

TTT4250 - Acoustical Measurement Techniques

Laboratory Exercise: Impedance

Laboratory Exercise 2: Acoustic Impedance Measurement

performed by

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Report by

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Summary

ROCKWOOL is a commonly used insulation for standard homes when insulating the exterior walls. 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 as well as 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, under 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.

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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: ISO 10534-2

The first method measure the acoustic impedance of a test material through the normal incidence. This is done inside an impedance tube where the pressure waves inside the tube are assumed to be plane waves. 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_l 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 at the loudspeaker element. 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

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

and

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

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

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

where T is the temperature 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 microphone are interchanged between the two measurements. The transfer function for both measurements are found as

$$H_{12}^I = \frac{p_2}{p_1}, \quad H_{12}^{II} = \frac{p_2}{p_1} \quad (2.4)$$

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

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

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].

$$H_I = e^{-jks}, \quad H_R = e^{jks} \quad (2.6)$$

The sound reflection factor is given as

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

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

$$\alpha = 1 - |R|^2 \quad (2.8)$$

and the acoustic impedance as

$$Z = \frac{R + 1}{R - 1} \cdot \rho c_0 \quad (2.9)$$

where ρ 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 first microphone position 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. For consistency, the frequency area of interest remains the same as for 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 be found. The direct path r_d is given as

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

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

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

The angle of reflection is given as

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

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

$$\mathbf{R}(\theta) = \frac{\frac{e^{-jkr_{d2}}}{r_{d2}} - \mathbf{H}_{12} \cdot \frac{e^{-jkr_{d1}}}{r_{d1}}}{\frac{e^{-jkr_{r1}}}{r_{r1}} \cdot \mathbf{H}_{12} - \frac{e^{-jkr_{r2}}}{r_{r2}}} \quad (2.13)$$

where k is the wave number.

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

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

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, σ , of the test material. The characteristic impedance Z_C is calculated as

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

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

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

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: Measurements in an Impedance tube

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 the output 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, 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.

