**TTT4250 - Acoustical Measurement Techniques**

# Laboratory Exercise 2: Acoustic Impedance Measurement


performed by

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# Summary

ROCKWOOL is a commonly used insulation inside the exterior walls of standard homes. Considering many homes are in noisy environments, it is of interest to see the absorption coefficient for the used material of a specific thickness. This can help choose what thickness to use for of specific material in the given environment.

This rapport guides you through two measurement methods of calculating the acoustic impedance, the absorption-and reflection coefficient of a test material, as well as discussing the calculated values for all three methods. The first method is done inside an impedance tube as described in ISO 10534-2[3], and the second method is done in a free field environment with the test material covering the floor between the microphone and loudspeaker. The results will then be compared to the simple empirical model for the acoustic properties of a porous material proposed by Miki in 1990[4]. The test material used for this rapport is ROCKWOOL, more commonly known as GLAVA, and the absorption coefficient were found to be, for all three calculations, above 0.9 at frequencies above 500Hz, and not higher than 0.5 for frequencies below 200Hz. The acoustic impedance show that the resistivity was high for the low frequencies and lower for the high frequencies.

# Contents


**1 Introduction** **1**

**2 Theory** **2**
2.1 Method 1: Impedance Tube Measurements (ISO10534-2) . . . . . 2
2.2 Method 2: Free Field Measurements . . . . . 3
2.3 Delany-Bazley-Miki model . . . . . 4

**3 Method and Equipment** **5**
3.1 Method 1: Impedance Tube Measurements(ISO10534-2) . . . . . 5
3.2 Method 2: Free Field Measurements . . . . . 6

**4 Results** **9**
4.1 Method 1: Impedance Tube Measurements(ISO10534-2) . . . . . 9
4.2 Method 2: Free Field Measurements . . . . . 9
4.3 Delany-Bazley-Miki Model . . . . . 10
4.4 Comparison . . . . . 11

**5 Discussions** **13**

**6 Conclusions** **14**

**7 Appendix** **16**

**8 Appendix** **20**

**9 Appendix** **24**

# 1 Introduction

This rapport will show how to find the acoustic impedance as well as the absorption-and reflection coefficient of a test material. This will be done using two measurement methods and a simple mathematical model called Mikis model [4]. The first measurement is done inside an impedance tube by following ISO 10534-2 [3], and the second measurement is done in a free field. By finding the absorption- and reflection coefficient for the test material one can determine for what frequencies the given material will absorb sound waves. This is especially useful for deciding what materials to use when creating buildings and rooms, sound insulation barriers, and other specific needs. The test material used for this rapport is ROCKWOOL, commonly known as GLAVA, which is frequently used as insulation in standard homes.

The rapport will give the necessary data and equations to reproduce the calculations as well as discuss the results given by the two measurement techniques with the empirical model proposed by Miki in 1990.

# 2 Theory

## 2.1 Method 1: Impedance Tube Measurements (ISO10534-2)

The first method measure the acoustic impedance of a test material through normal incidence. This is done inside an impedance tube where the pressure waves inside the tube are assumed to be plane waves at the microphone positions. The impedance tube can be both rectangular and circular, but for this rapport, the focus remains on the use of a circular impedance tube. The first step is to determine the operating frequency range of the impedance tube. This is done by finding the upper and lower boundary. The lower boundary $f_1$ is determined by the equipment used. Since the impedance tube is airtight, the lower frequency can damage the equipment due to resonances and high pressure inside the impedance tube. The upper frequency, $f_u$, is determined by both the diameter $d$ of the impedance tube as well as the spacing distance $s$ between the microphone positions. The arguments for $f_u$ are given as

$$f_u < \frac{0.58 \cdot c_0}{d} \quad \text{Hz} \tag{2.1}$$

and

$$f_u < \frac{0.45 \cdot c_0}{s} \quad \text{Hz} \tag{2.2}$$

where $c_0$ is the speed of sound in air and is given as

$$c_0 = 343.2\sqrt{T/293} \quad \text{m / s} \tag{2.3}$$

where T is the temperature, in kelvin, inside the impedance tube.

Resonance in the impedance tube will always arise. To suppress the resonances inside the tube, the casing behind the loudspeaker is lined with a sound-absorbent material with a thickness of at least 200mm.

Due to microphone mismatch, the microphones are interchanged between the two measurements. The transfer function for both measurements are found as

$$H_{12}^{\mathrm{I}} = \frac{p_2}{p_1}, \qquad H_{12}^{\mathrm{II}} = \frac{p_2}{p_1} \tag{2.4}$$

where the number $I$ and $II$ mark the transfer-function for, respectively, measurement one and two, and $p_1$ and $p_2$ is the pressure at, respectively, microphone position 1 and 2. The calibrated transfer-function is given as

$$H_{12} = \sqrt{H_{12}^{\mathrm{I}} \cdot H_{12}^{\mathrm{II}}} = \sqrt{\left(\frac{p_2}{p_1}\right)^2} \tag{2.5}$$

The transfer function for both the incident and reflected wave can be determined as an exponential function given by the wavenumber and the separation distance $s$. This is seen in Equation (2.6) and are further explained in Annex.D in [3].

$$H_I = e^{-jks}, \qquad H_R = e^{jks} \tag{2.6}$$

The sound reflection factor is given as

$$R = \frac{H_{12} - H_I}{H_R - H_{12}} \cdot e^{-2jkx_1} \tag{2.7}$$

where $x_1$ is the distance from the first microphone position to the beginning of the test material. From the reflection factor both the absorption factor and the acoustical impedance can be found. The absorption factor is determined as

$$\alpha = 1 - |R|^2 \tag{2.8}$$

and the acoustic impedance as

$$Z = \frac{R+1}{R-1} \cdot \rho c_0 \tag{2.9}$$

where $\rho$ is the density of air. The length of the impedance tube must be long enough to ensure plane waves at the microphone positions. The loudspeaker will generally produce non-plane waves, but the non-plane waves will vanish after the length of three times the diameter of the tube. The microphone positions should therefore exceed this distance.

## 2.2 Method 2: Free Field Measurements

The second method will measure the acoustic impedance of the test material by covering the floor between the loudspeaker and the microphone with the test material. Compared to the first method, there exist no lower or upper bounds that will affect the measurements to such a degree as in method 1.

