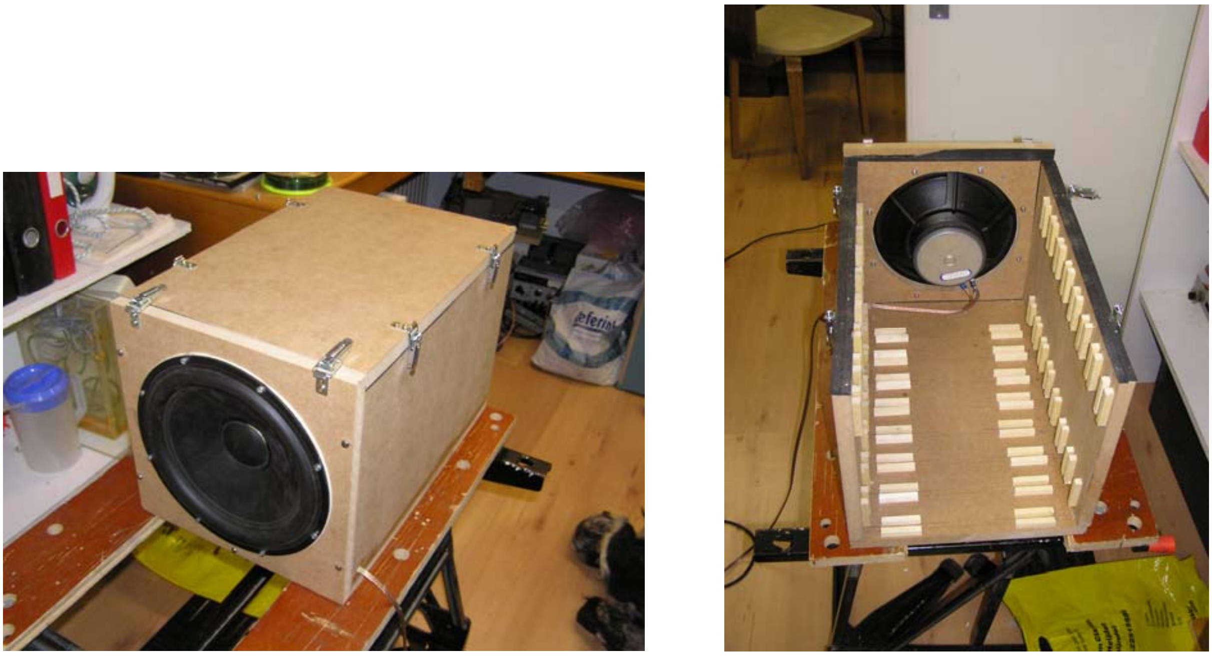
U-frame experiments and measurements

by Gerard Janssen

A test U-frame was built as shown in the pictures below. The internal measures of the rectangular pipe are 45cm x 27cm x 27cm. The top can be removed to add damping material, partial partitioning or a grid.



Figuur 1: Test box for U-frame measurements.

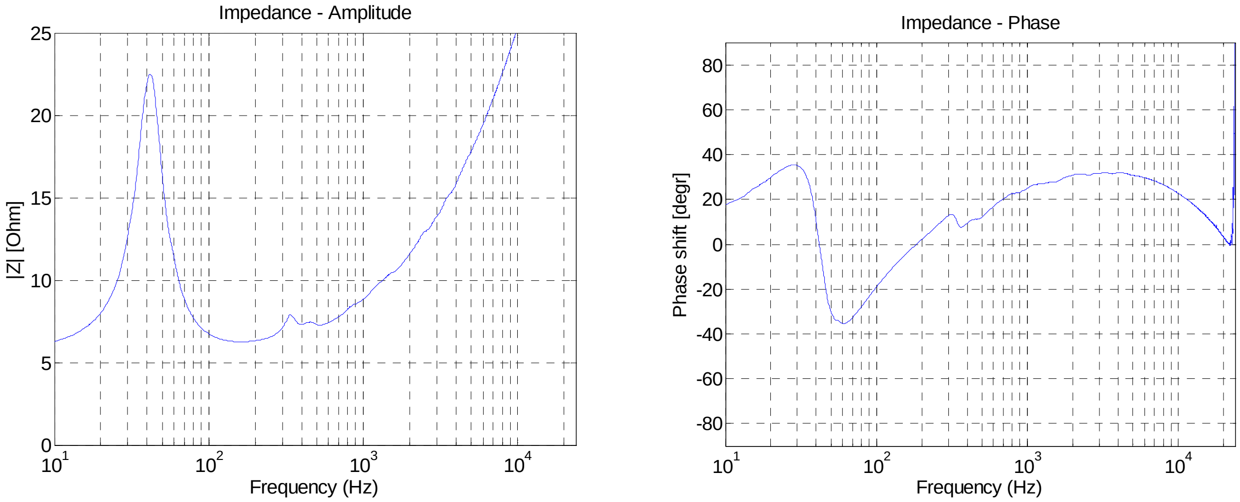


Figure 2: Impedance (amplitude and phase) of the loudspeaker in free space.

The loudspeaker is an old 25cm woofer SEAS P25REX-DD which I had lying around. The basic Thiele-Small parameters were measured in free space as:

- f_s = 41.5 Hz - R_{DC} = 6.35Ω - Q_{ms} = 2.68
- Q_{es} = 1.10 - Q_{ts} = 0.76.

The absolute value of the impedance and its phase are shown in figure 2. The small bump near 350 Hz is an irregularity of the loudspeaker.

1. Measurements in the empty box.

1.1 Impedance measurement

The measured impedance of the loudspeaker in the empty box without any damping material is as shown in figure 3 and the derived TS-parameters are:

- f_s = 36.6 Hz - R_{DC} = 6.35Ω - Q_{ms} = 2.87
- Q_{es} = 1.20 - Q_{ts} = 0.83.