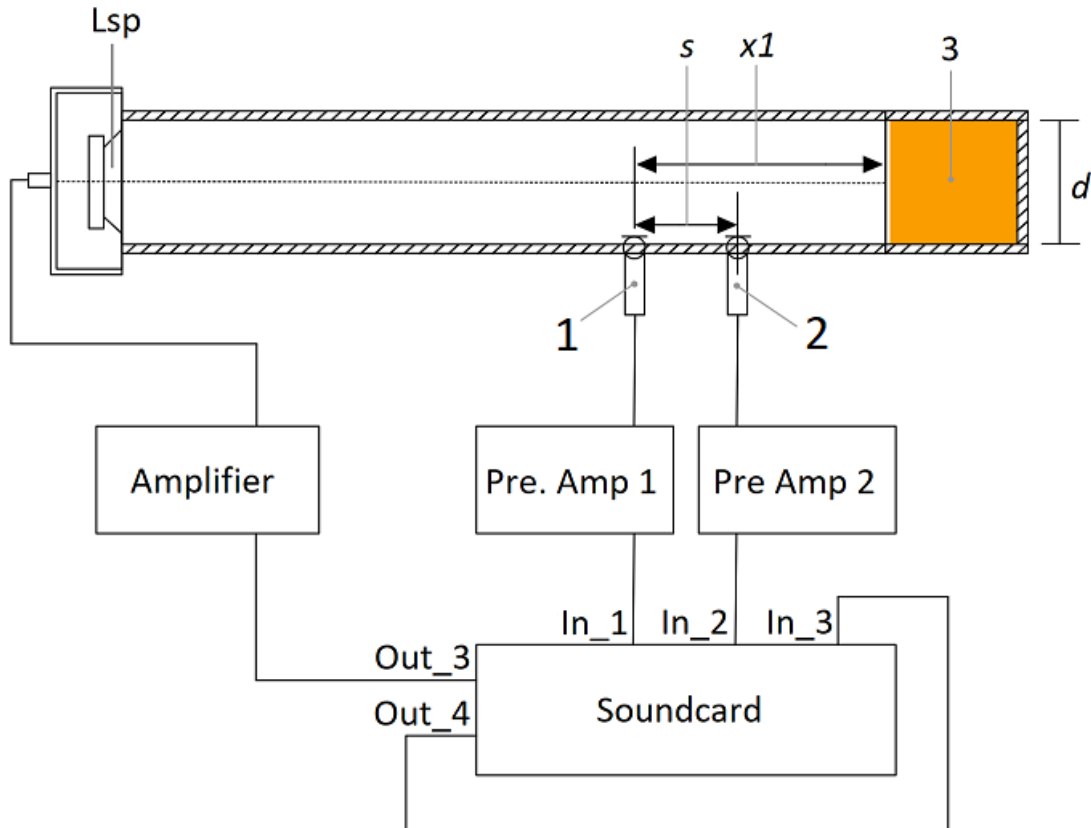


Figure 3.1: Layout of the setup for measurements done in the impedance tube. The numbers 1 and 2 marks the microphone positions used for the measurement with s marking the distance between the center of each microphone. x_1 is the distance from microphone 2 to the end of the impedance tube and where 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: Measurements done in a free field

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	Brüel&Kjær Type 1708	100407&100406
Soundcard	Roland Studio-Capture	
Pressure Microphone	Norsonic Type 1201/30490	
Microphone	Brüel&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 from 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

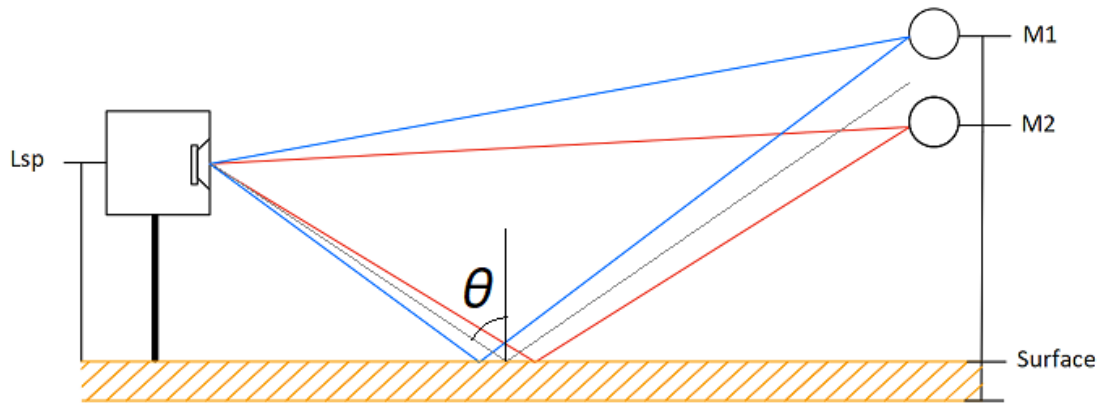


Figure 3.2: The setup for the free field test method as seen from the side. The Lsp is the loudspeaker used for the test, and $M1$ and $M2$ is the two microphone positions used. The bottom layer marked in orange is the test material and are marked as *Surface* in the figure. The blue and red lines show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

4 Results

4.1 Method 1: Impedance Tube Measurements

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 of interest 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 frequency range of 100-1923.9Hz. 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 inneccient 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 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.