The transfer function between the upper and lower microphone position can be calculated by using Equation (2.4).

To calculate the reflection coefficient, the distance traveled by the sound wave for both the direct and reflected path must first be found. The direct path $r_d$ is given as

$$r_d = \sqrt{\left((h_{lsp} - h_{Mic})^2 + d_d^2\right)} \tag{2.10}$$

where $h_{lsp}$ is the height of the center of the loudspeaker, $h_{Mic}$ is the height to the given microphone position and $d_d$ is the horizontal distance from the microphone to the loudspeaker.

The reflected path $r_r$ is given as

$$r_r = \sqrt{\left((h_{lsp} + h_{Mic})^2 + d_d^2\right)} \tag{2.11}$$

The angle of reflection is given as

$$\theta = \frac{\pi}{2} - \arccos\left(\frac{\mathrm{d_d}}{\mathrm{r_r}}\right) \tag{2.12}$$

Since the reflection is at an angle relative to the microphone, the reflection factor as a function of reflection angle, $\theta$, is given as

$$\mathbf{R}(\theta) = \frac{\dfrac{e^{-jkr_{d2}}}{r_{d2}} - \mathbf{H_{12}} \cdot \dfrac{e^{-jkr_{d1}}}{r_{d1}}}{\dfrac{e^{-jkr_{r1}}}{r_{r1}} \cdot \mathbf{H_{12}} - \dfrac{e^{-jkr_{r2}}}{r_{r2}}} \tag{2.13}$$

The angle for the reflected wave for both microphone positions can then be used to calculate the acoustic impedance as

$$Z = \frac{-\rho c}{\cos\theta} \cdot \frac{(R+1)}{(R-1)} \tag{2.14}$$

and the absorption coefficient is given as in Equation (2.8).

## 2.3 Delany-Bazley-Miki model

The third method is a simple empirical model for the acoustic properties for a porous material. The characteristic impedance of the test material is determined by a mathematical model as a function of thickness, $e$, and the flow resistivity, $\sigma$, of the test material. The characteristic impedance $Z_C$ is calculated as

$$Z_C = -j\left[1 + 5.50\left(10^3\frac{f}{\sigma}\right)^{-0.632} - j8.43\left(10^3\frac{f}{\sigma}\right)^{-0.632}\right]\tan(k\cdot e) \tag{2.15}$$

where $f$ is the frequency in hertz and k is the wave number given as

$$k = \frac{w}{c}\left[1 + 7.81\left(10^3\frac{f}{\sigma}\right)^{-0.618} - j11.41\left(10^3\frac{f}{\sigma}\right)^{-0.618}\right] \tag{2.16}$$

where w is the angular frequency in radians.

The absorption coefficient is found by using Equation (2.8) and the reflection factor by using Equation (2.7).

# 3 Method and Equipment

The list of equipment used for this lab can be seen in Table 3.3. All post processing of the data where done using Matlab [5].

Table 3.1: Equipment list.

| Equipment | Model number/type | Serial number |
|---|---|---|
| Pre amplifier | Bruel&Kjær Type 1708 | 100407&100406 |
| Soundcard | Roland Studio-Capture | |
| Pressure Microphone | Norsonic Type 1201/30490 | |
| Microphone | Bruel&Kjær Type 4190 | 1837407 |
| Test material | Rockwool 100x570x1200mm | |
| Microphone stand | K&M | |
| Loudspeaker | Given at the acoustic lab | |
| Amplifier | Given at the acoustic lab | |
| Impedance tube 1m | Given at the acoustic lab | |
| Foam windscreen for microphone | | |

## 3.1 Method 1: Impedance Tube Measurements(ISO10534-2)

The first method was done in an impedance tube of length 1m. The tube had a loudspeaker securely attached to one end with acoustic padding behind it to reduce reflections. The other end of the tube is open, but at this end a sample holder can be tightly fixed. The sample holder is where the test material is placed. When inserting the test material into the sample holder, it is important to ensure that the fit is tight, but not so tight that bulging and altering of the test material will occur. On top of the impedance tube are 2 holes where the microphones will be fitted into. The spacing between the two holes are one of the two arguments that decide the upper frequency of interest.

The test material is then inserted into the sample holder and then securely fitted to the end of the impedance tube. The two microphones is placed into the holes on top of the tube and connected to the soundcard via a pre-amplifier. When fitting the microphones into the holes, it is important that the diaphragm are flush with the interior surface of the tube. A small recess is often necessary as seen in Chapter 4.5 in [3]. A feedback loop is created by connecting output $Out_4$ to input $In_3$ on the soundcard. The loudspeaker is then connected to output $Out_3$ of the soundcard through a separate amplifier. The final set-up can be seen in Figure 3.1 and all distance values are seen in Table 3.2. In the figure showing the setup, the case surrounding the loudspeaker have the interior walls lined with an effective sound-absorbent material. The soundcard is then connected to a PC running the EASERA software [6]. In the EASERA software, the mode multi-channel FFT should be selected. The input and output selection are selected according to Figure 3.1. Since there is little to no noise in the tube, there will be no need to turn up the gain for these measurement. To validate this, the signal strength can be visualized through the test function in the EASERA software. This allows for adjusting the gain live, while also being able to see the measured signal strength.

After the optimal gain is selected, the loudspeaker is then turned on to sweep from 100-22.500 Hz while the two microphones record the pressure inside the tube. After the first measurement, the microphones interchange positions, and the measurement is repeated. This is to adjust for any internal difference between the two microphones.