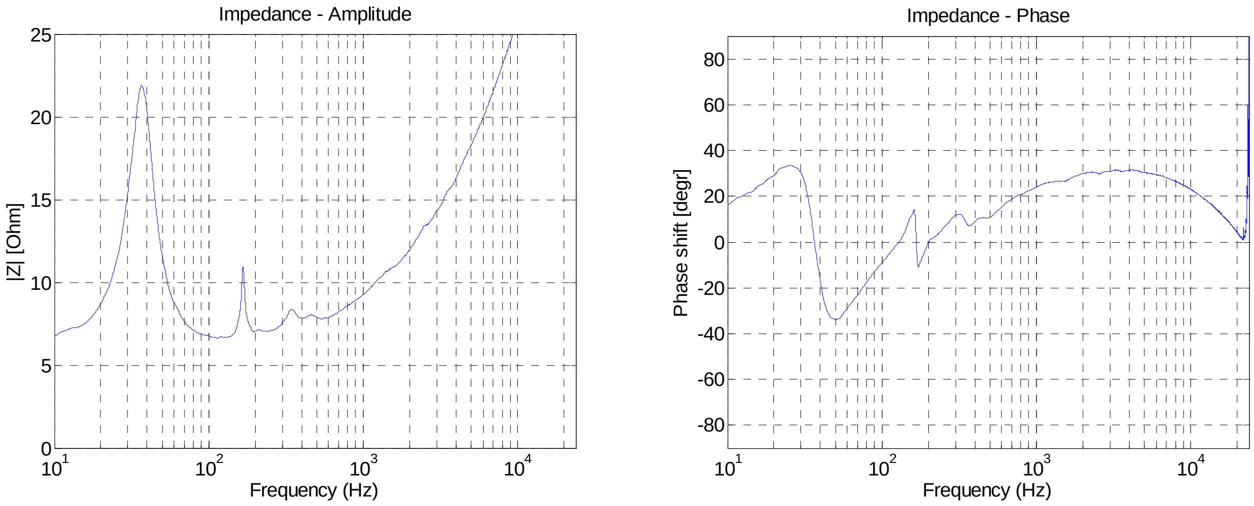


Figure 3: Impedance (amplitude and phase) of the loudspeaker in the empty U-frame.

From these results the following observations can be made:

1. The resonance frequency has been decreased by the increased effective mass of the loudspeaker due to the air in the pipe which has to be "dragged along".
2. A sharp high-Q resonance peak has appeared at $f_{\lambda/4}$ = 167 Hz due to the pipe resonance at a quarter wavelength. Based on the length pf the pipe, this resonance would be expected at a frequency of 343/(4*0.45) = 190.5 Hz. However, the effective length of a $\lambda/4$-pipe is slightly longer than the physical length. In [1], the effective length $l_{eff} = L + \phi/2$ is used with ϕ equal to the cross-section of the pipe. Based on the measured resonance frequency $f_{\lambda/4}$ the effective length of the pipe is 0.504 m.
3. The loudspeaker resonance and the pipe-resonance hardly affect each other. This means that both mass-compliance systems operate rather independent of each other. This is a big difference between the U-frame and a transmission line (TL) system. The pipe-resonance of a TL system is usually chosen much lower close to the loudspeaker resonance. This results in two impedance peaks, one below and one above the loudspeaker resonance, because both mass-compliance systems interact. A similar interaction is found in a bass-reflex enclosure.

1.2 Frequency response measurements

The frequency response is measured at the front and the rear of the U-frame. Both measurements are near-field measurements with the microphone place a few millimeters from the loudspeaker cone at the front and the cross-sectional plain at the rear, as shown in figure 4.

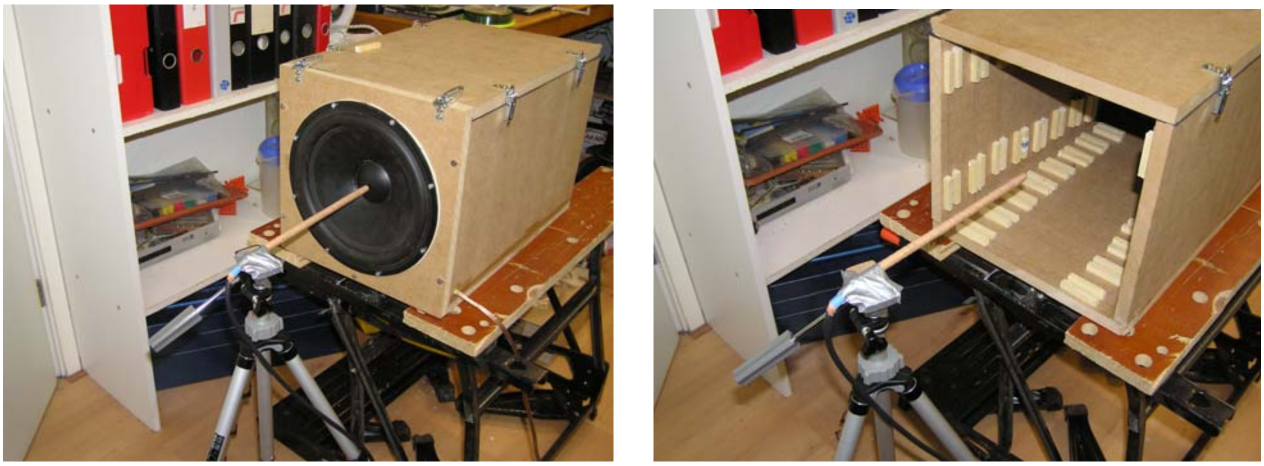


Figure 4: Near-field measurement setup for the front and the rear of the U-frame.