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

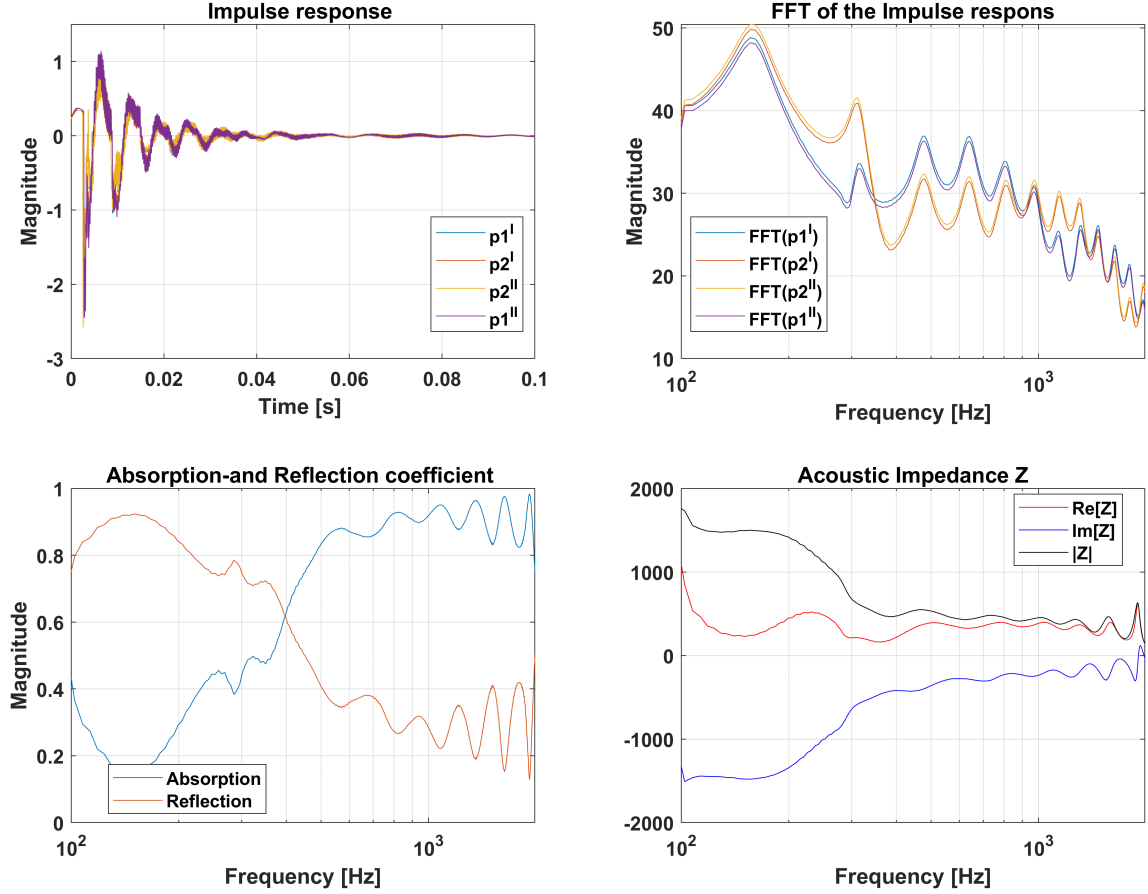


Figure 4.1: This 2x2 picture array consist of plots of the impulse response, FFT of the impulse response, Absorption-and Reflection coefficient and the acoustic impedance as calculated in Chapter 3.1. The Roman number I and II in the superscript for the pressure values indicate which of the two measurements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

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 results 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 9100 Pa s/m^2 and the thickness 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 ??.

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
θ_1	0.8721	rad
θ_2	0.8435	rad
θ_{mean}	0.8577	rad