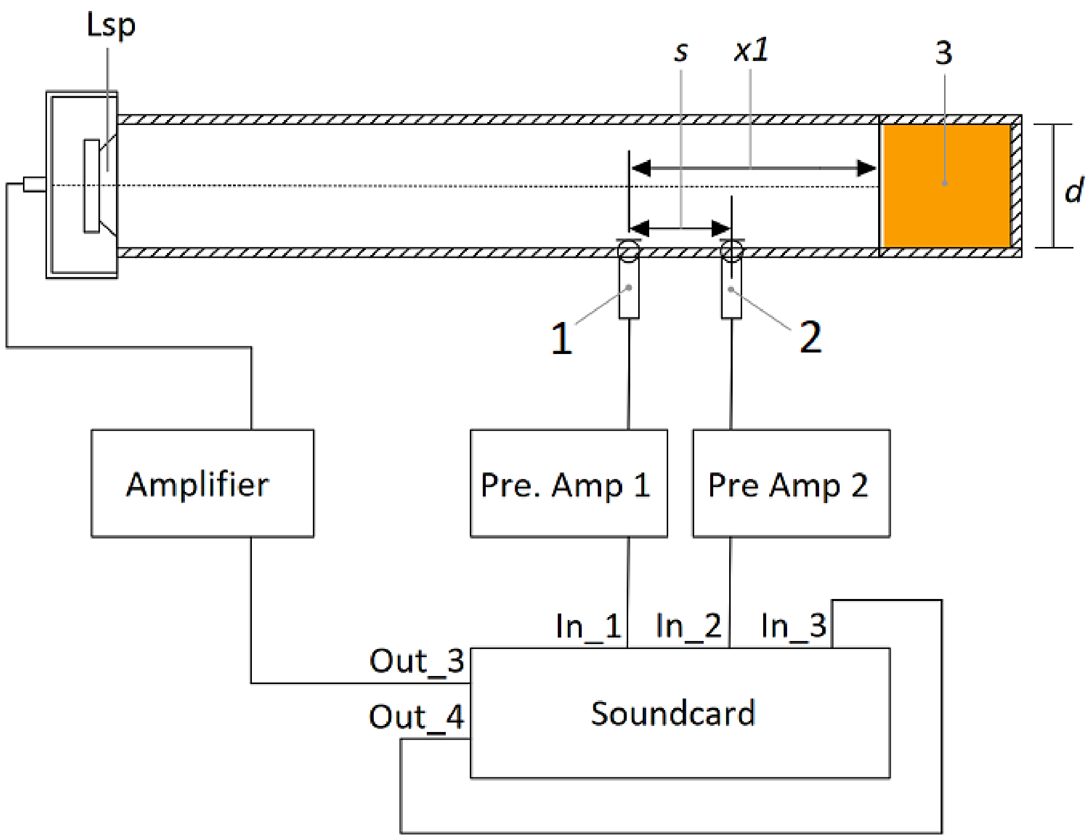


Figure 3.1: Layout of the setup for measurements done with the impedance tube. The numbers 1 and 2 marks the microphone positions used for the measurement with $s$ marking the distance between the center of each microphone. $x_1$ is the distance from microphone 1 to the end of the impedance tube where the test material begins. $d$ is the diameter of the tube and 3 marks the test material. The loudspeaker is placed at the left-most side and is marked as *Lsp*. The connections marked with *In* or *out* are, respectively, the inputs or outputs to the soundcard.

Table 3.2: Specific distances for method 1.

| | value | unit |
|---|---|---|
| $s$ | 8.0 | cm |
| $d$ | 10.0 | cm |
| $x_1$ | 18.0 | cm |

## 3.2 Method 2: Free Field Measurements

The second method were performed in room D0015 at NTNU, Gløshaugen, in the Elektro D+B2 building. The room is big and open enough to be considered a free field. The setup consists of a loudspeaker, a microphone, and the test material. The loudspeaker is placed at the height $h_h$

Table 3.3: Equipment list.

| Equipment | Model number/type | Serial number |
|---|---|---|
| Pre amplifier | Bruel&Kjær Type 1708 | 100407&100406 |
| Soundcard | Roland Studio-Capture | |
| Pressure Microphone | Norsonic Type 1201/30490 | |
| Microphone | Bruel&Kjær Type 4190 | 1837407 |
| Test material | Rockwool 100x570x1200mm | |
| Microphone stand | K&M | |
| Loudspeaker | Given at the acoustic lab | |
| Amplifier | Given at the acoustic lab | |
| Impedance tube 1m | Given at the acoustic lab | |
| Foam windscreen for microphone | | |

above the test material. The microphone is positioned at a horizontal distance, $d_d$, away from the loudspeaker at with the height $h_{m1}$ above the test material. The material was then placed at the flooring covering the surface area on the ground between the microphone and the loudspeaker. The EASERA software was then set to a single-channel setup with a sweep frequency of 100-22.500Hz. Same as for method 1, the gain of the soundcard was optimized for the test environment so to give more clear data in the recording. The sweep was then recorded for the first position and stored. While keeping the horizontal distance $d_d$ constant, the vertical distance of the microphone was increased to $h_{m2}$. The same measurement was then repeated for this height. The setup of the free field can be seen in Figure 3.2 and the distances can be seen in Table 3.4.

Table 3.4: Specific distances for method 2.

| | value | unit |
|---|---|---|
| $d_d$ | 100.0 | cm |
| $h_h$ | 39.0 | cm |
| $h_{m1}$ | 45.0 | cm |
| $h_{m2}$ | 50.0 | cm |

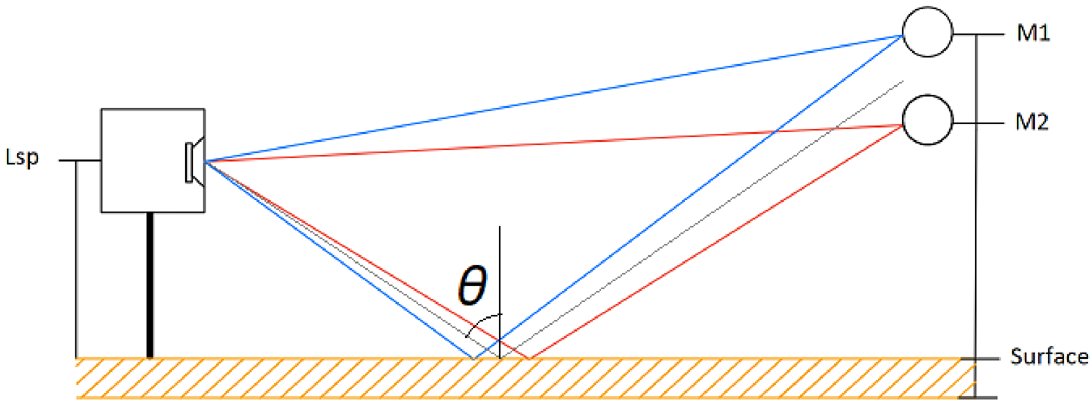


Figure 3.2: The setup for the free field test method as seen from the side. The *Lsp* is the loudspeaker used for the test, and M1 and M2 is the two microphone positions used. The bottom layer marked in orange is the test material and are marked as $Surface$ in the figure. The blue and red lines show the direct and reflected path for the sound wave, and $\theta$ is the angle of reflection.