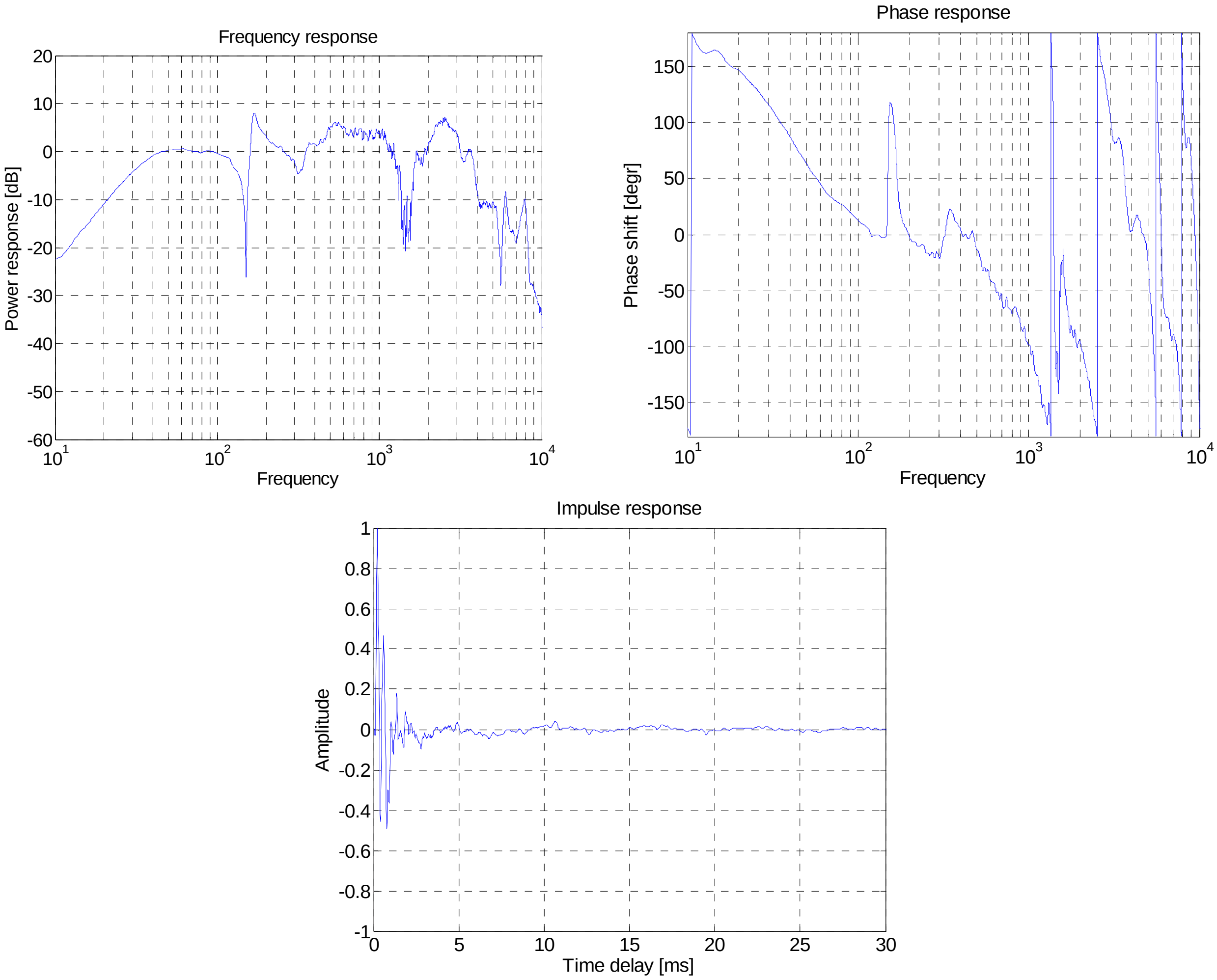


Figure 5: Amplitude-, phase- and impulse response at the front of the empty U-frame.