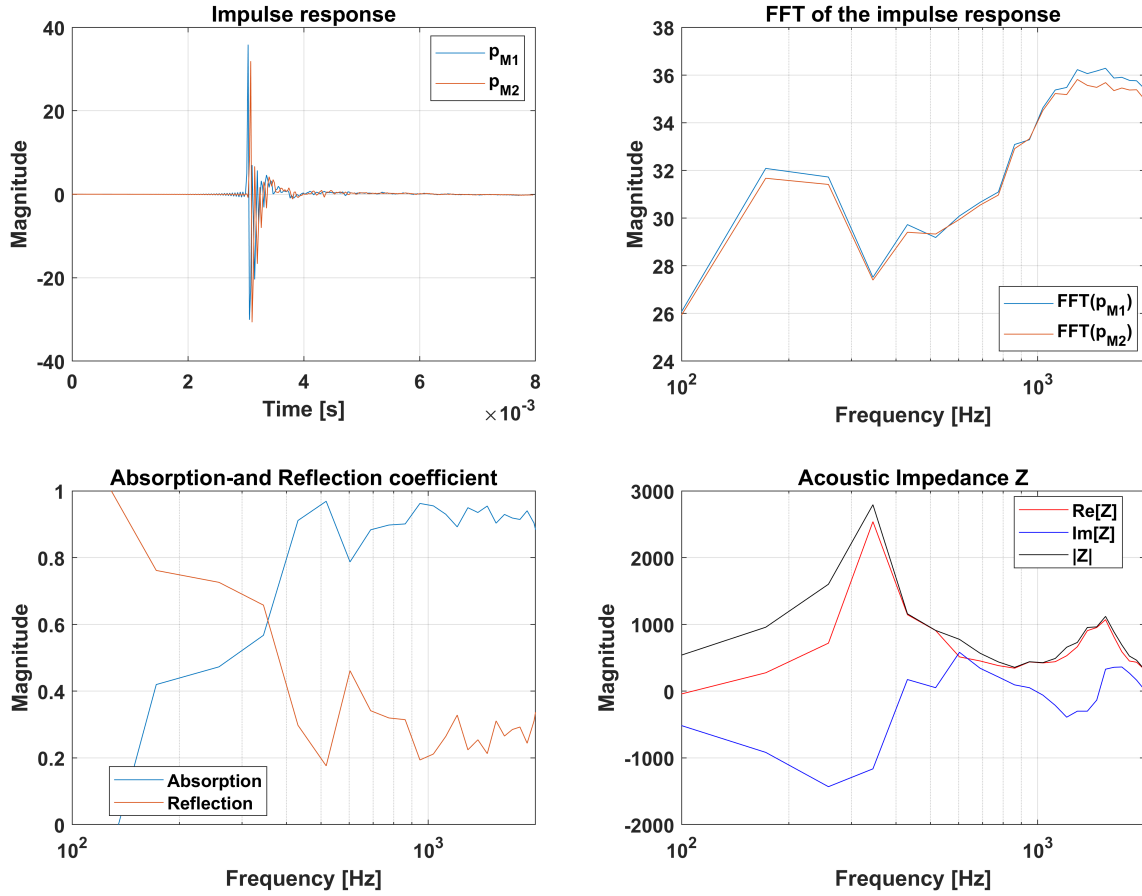


Figure 4.2: This 2x2 picture array consist of plots of the impulse response, FFT of the impulse response, Absorption-and Reflection coefficient and the acoustic impedance as calculated in Chapter 3.2. The Roman number *I* and *II* in the superscript for the pressure values indicate which of the two measurements 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, method 1 seem to be closest. The impedance curve for method 2 has a slight increase at 1500Hz which is an abnormality compared to the two other methods as well as a very