# 4 Results

## 4.1 Method 1: Impedance Tube Measurements(ISO10534-2)

Since the equipment used for the impedance tube can be damaged for frequencies under 40Hz, the lower frequency range for the tests were set to 100Hz. The upper frequency was then calculated using Equation (2.1) and verified using Equation (2.2). The two values for the upper frequencies can be seen in Table 4.1 showing that $f_u$ cant exceed 1923.9Hz. To maintain consistency with the results and calculations, the frequency range remain the same for all three methods.

Table 4.1: Upper frequency given by the diameter, $d$, of the impedance tube, and the spacing, $s$, between the microphones.

| Parameter | $f_u$ | unit |
|---|---|---|
| $d$ | 1983.8 | Hz |
| $s$ | 1923.9 | Hz |

$s$ and $d$ marks, respectively, Equation (2.2) and Equation (2.2).

With a sampling frequency of 44.1KHz and the length of the impulse response being 200ms, the frequency resolution after the FFT(Fast Fourier Transform)[7] is 5.4Hz. This will result in smooth lines for the given frequency range. The calibrated transfer function for the impulse response was then found as described in Chapter 2.1. The transfer-function for the incident and reflected wave was calculated using Equation (2.6). Together with the transfer-function for the impulse response, the acoustic impedance as well as the absorption-and reflection coefficient was plotted as seen in Figure 4.1.

It is clear from the absorption-and reflection coefficient curve that the test material is highly efficient as a sound absorber for frequencies over 500Hz. It is also clear that that the material is highly innecicient as a sound-absorbent material for sound waves below 150Hz. The acoustic impedance graph shows that the highest resistance the sound wave encounters are for the lowest frequencies, at around 1500 rayl, and for the high frequencies, the impedance is at around 400 rayl.

## 4.2 Method 2: Free Field Measurements

The impulse response for the free field is considerable shorter than for method 1. This is due to the measurements being done in an open environment and the sound waves spread in all directions. There are no close surfaces that reflect the sound waves in the same sense as in the impedance tube. The gain was therefore set to 38.5dB. The test material covering the floor had a total surface area of 5.8m$^2$, with each GLAVA sheet having the dimensions 100x570x1200 mm. A total of 8 sheets where therefore used. The length of the impulse response is 8ms which equal 352 samples. This is equivalent to an FFT length of 512 samples which gives a frequency resolution of 86.1Hz. This is low compared to the first method and will result in a less smooth curve for the lower frequencies as well as more inaccurate results for the lower frequencies.

The direct and reflected distance were found using, respectively, Equation (2.11) and Equation (2.10). With the distances found, the angles were calculated using Equation (2.12). The distances and reflection angle for both microphone positions as well as the mean values for all distances and the reflection angle is seen in Table 4.2.

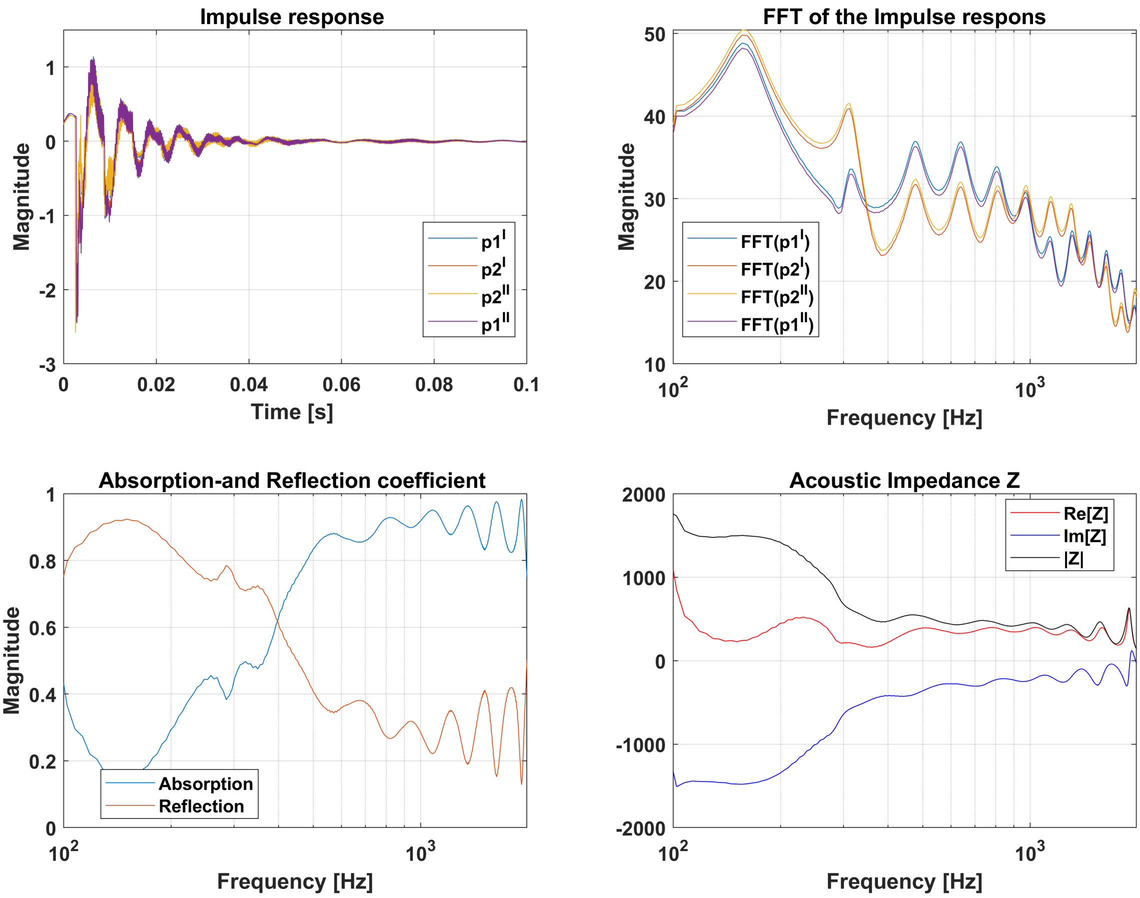


Figure 4.1: This 2x2 picture array consist of plots of the impulse response, FFT of the impulse response, Absorption-and Reflection coefficient and the acoustic impedance as calculated in Chapter 3.1. The Roman number $I$ and $II$ in the superscript for the pressure values indicate which of the two measurements they belong to.

