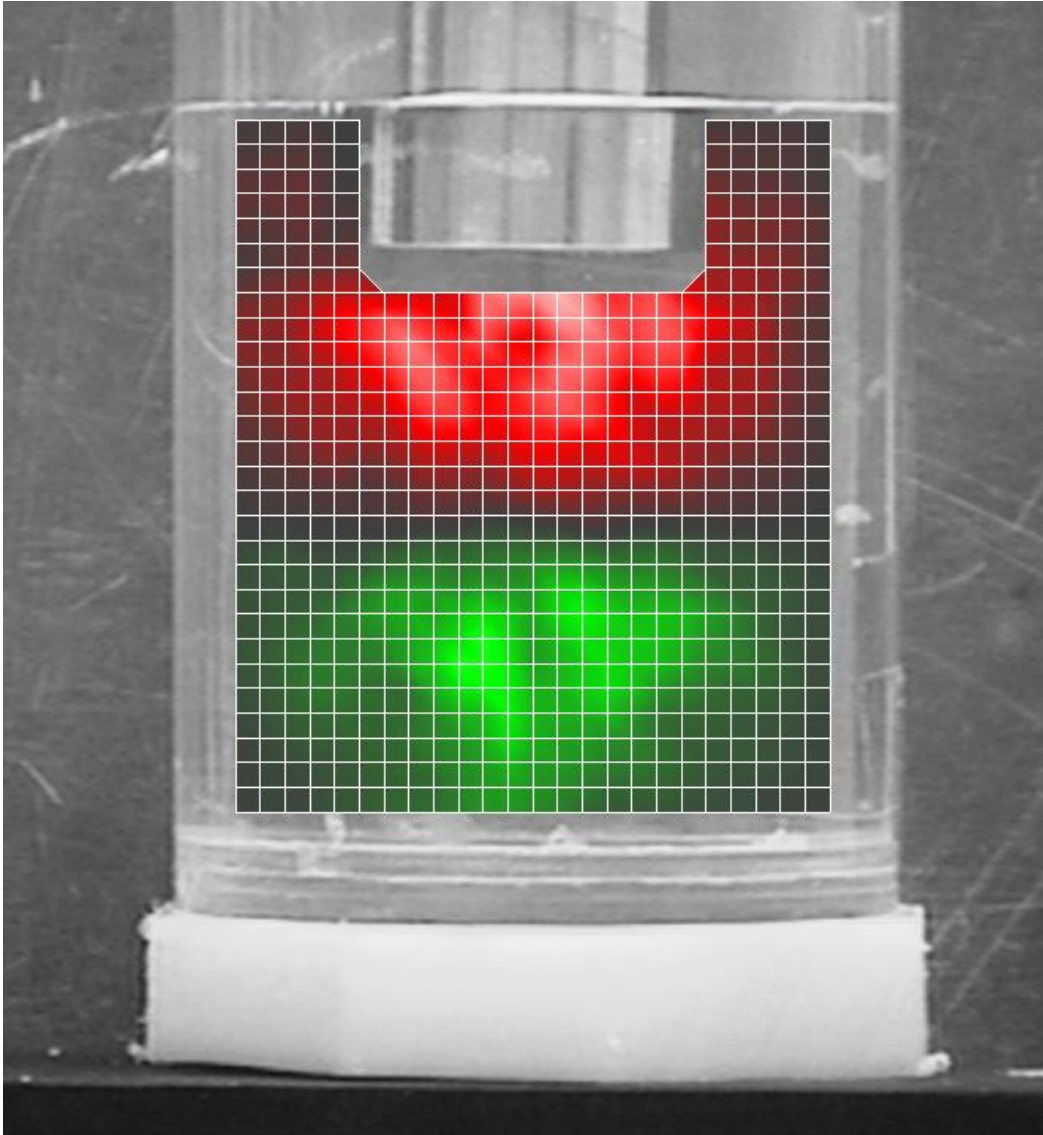


Figure 34. Glass Bottom

FFT graphic:

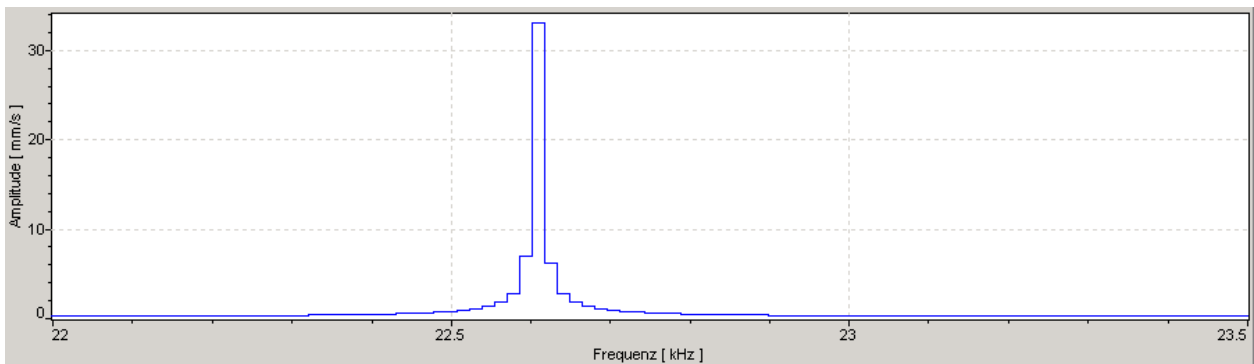


Figure 35. FFT

Comments:

This measurement looks really similar to the measurement in figure 6. It can be concluded that the distance from the transducer to the laser vibrometer didn't affect this measurement.

4 Conclusions and Recommendations

The conclusions that can be done are:

- In the theoretical analysis the main goal of having parallel lines was achieved by putting a cylindrical vessel, but because of the experimental limitations that idea was not carried out. If the divergence of the laser beam is corrected, then the problem would be solved, but that is not an easy task to do.
- In the figures 6, 7 and 8, it could be seen the dependence of the firing angle and the variation of the angles inside the vessel filled with water. If we knew what the maximum angle we can tolerate is, then this data could be used.

Further calculations will have to be done to determine what the value of this tolerance is.

- In all the experimental work that had been done, one clear parameter appears. It is observed that under the transducer there is always higher amplitude than in the top. This pattern is observed even in the measurements 3.1.7 and 3.1.8, which are the measurements done in the water outside the cylindrical vessel.
- It can be seen that when using the metallic vessel, the sound wave doesn't go through the bottom of the vessel
- In the FFT graphic there is always a clear peak in the resonance frequency.
- It is seen that there is a reflected wave in the bottom of the vessel, especially in the measurement with the glass with the metal bottom.
- The vibrations of the vessels can affect the measurements of the sound fields in water.

The recommendations I can give are:

- Align the positions on the live video image with the position of the laser in the cylindrical vessel, otherwise the laser won't move the way you expect. Always be aware of checking this in order to obtain good results!
- Use a refractive tape if the signal of the laser is not good enough for the measurements.

- Always try to get the best resolution by adding more scanning points in order to get the best results. It might take a little bit more time but the results may change if the scanning points are not enough
- To get other mode shapes, the distance from the bottom to the transducer should be changed. Further experiments must be done to prove this.

5 Bibliography

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