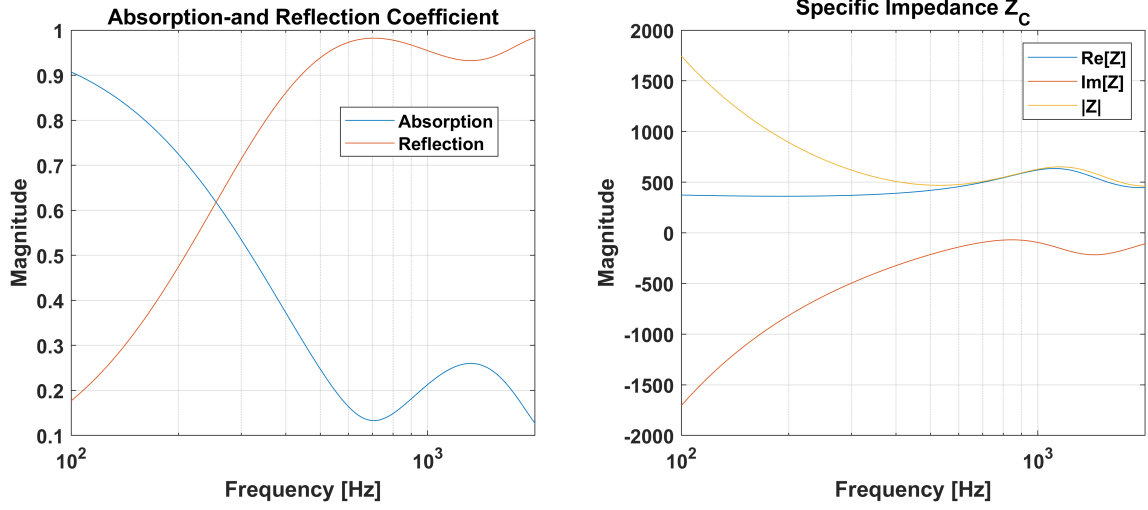


Figure 4.3: The left-most plot show the absorption-and reflection coefficient and the right-most plot show the specific impedance. The plots are calculated using Mikis model[4].

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 signal-to-noise(SNR) ratio 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. 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 very high for frequencies over 500Hz but is very 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 this will not be good towards blocking out sound for a human talking, low frequent noise produces by vehicles and more.

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7 Appendix

Impedance_tube.m

```
1
2 %% Input
3 close all
4 clear
5 clc
6 rho_0 = 1.186;
7 p_0 = 101.325;
8
9 T = 20; % Celcius
10 rho = 1.225; % kg/m3, density of air
11 c = 343.2*sqrt((T + 271) / 293); % m/s, sound speed in air
12
13 %1.004041 / c
14
15
16 dd = 1; % Horizontal distance mic -
    loudspeaker
17 hh = 0.39; % Height loudspeaker
18 hm1 = 0.45; % Height mic 1
19 hm2 = 0.5; % Height mic 2
20
21 % From Figure 3 (lecture notes) ir Figure 2 (exercise sheet)
22 rd1 = sqrt((hh - hm1)^2 + dd^2); % Total direct distance travelled
    to mic 1
23 rd2 = sqrt((hh - hm2)^2 + dd^2);
24 rd = sqrt(((hh - (hm1 + hm2) / 2))^2 + dd^2);
25 rr1 = sqrt((hh + hm1)^2 + dd^2); % Total reflected distance
    travelled to mic 1
26 rr2 = sqrt((hh + hm2)^2 + dd^2);
27 rr = sqrt((hh + ((hm1 + hm2) / 2))^2 + dd^2);
28 theta1 = (pi/2 - acos(1/rr1)); %
    Reflection angle
29 theta2 = (pi/2 - acos(1/rr2));
30 theta = (pi/2 - acos(1/rr));
31
32 %% Importing measuremen
33
34 tmax = 0.20; % Extract only direct and the
    primary reflected puls from the rockwool
35 %path2data = % Path to the folder containing the
    data
36 FFfile1 = 'Free_Field_45cm_Height_d1m.etx'; % Or .txt
37 FFfile2 = 'Free_Field_50cm_Height_d1m.etx'; % Or .txt
```

```

38
39 Psamp1_in = importdata([FFfile1], '\t', 22);
40 Psamp2_in = importdata([FFfile2], '\t', 22);
41
42 tt          = Psamp1_in.data(:, 1) ;
43 dt          = tt(2) - tt(1);          % Sample time
44 fs          = 1/dt;                    % Sample frequency
45
46 idx_tmax    = 8e-3/(tt(2)-tt(1));      % or, find( tt == tmax )
47          ;
48 % Extract signal of interest
49 p1 = Psamp1_in.data(1:idx_tmax, 2);
50 p2 = Psamp2_in.data(1:idx_tmax, 2);
51 tt = tt(1:idx_tmax);
52
53 % Quality control of input signal, also for prep questions
54 figure(32)
55 subplot(2,2,1)
56 plot(tt, p1)
57 hold on
58 plot(tt, p2)
59 hold off
60 ylabel("Magnitude")
61 xlabel("Time [s]")
62 legend("p_{M1}", "p_{M2}", "Location", "best")
63 grid on
64 title("Impulse response")
65 set(gca, 'FontSize', 12, 'Fontweight', 'bold')
66 set(gcf, 'units', 'centimeters', 'position', [2, 1, 29.7, 21.0])
67
68 %% Frequency analysis, also for prep
69 n = 2^nextpow2( size(p1, 1) );
70 paddingnumber = n - size(p1, 1);
71 p1 = padarray(p1, paddingnumber, 0, "post");
72 p2 = padarray(p2, paddingnumber, 0, "post");
73
74 ff = fs*(0:(n-1))/n;
75 fvecvec1 = fft(p1, n);
76 fvecvec2 = fft(p2, n);
77
78 % Plot it in dB
79 figure(32)
80 subplot(2,2,2);
81 semilogx(ff, 20*log10(fvecvec1))
82 hold on
83 grid on
84 semilogx(ff, 20*log10(fvecvec2))
85 hold off
86 xlabel("Frequency [Hz]");
87 title("FFT of the impulse response")
88 ylabel("Magnitude")
89 legend("FFT(p_{M1})", "FFT(p_{M2})", "Location", "best")