The transfer function is calculated using Equation (2.4), and with the reflected-and direct distance calculated, the reflection coefficient is found using Equation (2.13). The absorption coefficient is found as in method 1 by using Equation (2.8), but the acoustic impedance is found by using Equation (2.14). The plot for the impulse response and its FFT, the acoustic impedance, and the absorption-and reflection coefficient is seen in Figure 4.2.

For the lowest frequency, the first valid frequency is at 160Hz due to the frequency resolution. This results in inaccurate calculations for the lowest frequencies, and as seen, the graph is considerably less smooth than that in method 1.

## 4.3 Delany-Bazley-Miki Model

For the test material GLAVA, the air flow resistivity is 9100Pa s/m$^2$ and the thickness of each sheet is 100mm. By inserting the thickness and airflow resistivity of the test material into Equation (2.15) the specific impedance for the test material is found. The impedance is then inserted into Equation (2.8) and Equation (2.7) to get, respectively, the absorption-and reflection coefficient. The graphical model can be seen in Figure 4.3.

Table 4.2: Values for each direct- and reflected path as well as the angle of reflection. The subscript *mean* indicate the mean value for the height M1 and M2.

| | value | unit |
|---|---|---|
| $r_{r1}$ | 1.3060 | m |
| $r_{r2}$ | 1.3387 | m |
| $r_{r,mean}$ | 1.3222 | m |
| $r_{d1}$ | 1.0018 | m |
| $r_{d2}$ | 1.0060 | m |
| $r_{d,mean}$ | 1.0036 | m |
| $\theta_1$ | 0.8721 | rad |
| $\theta_2$ | 0.8435 | rad |
| $\theta_{mean}$ | 0.8577 | rad |

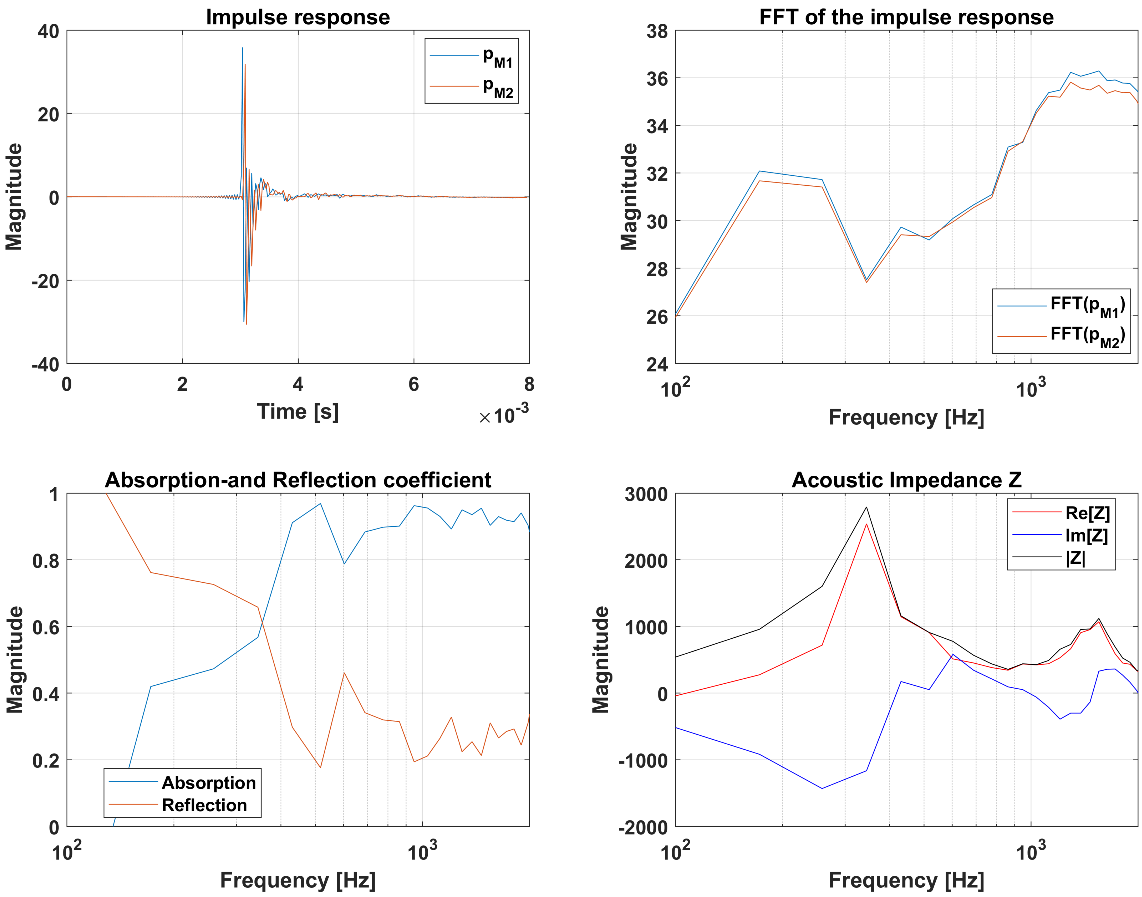


Figure 4.2: This 2x2 picture array consist of plots of the impulse response, FFT of the impulse response, Absorption-and Reflection coefficient and the acoustic impedance as calculated in Chapter 3.2. The Roman number $I$ and $II$ in the superscript for the pressure values indicate which of the two measurements they belong to.