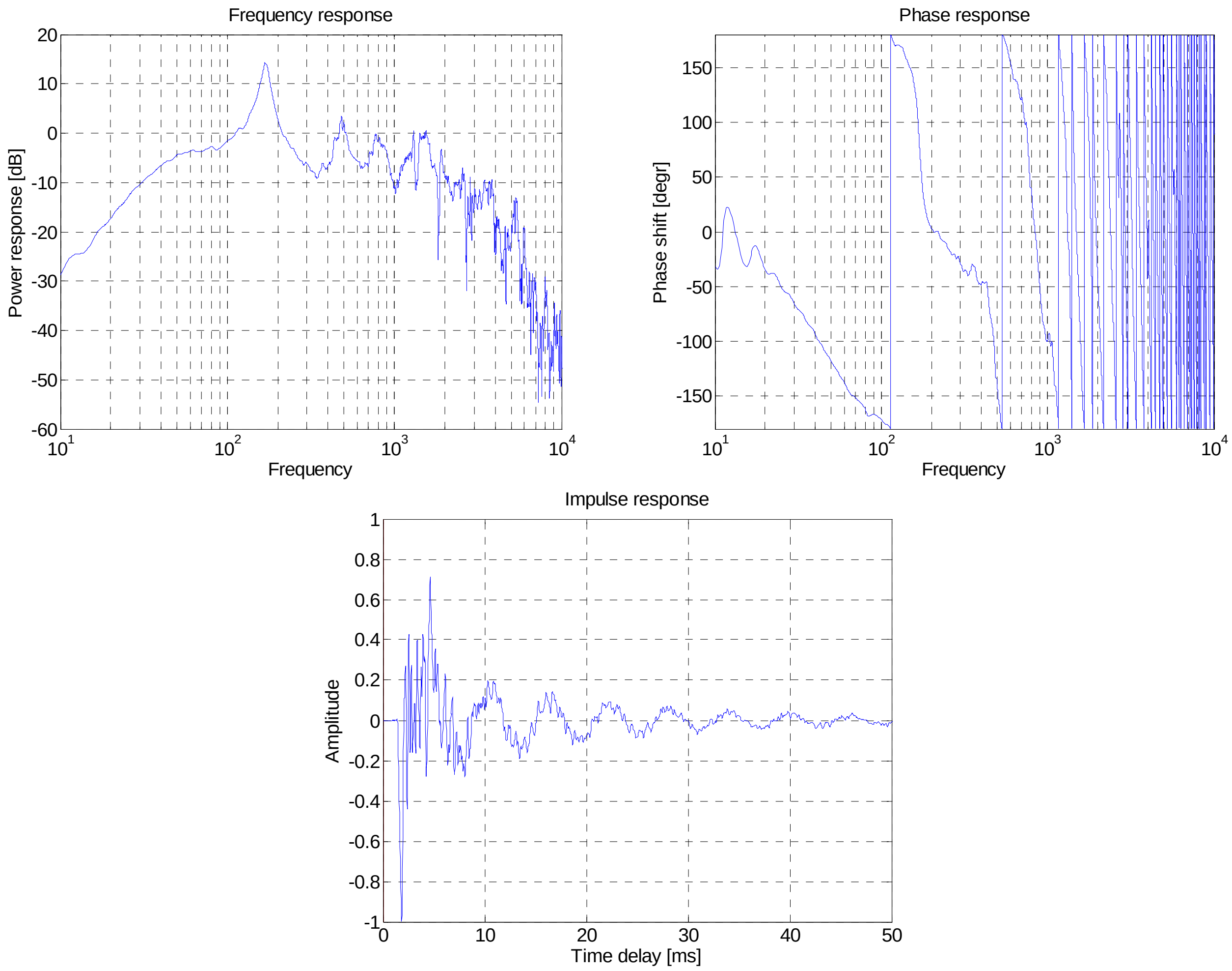


Figure 6: Amplitude-, phase- and impulse response at the rear of the empty U-frame.

In addition to the $\lambda/4$-resonance, the impulse responses at the front and the rear show a stark resonance at about 2 kHz. I don't know the reason for this resonance. Sometimes it can be clearly heard at the rear: cavity resonances?, loudspeaker basket? It does not disappear or change when I fixate the U-frame side-panels. So it is likely not due to panel vibration.

The front and rear responses show the following differences:

1. they are 180^o out of phase,
2. there should be an extra time delay for the rear due to the propagation delay of the pipe,. This is seen in the impulse responses, however, not from the phase difference at low frequencies between the front and the rear,
3. higher frequencies are attenuated more at the rear because the pipe and the presence of the loudspeaker magnet and basket show a lowpass characteristic,
3. The power level at the rear is lower because the cross-section area of the rear is larger than the effective cone area which results in a lowering of the pressure at the rear.

How can we compare the front and rear responses? For this comparison I have made the assumption that the volume displacement at the front and the rear of an empty U-frame should be the identical for low frequencies, i.e. in the far-field front and rear produce the same sound pressure. This is used as reference level. For very low frequencies the expected phase difference is 180^o plus a phase shift due to the propagation delay of the pipe.

When we add damping material in the pipe, the following can be expected:
1. the level and frequency response of the rear will change,
2. the level (and maybe also the frequency response) of the front will change (but less than at the rear) due to a different acoustic load/impedance at the woofer's backside. In order to observe these differences, all measurements are made at a constant rms-amplitude of the loudspeaker input signal as measured with an HP3400A.

For the empty U-frame, the sound level at the back is a factor 2.05 less than than the level at the front, i.e. about 3 dB. The required amplitude correction is almost perfectly equal to $S_{rear} / S_{LS} = 27^2 / 350 = 2.08$, where S_{rear} is the cross section of the pipe and S_{LS} is the effective area of the woofer cone.

In Matlab software developed for this purpose, the responses for the front and the rear can be compared after making the desired corrections in amplitude and phase. Also it is possible to add a time-delay and sum the resulting responses with the phase taken into account. In figure 7, the corrected amplitude and phase responses for the front (180^o phase shifted) and the rear are shown.