```

```

90 xlim([100,2000])
91 set(gca,'fontsize',12,'fontweight','bold'); % ++++
92
93 %% Computation
94
95 H12_Free = transpose(sqrt((p2./p1).^2));
96 figure(12)
97 plot(ff, H12_Free)
98 title("Transfer function")
99 xlim([100 2000])
100
101 ww = 2*pi*ff;
102 k = ww / c; % Wave number
103
104 R_num = ((exp(-1i*k*rd2))/rd2) - H12_Free .* ((exp(-1i*k*rd1))/rd1);
105 R_den = H12_Free .* ((exp(-1i*k*rr1))/rr1) - ((exp(-1i*k*rr2))/rr2);
106
107 R = R_num ./ R_den;
108
109 %% Stegvis utregning av Impedansen med og uten skalaren
110 scalar = (-1*rho*c) / cos(theta);
111 Z = (R+1) ./ (R-1);
112 Z = scalar * Z;
113
114 %% Formel for Impedanse
115 %Z = (-1*c*rho*(1+R)) ./ (cos(theta)*(R-1));
116
117 %Z = -1*(rho*c*(R+1)*sec(theta)) ./ (R-1);
118 alpha = 1 - abs(R).^2;
119 figure(32)
120 subplot(2,2,3)
121 semilogx(ff, alpha)
122 hold on
123 semilogx(ff, abs(R))
124 xlim([100 2000])
125 ylim([0 1])
126 grid on
127 title("Absorption-and Reflection coefficient")
128 xlabel("Frequency [Hz]")
129 ylabel("Magnitude")
130 legend("Absorption", "Reflection", "Location", "best")
131 set(gca,'fontsize',12,'fontweight','bold');
132
133 figure(32)
134 subplot(2,2,4)
135 semilogx(ff, real(Z), 'r')
136 hold on
137 semilogx(ff, imag(Z), 'b');
138 semilogx(ff, abs(Z), 'k');
139 grid on
140 % ylim([-4 4])
141 xlim([100 2000]);
142 title('Acoustic Impedance Z')