## 4.4 Comparison

For all three methods the general shape of the curves are close to equal. Comparing the graph in Miki's model to the two test methods, method 1 seem to be closest to the curves given from Miki's model. The impedance curve for method 2 has a slight increase at 1500Hz which is an abnormality

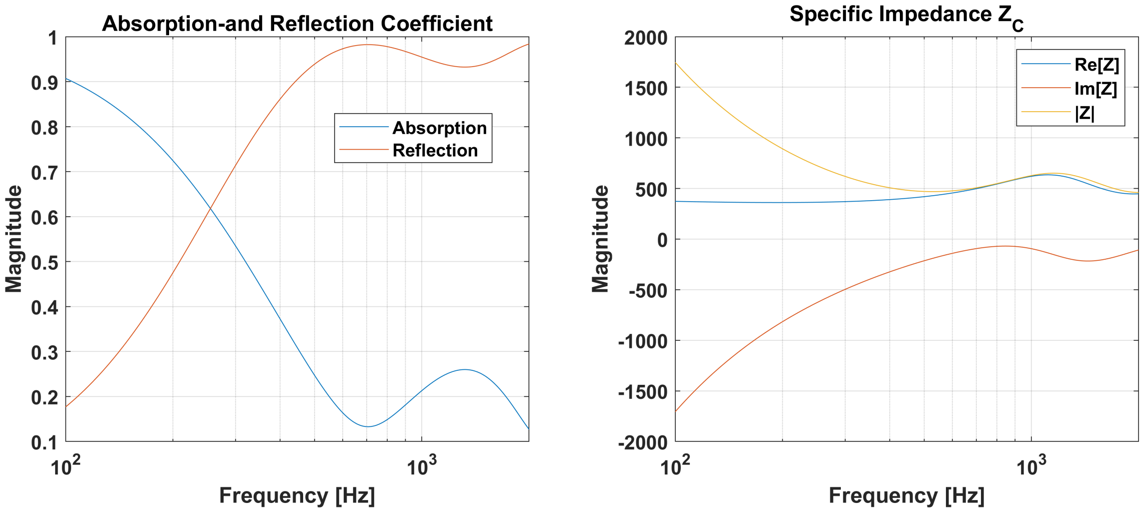


Figure 4.3: The left-most plot show the absorption-and reflection coefficient and the right-most plot show the specific impedance. The plots are calculated using Mikis model[4].

compared to the two other methods as well as a very low impedance for frequencies below 200Hz. From the absorption curves, method 2 have a slightly higher value at 180Hz than for the other two methods.

# 5 Discussions

By comparing Figure 4.1 and Figure 4.2 it is clear that the shape of the absorption-and reflection curve is close, but not equal, for the given frequency range. The length of the impulse response is considerably longer for the impedance tube measurement than that of the free field method which results in a significantly higher resolution for the impedance tube method. Since the impedance tube measurement experience close to no noise, the SNR(signal-to-noise ratio)[9] will be high compared to the free field measurement. Due to construction work being done nearby where the measurements were done, the background noise is non-negligible for the free field method. This will cause the SNR ratio to decrease significantly with an increase in the impulse response length. The trade-off is then a lower resolution for the free field measurements explaining why the results is bad for the lower frequencies. Comparing the results from methods 1 and 2 with the graph from the Mikis model, it is again clear that the general shape of the absorption-and reflection curve is close, but not equal, to one another. The model gives therefore a good estimate for the acoustic properties for the given test material but misses any high details in the curve due to its smooth lines.

If the free-field measurements were done in a less noisy room, the resolution and SNR for the frequency could have been increased to get more accurate results.

Considering the amount of equipment needed for method 1 over method 2 the best results are given by method 1. If the environment was quieter and may be done in an anechoic chamber to simulate no reflections from other surfaces than that of the test material, the second method could serve to be as good as the first method.

For method 1 there was little room for human error due to most of the equipment being pre-made. When inserting the ROCKWOOL into the sample holder it is important not to mess with the structural integrity of the material. This could alter the results. The material was pre-installed into the sample holder before the lab begun, and could have a bulging surface due to not fitting properly into the sample holder. In method 2, the measuring process where done by a ruler of length 1m. The precision was relative low and most of the measuring process where done by estimating distances to a certain degree. This could have a slight affect on the final result, but to such a low degree that it is negligible.

# 6 Conclusions

The acoustic properties of the test material, GLAVA, were found using two measurement methods and comparing these to Miki's mathematical model for porous materials. The sound absorption for the test material is above 0.9 for frequencies over 500Hz but below 0.5 low for frequencies below 200Hz. The acoustic impedance was found to be higher for the lower frequencies than that for the higher frequencies. Method 2 where affected by construction noise that had a slight impact on the results. It is clear that the test material ROCKWOOL is a good absorber for high frequencies, but not towards blocking out noise with frequency below 200Hz. For a musician playing the flute, a rehearsal room having the inside of the walls lined in sheets of GLAVA would be a decent choice for a sound absorbent material. On the other side of the scale, GLAVA would not be a sufficient sound absorber if the musician played the tuba.

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[8] www.github.com/erlenkb/TTT4250_Lab2/tree/main/Matlab, https://github.com/Erlenkb/TTT4250_Lab2/tree/main/Matlab

[9] Signal-To-Noise ratio(SNR), https://no.wikipedia.org/wiki/SNR.