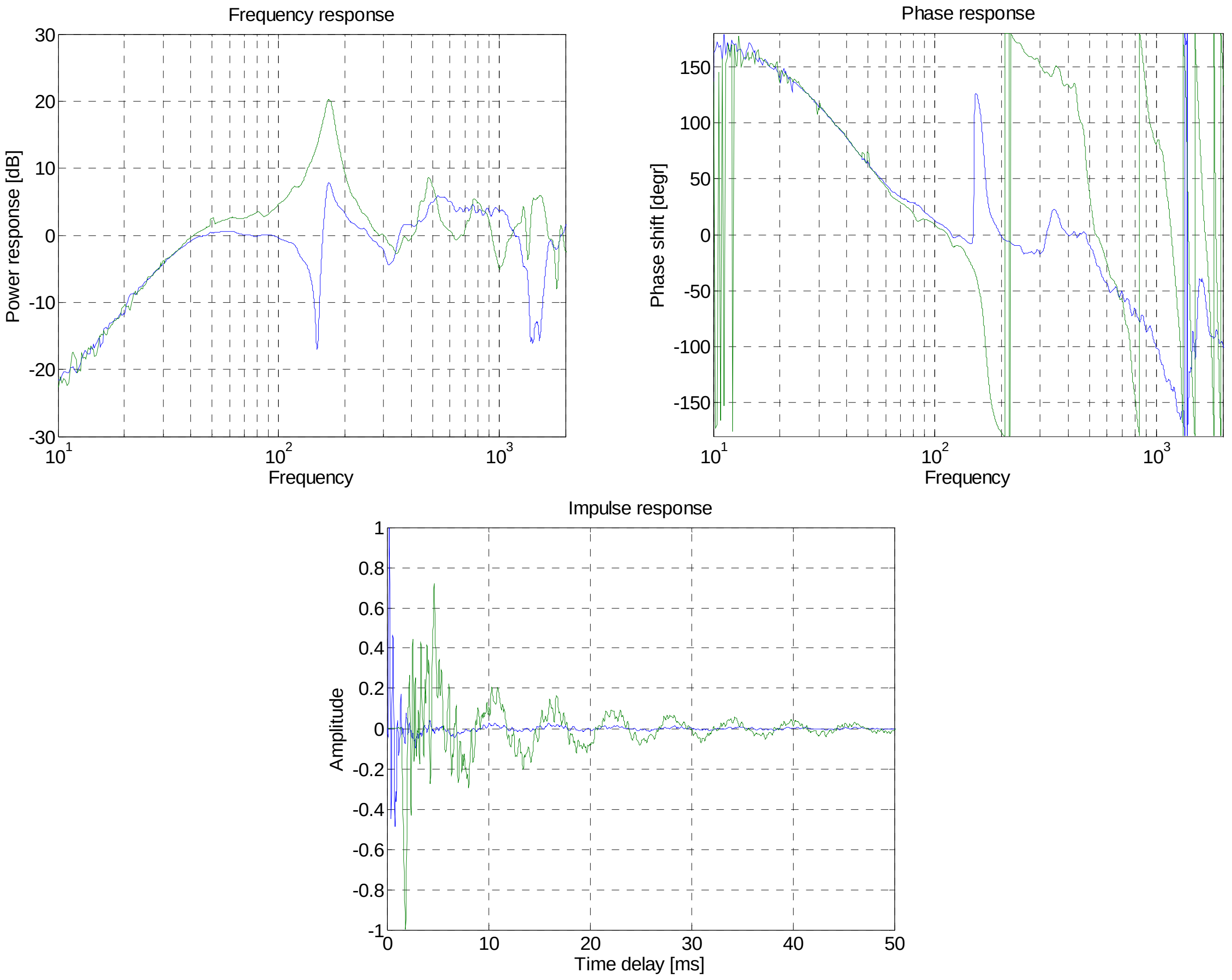


Figure 7: Amplitude (corrected), phase and impulse responses for the front (blue, with 180^o additional phase shift in the phase plot) and rear (green).

The measured responses for the front $H_f(f)$ and rear $H_r(f)$ are almost perfectly 180° out of phase for low frequencies (below 100 Hz). This is rather unexpected because an additional frequency dependent phase shift due to the propagation delay in the pipe seems to be missing. At 50Hz, a 1.3 ms delay would result in a well detectable phase shift of 23.4°. This observation is also made by John Kreskovski, [2]. He says: "The reason is that the quarter wave resonance introduces a phase shift that cancels the excess rear phase from the propagation delay. This internal delay must be restored by damping the U-frame to attenuate the resonance.". This explanation is not really satisfying: what is going on? It is rather strange/unexpected that the rather high-Q $\lambda/4$-resonance at 170 Hz causes such a strong influence on the phase at frequencies < 40 Hz, whereas the pipe-resonance is well decoupled of the mass-compliance system of the loudspeaker. Siegfried Linkwitz derives this behavior based on the transmission-line analogy for the U-frame in [3], where he shows that the phase shift and radiation pattern are very much dependent on the impedance matching at the end of the pipe.

Figure 8 shows the responses at the front $H_{front}(f)$ and at the rear $H_{rear}(f)$ when combining the near-field responses in the following way:

$$\begin{aligned} H_{front}(f) &= H_f(f) + \frac{S_{rear}}{S_{LS}} H_r(f) e^{-j2\pi f \tau_d} \\ H_{rear}(f) &= H_f(f) e^{-j2\pi f \tau_d} + \frac{S_{rear}}{S_{LS}} H_r(f) \end{aligned} \qquad (1.1)$$

in order to get an impression of the radiated sound pressure at the front and the rear. In eqn. (1.1) the variable τ_d is the propagation-delay due to the distance difference between the front and the rear outside the pipe and is set to $\tau_d = 0.45/343 = 1.31$ms. Note that the propagation delay for the sound wave traveling outside the pipe will be slightly larger than for the wave traveling inside the pipe. Also when adding damping material in the pipe, the propagation delay in the pipe will increase due to the decreasing sound speed as also shown by Martin J. King in [1].

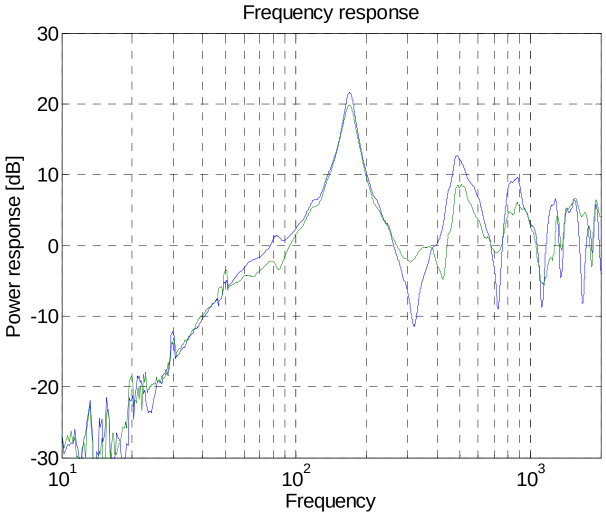


Figure 8: Combined responses for the front (blue) and rear (green) after amplitude- and delay-time correction.

The front and rear response are nearly similar with a clear omission of the attenuation of the combined rear signal when compared to the front, which is so characteristic for the cardioid U-frame response. The undamped U-frame acts like a dipole. Also it is observed that the combined response at the front shows a drop with 6 dB/oct for the flat part in Figure 7, which increases below te woofer resonance to about 18 dB/oct. According to John Kreshkovsky, adding damping material in the pipe should restore the lost propagation delay in the pipe and thus improve this behavior.

To check this, an delay of $\tau_d = 1.31$ ms is added to the rear response and again the total responses:

$$\begin{aligned} H_{front}(f) &= H_f(f) + \frac{S_{rear}}{S_{LS}} H_r(f) e^{-j4\pi f \tau_d} \\ H_{rear}(f) &= H_f(f) e^{-j2\pi f \tau_d} + \frac{S_{rear}}{S_{LS}} H_r(f) e^{-j2\pi f \tau_d} \end{aligned} \tag{1.2}$$

are determined and shown in figure 9.

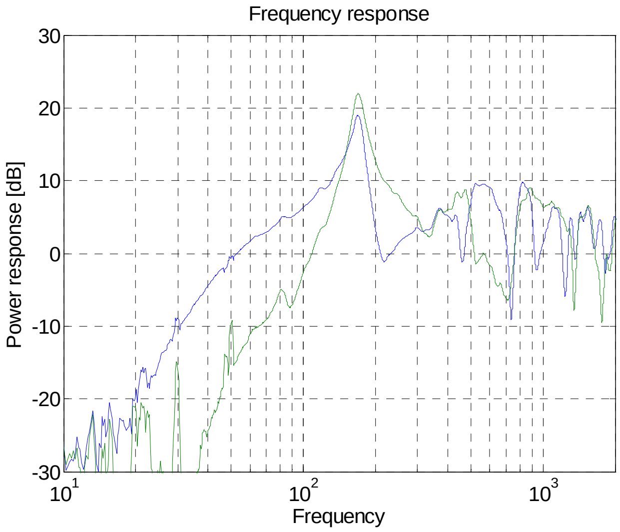


Figure 9: Combined responses for the front (blue) and rear (green) after amplitude- and extra delay-time correction for the rear.