```

```

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

```

8 Appendix

Free_Field.m

```
1 close all
2 clear
3 clc
4
5 T = 291; % Assumed temperature
6 rho = 1.225;
7 c = 343.2*sqrt(T/293); % eq. (5)
8
9 x_1 = 0.180; %Distance mic 1
10 d = 0.1; %Diameter of tube
11 s = 0.08; %Distance between microphones
12
13 %% Working frequency range 4.2
14 f_l = 100;
15 f_u = .58*c/d;
16 f_us = .45*c/s;
17
18 %% Load .etx files to Matlab
19 path2files = "C:\Users\erlen\Downloads\Lab2_TTT4250"
20 fileName1 = "Imp_tube_12.etx"
21 fileName2 = "Imp_tube_21.etx"
22
23 Tube_f1 = fileName1;
24 Tube_f2 = fileName2;
25 Psamp1 = importdata(Tube_f1, '\t', 22); % 22 is the number of header
    lines
26 Psamp2 = importdata(Tube_f2, '\t', 22);
27
28 %% Extract data
29 tt = Psamp1.data(:, 1)';
30 ind = 150e-3/(tt(2)-tt(1)); % Extract a part of the signal
31
32 tt = tt(1:ind);
33 p1(1,:) = Psamp1.data(1:ind, 2)'; % Mic 1 in coulumn 2 for rec. 1 - to p1
34 p1(2,:) = Psamp1.data(1:ind, 3)';
35 p2(1,:) = Psamp2.data(1:ind, 3)'; % Mic 1 in coulumn 2 for rec. 2 - to p1
36 p2(2,:) = Psamp2.data(1:ind, 2)';
37
38 %% Plot for quality control and prep question
39 figure(11)
40 subplot(2, 2, 1)
41 plot1=plot(tt, p1)
42 hold on
```

```

43 plot2=plot(tt,p2)
44 ylim([-3 1.5])
45 legend("p1^I", "p2^I", "p2^{II}", "p1^{II}" ,"Location", "best")
46 hold off
47 grid on
48 xlabel('Time [s] '), ylabel('Magnitude'), title('Impulse response ');
49 set(gca,'fontsize',12,'fontweight','bold');
50 set(gcf,'units','centimeters','position',[2,1,29.7,21.0]) % Set size of
    plot to A4 size
51
52 %% Start computation
53 % FFT
54 n = 2^nextpow2( size(p1,2) ); % Number of
    element in signal into fft
55 fs = 44100; % (should be 2 to some power
    for better execution of fft)
56 df = fs / n;
57
58 ff = fs*(0:(n-1))/n; % Frequency vector
59 ww = 2*pi*ff; % Angular frequency
60
61 frecv1 = fft(p1(1,:),n); % Repeat for all data
62 frecv2 = fft(p1(2,:),n);
63 frecv3 = fft(p2(2,:),n); % Repeat for all data
64 frecv4 = fft(p2(1,:),n);
65
66 %% Plot fft
67 figure(20)
68
69 semilogx(ff,20*log10(frecv1));
70 hold on;
71 semilogx(ff,20*log10(frecv2));
72 semilogx(ff,20*log10(frecv3));
73 semilogx(ff,20*log10(frecv4));
74 title("FFT of P1");
75 xlim([f_l f_u]);
76 hold off;
77
78 %% Transfer function – see ISO standard for equations
79
80 H12I = frecv2 ./ frecv1;
81 H12II = frecv3 ./ frecv4;
82
83 HC = sqrt(H12I ./ H12II);
84 H12 = H12I ./ HC;
85
86 HI = exp(-1i*ww/c *s );
87 HR = exp( 1i*ww/c *s );
88
89 %% Compute the absorption coefficient (alpha) and impedance (Z)
90 R =( (H12 - HI)./(HR - H12) ).*exp(2*1i*(ww/c)*x_1); % eq. 17;
91
92 alpha = 1 - abs(R).^2;