# 7 Appendix

## Impedance_tube.m

```

%% Input
close all
clear
clc
rho_0 = 1.186;
p_0 = 101.325;

T = 20;                                   % Celcius
rho = 1.225;                              % kg/m3, density of air
c = 343.2*sqrt( ( T + 271 ) / 293 );    % m/s, sound speed in air

%1.004041 / c


dd  = 1;                                  % Horizontal distance mic - loudpeaker
hh  = 0.39;                               % Height loudspeaker
hm1 = 0.45;                               % Height mic 1
hm2 = 0.5;                                % Height mic 2

% From Figure 3 (lecture notes) ir Figure 2 (exercise sheet)
rd1 = sqrt ( (hh - hm1)^2 + dd^2 );  % Total direct distance travelled to mic 1
rd2 = sqrt ( (hh - hm2)^2 + dd^2 );
rd = sqrt((hh-(hm1+hm2)/2)^2 + dd^2);
rr1 = sqrt ( (hh + hm1)^2 + dd^2);   % Total reflected distance travelled to mic 1
rr2 = sqrt ( (hh + hm2)^2 + dd^2);
rr  = sqrt ( (hh + ((hm1+hm2)/2))^2 + dd^2);
theta1 = (pi/2 - acos(1/rr1));                          % Reflection angle
theta2 = (pi/2 - acos(1/rr2));
theta  = (pi/2 - acos(1/rr));

%% Importing measuremen

tmax      = 0.20;                        % Extract only direct and the primary reflected puls from the rockwool
%path2data =                             % Path to the folder containing the data
FFfile1   = 'Free_Field_45cm_Height_d1m.etx';             % Or .txt
FFfile2   = 'Free_Field_50cm_Height_d1m.etx';             % Or .txt
```

```
Psamp1_in = importdata([FFfile1],'\t',22);
Psamp2_in = importdata([FFfile2],'\t',22);

tt          = Psamp1_in.data(:,1) ;
dt          = tt(2) - tt(1);        % Sample time
fs          = 1/dt;                  % Sample frequency

idx_tmax   = 8e-3/(tt(2)-tt(1));                  % or, find( tt == tmax )
    ;

% Extract signal of interest
p1 = Psamp1_in.data(1:idx_tmax,2);
p2 = Psamp2_in.data(1:idx_tmax,2);
tt = tt(1:idx_tmax);

% Quality control of input signal, also for prep questions
figure(32)
subplot(2,2,1)
plot(tt, p1)
hold on
plot(tt, p2)
hold off
ylabel("Magnitude")
xlabel("Time [s]")
legend("p_{M1}", "p_{M2}","Location", "best")
grid on
title("Impulse response")
set(gca,'FontSize',12,'Fontweight','bold')
set(gcf,'units','centimeters','position',[2,1,29.7,21.0])

%% Frequency analysis, also for prep
n  = 2^nextpow2( size(p1,1) );
paddingnumber = n - size(p1,1);
p1 = padarray(p1, paddingnumber, 0, "post");
p2 = padarray(p2, paddingnumber, 0, "post");

ff = fs*(0:(n-1))/n;
frecvec1 = fft(p1,n);
frecvec2 = fft(p2,n);

% Plot it in dB
figure(32)
subplot(2,2,2);
semilogx(ff, 20*log10(frecvec1))
hold on
grid on
semilogx(ff, 20*log10(frecvec2))
hold off
xlabel("Frequency [Hz]");
title("FFT of the impulse response")
ylabel("Magnitude")
legend("FFT(p_{M1})","FFT(p_{M2})","Location", "best")
```

```
xlim([100,2000])
set(gca,'fontsize',12,'fontweight','bold'); % ++++

%% Computation

H12_Free = transpose(sqrt(( p2./p1).^2));
%figure(12)
%plot(ff, H12_Free)
%title("Transfer function")
%xlim([100 2000])

ww = 2*pi*ff;
k =  ww / c;            % Wave number

R_num = ((exp(-1i*k*rd2))/rd2)   -  H12_Free .*((exp(-1i*k*rd1))/rd1);
R_den = H12_Free.*((exp(-1i*k*rr1))/rr1)   - ((exp(-1i*k*rr2))/rr2);

R = R_num ./ R_den;

%% Stegvis utregning av Impedansen med og uten skalaren
scalar = (-1*rho*c) / cos(theta);
Z = (R+1) ./ (R-1);
Z = scalar * Z;

%% Formel for Impedanse
%Z = (-1*c*rho*(1+R)) ./ (cos(theta)*(R-1));

%Z = -1*(rho*c*(R+1)*sec(theta)) ./ (R-1);
alpha = 1 - abs(R).^2;
figure(32)
subplot(2,2,3)
semilogx(ff, alpha)
hold on
semilogx(ff, abs(R))
xlim([100 2000])
ylim([0 1])
grid on
title("Absorption-and Reflection coefficient")
xlabel("Frequency [Hz]")
ylabel("Magnitude")
legend("Absorption", "Reflection", "Location", "best")
set(gca,'fontsize',12,'fontweight','bold');

figure(32)
subplot(2,2,4)
semilogx(ff,real(Z),'r')
hold on
semilogx(ff,imag(Z),'b');
semilogx(ff,abs(Z),'k');
grid on
% ylim([-4 4])
xlim([100 2000]);
title('Acoustic Impedance Z')
```

```
xlabel('Frequency [Hz]' )
ylabel("Magnitude")
legend('Re[Z]', "Im[Z]", "|Z|", "Location", "best")
set(gca,'fontsize',12,'fontweight','bold');
hold off
exportgraphics(figure(32), ['Free_Field.png'],'Resolution',450)
```