After adding an extra delay for the rear signal to restore the additional phase shift, the behavior of the combined responses correspond very well to the expected cardioid behavior. The rear response shows a good suppression (> 15 dB) for frequencies less than 50 Hz. Also the result for the front signal is much closer to the expected result for a U-frame: close to a -6 db/oct slope below the pipe resonance which changes to -18 dB/oct below the loudspeaker resonance.

2 Adding damping in the pipe by flow-resistor boards and wool stuffing

My first approach of adding damping in the pipe is by means of a kind of Brigg's filter or flow-resistor. The flow-resistor is constructed as a square piece of 6 mm MDF board with 196 holes of 10.5 mm and has the size of the pipe's cross-section. An MDF board can be put in the slots of the pipe as shown in the picture of figure 10.

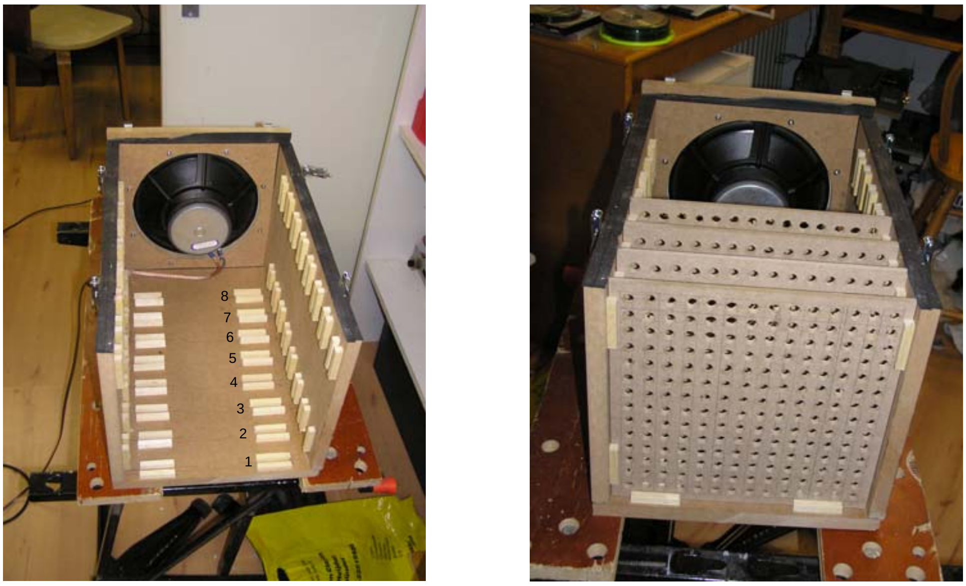


Figure 10: U-frame with slot numbering and the flow-resistors in positions 1-2-3-4.

2.1 Flow-resistor boards at 5 cm spacing

Measurements have been carried out with up to four flow-resistors put in successive slots with 5 cm separation distance at the end of the pipe where the speed of the moving air is highest and thus the effect of the flow-resistor boards is maximum. By adding flow-resistance, the resonance frequency decreases because of the decreasing air speed, and the Q of the $\lambda/4$-resonance decreases. Also the flow resistance has a small effect on the measured TS parameters of the loudspeaker. An overview of these measurements is given in Table 1.

Table 1: TS-parameters of the loudspeaker and the $\lambda/4$ resonance frequencies for different number of flow-resistor boards.

# boards	f_s [Hz]	Q_{mc}	Q_{ec}	Q_{tc}	$f_{\lambda/4}$	Positions
0	36.9	2.97	1.2	0.85	167	-
1	36.2	3.03	1.2	0.84	160	1
2	36.1	2.88	1.2	0.85	153	1-2
3	35.7	2.91	1.2	0.85	149	1-2-3
4	35.3	2.94	1.2	0.85	147	1-2-3-4

The most remarkable result is the drop of $f_{\lambda/4}$ from 167 Hz without damping to 147 Hz with four boards in place, which is a drop of 12 %. When we calculate the effective air speed, this would drop from 343 m/s to 302 m/s, which is rather a lot. The flow-resistance causes a small effect on the TS-parameters in that the loudspeaker resonance frequency decreases from 36.9 Hz to 35.3 Hz, which is a drop of about 4.4%. The flow-resistor clearly does not increase the air-stiffness, since this would have resulted in an increase of f_s. The measured impedance of the loudspeaker in the U-frame with flow-resistor boards at positions 1-2-3-4, is shown in figure 11.