```



```

93 Z = (1+R) ./ (1-R) * rho * c;
94
95 %% Plotting final results
96
97 figure(11)
98 subplot(2,2,2)
99 semilogx(ff,20*log10(frecvec1));
100 hold on;
101 semilogx(ff,20*log10(frecvec2));
102 semilogx(ff,20*log10(frecvec3));
103 semilogx(ff,20*log10(frecvec4));
104 xlabel("Frequency [Hz]");
105 ylabel("Magnitude");
106 title("FFT of the Impulse respons")
107 set(gca,'fontsize',12,'fontweight','bold');
108 legend("FFT(p1^I)", "FFT(p2^I)", "FFT(p2^{II})", "FFT(p1^{II})", "Location",
        "", "best")
109 grid on
110 %ylim
111 xlim([f_l f_u]);
112 hold off
113
114 figure(11)
115 subplot(2,2,3)
116 semilogx(ff,alpha);
117 hold on
118 semilogx(ff,abs(R));
119 grid on
120 legend("Absorption", "Reflection", "Location", "best")
121 hold off
122 xlim([f_l f_u]);
123 xlabel('Frequency [Hz]'), ylabel('Magnitude')
124 title('Absorption-and Reflection coefficient')
125 set(gca,'fontsize',12,'fontweight','bold');
126
127
128 figure(11)
129 subplot(2,2,4)
130 semilogx(ff,real(Z),'r')
131 hold on
132 semilogx(ff,imag(Z),'b');
133 semilogx(ff,abs(Z),'k');
134 grid on
135 % ylim([-4 4])
136 xlim([f_l f_u]);
137 title('Acoustic Impedance Z')
138 xlabel('Frequency [Hz]')
139 legend('Re[Z]', "Im[Z]", "|Z|", "Location", "best")
140 set(gca,'fontsize',12,'fontweight','bold');
141 hold off
142
143 %% Mikis model
144

```

```

145 f = [100:1:2000];
146 omega = 2*pi*f;
147
148 rho_0 = 1.225;           % [Kg.m-3] density at rest of air at 18C, 1atm
149 c_0    = 342.2;          % [m.s-1] speed of sound in air at 18C, 1atm
150 P_0    = 1.0132e+05;     % [N.m-2] atmospheric pressure at 18C, 1atm
151 sigma = 9100             % [N.s.m-4] static air flow resistivity of material
152 h      = 0.1             % [m] thickness of material
153 X = f/sigma;
154
155 Z = rho_0*c_0*( 1 + 5.50*(X*1000).^(-0.632) ...
156               - i*8.43*(X*1000).^(-0.632) );
157
158 k = omega/c_0 .* (-i) .* ( 11.41*(X*1000).^(-0.618) ...
159               + i*(1 + 7.81*(X*1000).^(-0.618)
160               ) );
160 Z = -1i.*Z./tan(k*h);
161
162 R = (Z-rho_0*c_0)./(Z+rho_0*c_0);
163 a = 1-abs(R).^2
164
165 figure(10)
166 subplot(1,2,2)
167 semilogx(f, real(Z))
168 hold on
169 semilogx(f, imag(Z))
170 semilogx(f, abs(Z))
171 grid on
172 title('Specific Impedance Z_C')
173 xlabel('Frequency [Hz]')
174 ylabel('Magnitude')
175 legend('Re[Z]', 'Im[Z]', '|Z|')
176 set(gca, 'fontsize', 12, 'fontweight', 'bold');
177 set(gcf, 'units', 'centimeters', 'position', [2,1,29.7,11.0])
178 hold off
179
180 figure(10)
181 subplot(1,2,1)
182 semilogx(f, abs(R))
183 hold on
184 semilogx(f, abs(a))
185 title('Absorption-and Reflection Coefficient')
186 xlabel('Frequency [Hz]')
187 ylabel('Magnitude')
188 legend('Absorption', 'Reflection', 'Location', 'best')
189 set(gca, 'fontsize', 12, 'fontweight', 'bold');
190 grid on
191 hold off
192
193 %% Save the results
194 exportgraphics(figure(10), ['Mikis_Model.png'], 'Resolution', 450)
195 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