# 8 Appendix

## Free_Field.m

```
close all
clear
clc

T   = 291;      % Assumed temperature
rho = 1.225;
c   = 343.2*sqrt(T/293);        % eq. (5)

x_1 = 0.180;        %Distance mic 1
d   = 0.1;          %Diameter of tube
s   = 0.08;         %Distance between microphones

%% Working frequency range 4.2
f_l =  100;
f_u = .58*c/d;
f_us = .45*c/s;

%% Load .etx files to Matlab
path2files = "C:\Users\erlen\Downloads\Lab2_TTT4250"
fileName1  = "Imp_tube_12.etx"
fileName2  = "Imp_tube_21.etx"

Tube_f1     = fileName1;
Tube_f2     = fileName2;
Psamp1      = importdata(Tube_f1,'\t',22); % 22 is the number of header
    lines
Psamp2      = importdata(Tube_f2,'\t',22);

%% Extract data
tt        = Psamp1.data(:,1)';
ind       = 150e-3/(tt(2)-tt(1));          % Extract a part of the signal

tt        = tt(1:ind);
p1(1,:)  = Psamp1.data(1:ind,2)'; % Mic 1 in coulmn 2 for rec. 1 - to p1
p1(2,:)  = Psamp1.data(1:ind,3)';
p2(1,:)  = Psamp2.data(1:ind,3)'; % Mic 1 in coulmn 2 for rec. 2 - to p1
p2(2,:)  = Psamp2.data(1:ind,2)';

%% Plot for quality control and prep question
figure(11)
subplot(2,2,1)
plot1=plot(tt,p1)
hold on
```

```
plot2=plot(tt,p2)
ylim([-3 1.5])
legend("p1^I", "p2^I", "p2^{II}","p1^{II}" ,"Location", "best")
hold off
grid on
xlabel('Time [s] '), ylabel('Magnitude'), title( 'Impulse response ');
set(gca,'fontsize',12,'fontweight','bold');
set(gcf,'units','centimeters','position',[2,1,29.7,21.0]) % Set size of plot to A4 size

%% Start computation
% FFT
n  = 2^nextpow2( size(p1,2) );                          % Number of element in signal into fft
fs = 44100;                             % (should be 2 to some power for better execution of fft)
df = fs / n;

ff = fs*(0:(n-1))/n;             % Frequency vector
ww = 2*pi*ff;                    % Angular frequency

frecvec1 = fft(p1(1,:) ,n);      % Repeat for all data
frecvec2 = fft(p1(2,:) ,n);
frecvec3 = fft(p2(2,:) ,n);      % Repeat for all data
frecvec4 = fft(p2(1,:) ,n);

%% Plot fft
figure(20)

semilogx(ff,20*log10(frecvec1));
hold on;
semilogx(ff,20*log10(frecvec2));
semilogx(ff,20*log10(frecvec3));
semilogx(ff,20*log10(frecvec4));
title("FFT of P1");
xlim([f_l f_u]);
hold off;

%% Transfer function - see ISO standard for equations

H12I  = frecvec2 ./ frecvec1;
H12II = frecvec3 ./ frecvec4;

HC    = sqrt(H12I ./ H12II);
H12   = H12I ./ HC;

HI    = exp(-1i*ww/c  *s );
HR    = exp( 1i*ww/c  *s );

%% Compute the absorption coefficient (alpha) and impedance (Z)
R =( (H12 - HI)./(HR - H12) ).*exp(2*1i*(ww/c)*x_1);    % eq. 17;

alpha = 1 - abs(R).^2;
```

```
Z = (1+R) ./ (1-R) * rho * c;

%% Plotting final results

figure(11)
subplot(2,2,2)
semilogx(ff,20*log10(frecvec1));
hold on;
semilogx(ff,20*log10(frecvec2));
semilogx(ff,20*log10(frecvec3));
semilogx(ff,20*log10(frecvec4));
xlabel("Frequency [Hz]");
ylabel("Magnitude");
title("FFT of the Impulse respons")
set(gca,'fontsize',12,'fontweight','bold');
legend("FFT(p1^I)","FFT(p2^I)","FFT(p2^{II})" ,"FFT(p1^{II})","Location
    ", "best")
grid on
%ylim
xlim([f_l f_u]);
hold off

figure(11)
subplot(2,2,3)
semilogx(ff,alpha);
hold on
semilogx(ff,abs(R));
grid on
legend("Absorption", "Reflection", "Location", "best")
hold off
xlim([f_l f_u]);
xlabel('Frequency [Hz]'), ylabel('Magnitude')
title('Absorption-and Reflection coefficient ')
set(gca,'fontsize',12,'fontweight','bold');


figure(11)
subplot(2,2,4)
semilogx(ff,real(Z),'r')
hold on
semilogx(ff,imag(Z),'b');
semilogx(ff,abs(Z),'k');
grid on
% ylim([-4 4])
xlim([f_l f_u]);
title('Acoustic Impedance Z')
xlabel('Frequency [Hz]' )
legend('Re[Z]', "Im[Z]", "|Z|", "Location", "best")
set(gca,'fontsize',12,'fontweight','bold');
hold off

%% Mikis model

```

```
f = [100:1:2000];
omega = 2*pi*f;

rho_0 = 1.225;       % [Kg.m-3] density at rest of air at 18C, 1atm
c_0   = 342.2;       % [m.s-1] speed of sound in air at 18C, 1atm
P_0   = 1.0132e+05; % [N.m-2] atmospheric pressure at 18C, 1atm
sigma = 9100        % [N.s.m-4]  static   air flow resistivity of material
h     = 0.1         % [m]  thickness   of material
X = f/sigma;

Z = rho_0*c_0*( 1 + 5.50*(X*1000).^(-0.632) ...
                        - i*8.43*(X*1000).^(-0.632) );

k = omega/c_0 .* (-i) .* ( 11.41*(X*1000).^(-0.618) ...
                              + i* (1 + 7.81*(X*1000).^(-0.618)
                                  ) );
Z = -1i.*Z./tan(k*h);

R = (Z-rho_0*c_0)./(Z+rho_0*c_0);
a = 1-abs(R).^2

figure(10)
subplot(1,2,2)
semilogx(f, real(Z))
hold on
semilogx(f, imag(Z))
semilogx(f, abs(Z))
grid on
title('Specific Impedance Z_C')
xlabel('Frequency [Hz]' )
ylabel("Magnitude")
legend('Re[Z]', "Im[Z]", "|Z|")
set(gca,'fontsize',12,'fontweight','bold');
set(gcf,'units','centimeters','position',[2,1,29.7,11.0])
hold off

figure(10)
subplot(1,2,1)
semilogx(f, abs(R))
hold on
semilogx(f, abs(a))
title('Absorption-and Reflection Coefficient')
xlabel('Frequency [Hz]')
ylabel("Magnitude")
legend('Absorption', "Reflection", "Location", "best")
set(gca,'fontsize',12,'fontweight','bold');
grid on
hold off

%% Save the results
exportgraphics(figure(10), ['Mikis_Model.png'],'Resolution',450)
exportgraphics(figure(11), ['Impedance_Tube.png'],'Resolution',450)
```

# 9 Appendix

Because of large data files, all etx files from the measurements are found in [8]. The description for the data files is seen in Table 9.1

Table 9.1: Name and description for the files used in this rapport. All files can be found in [8].

| filename | Description |
|---|---|
| Free_Field_45cm_height_d1m.etx | Free field measurement for the first microphone position |
| Free_Field_50cm_height_d1m.etx | Free field measurement for the second microphone position |
| Imp_tube_12 | Impedance tube measurement for the first microphone layout |
| Imp_tube_21 | Impedance tube measurement for the second microphone layout |