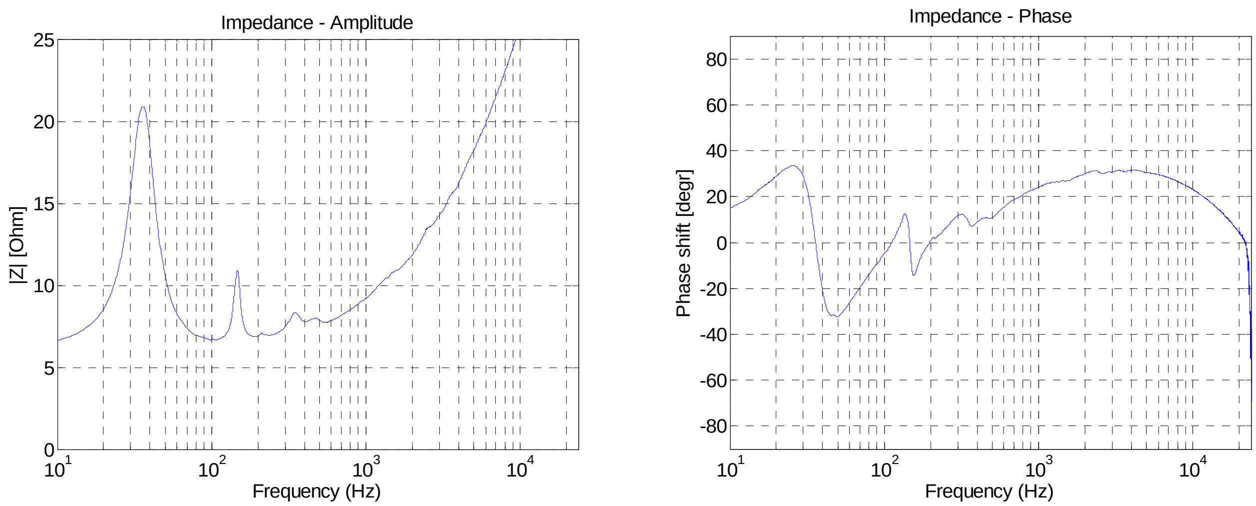


Figure 11: Impedance (amplitude and phase) of the loudspeaker in the damped U-frame with 4x MDF flow-resistor boards at 5 cm separation.

Figure 12 shows the amplitude, phase, impulse responses for the front and the rear in the same way processed as indicated for figure 7, and the combined responses as in equation 1.1 (similar to figure 8).

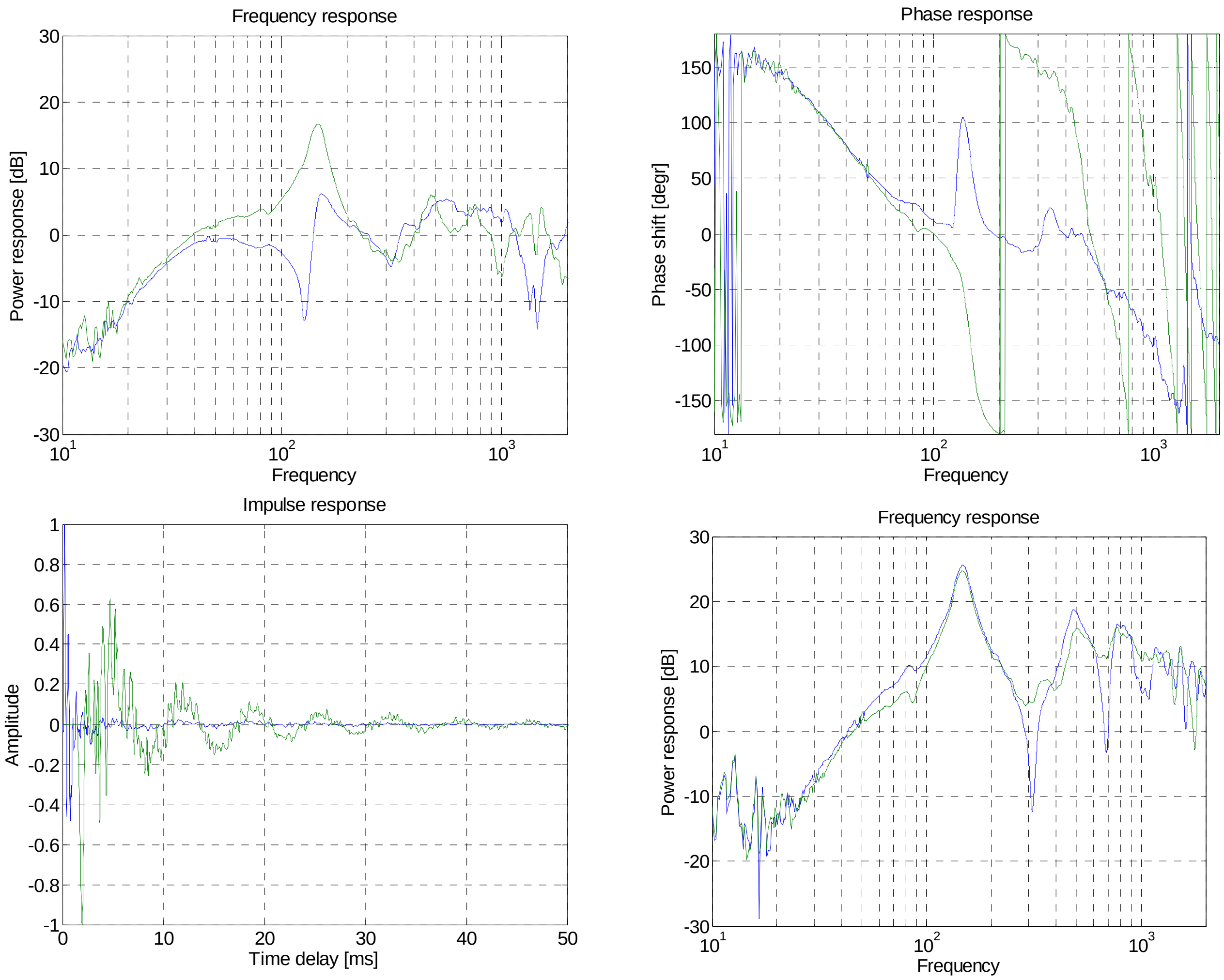


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Figure 12: Amplitude (corrected), phase and impulse responses for the front (blue, with 180^o additional phase shift in the phase plot) and rear (green), and the combined responses.

Amplitude and phase results show a decreased Q-value for the $\lambda/4$-resonance frequency as expected. The amplitude of the rear after correction seems a bit too high. This may be caused by the placement of the microphone, which is about 5 mm from the last board and may have been in front of one of the holes. The phase plot clearly shows the same behavior at low frequencies as in the case without damping with front and rear are almost perfectly out of phase, despite added damping.

2.2 Flow-resistor boards at different spacing

Measurements are done with 4 flow-resistor boards at different locations in the pipe. The locations are numberd as shown in figure 10.

Figure 13: U-frame with the flow-resistors in positions 1-1$\frac{1}{3}$-1$\frac{2}{3}$-2.

First the $\lambda/4$-resonance frequency is compared for the following settings:
- no flow-resistors,
- flow-resistors at 2-4-6-8
- flow-resistors at 1-3-5-7
- flow-resistors at 1-2-3-4
- flow-resistors at 1-1$\frac{1}{3}$-1$\frac{2}{3}$-2 (all 4 between slots 1 and 2, see figure 13).

The resonance frequency is determined from the impedance measurement. In addition, the $Q_{\lambda/4} \triangleq BW_{3dB} / f_{\lambda/4}$ of the $\lambda/4$-resonance peak in the impedance curve has been determined to get an impression of the effect of different flow-resistor locations. The results are given in Table 2.

Table 2: The $\lambda/4$-resonance frequencies and their $Q_{\lambda/4}$ based on loudspeaker impedance measurements.

Boards locations	$f_{\lambda/4}$ [Hz]	$Q_{\lambda/4}$
none	167	20.8
2-4-6-8	156.5	17.4
1-3-5-7	152.5	16.1
1-2-3-4	147	16.3
1-1$\frac{1}{3}$-1$\frac{2}{3}$-2	142.2	14.2

These results show a substantial decrease of $f_{\lambda/4}$ with more flow resistance at the end of the pipe, which is to be expected because at that location the air speed is highest. However, the decrease of $Q_{\lambda/4}$ is not very large, e.g. the resonance $\lambda/4$-frequency is lowered, but not damped very much.

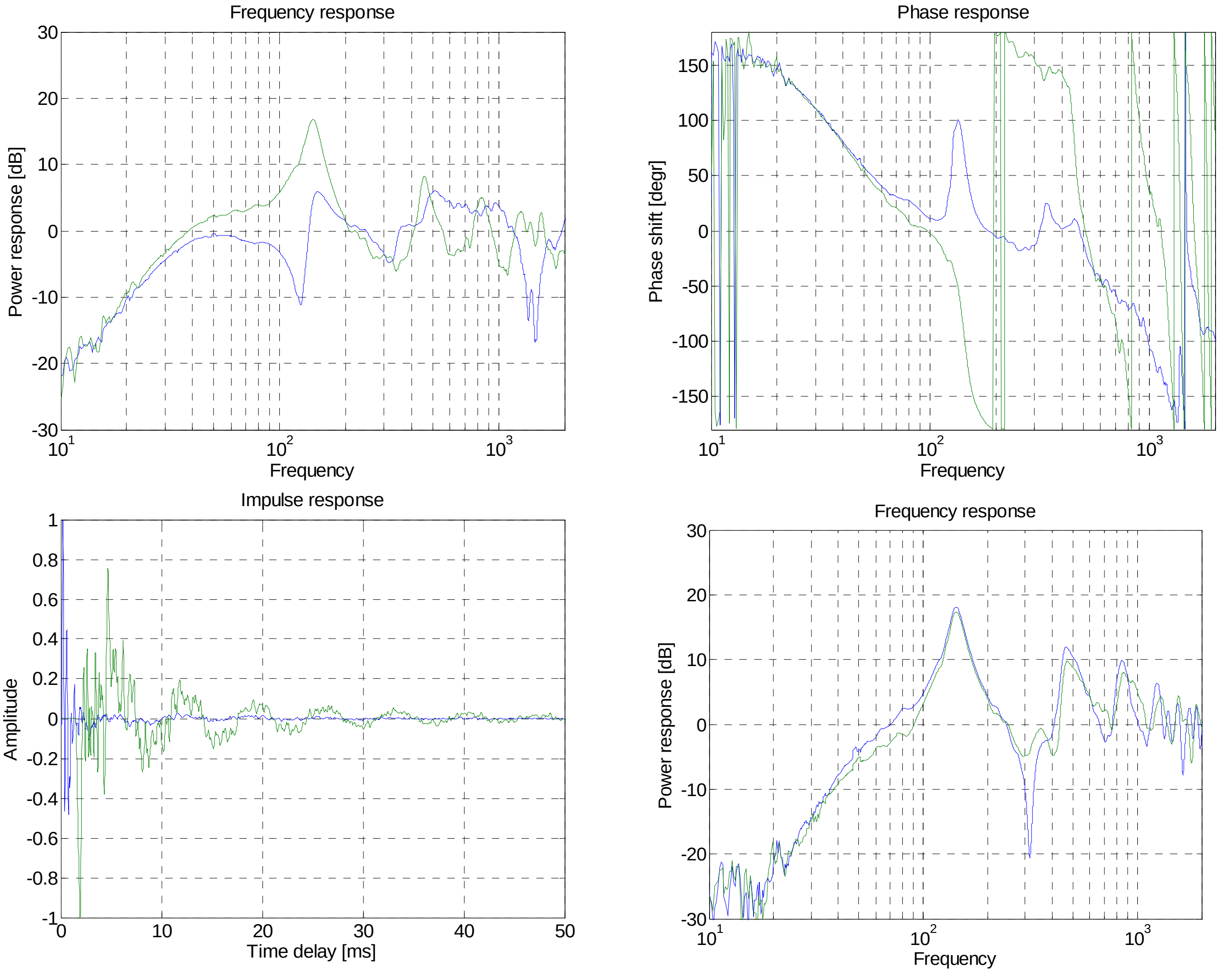

Figure 14: Amplitude (corrected), phase and impulse responses for the front (blue) and rear (green), and the combined responses: flow-resistors in positions 1-1$\frac{1}{3}$-1$\frac{2}{3}$-2.

The front and rear responses for the flow-resistors in positions 1-1$\frac{1}{3}$-1$\frac{2}{3}$-2 still show 180^{o} phase shifted responses for low frequencies, i.e. a dipole response, and the $\lambda/4$-resonance is hardly dampened.

2.3 Flow-resistor boards with fiber-cloth

In the following, these measurements are repeated with the 4 flow-resistors covered with fiber-cloth and put in positions 1-1$\frac{1}{3}$-1$\frac{2}{3}$-2, as shown in figure 15.

Figure 15: Flow-resistor covered with fiber-cloth.

The measured impedance is shown in Figure 16. It is clear that the resonance frequency is lowered further to $f_{\lambda/4}$ = 138 Hz. The basic TS-parameters are: f_s = 35.9 Hz, Q_{ms} = 2.03, Q_{es} = 1.30 and Q_{ts} = 0.78.

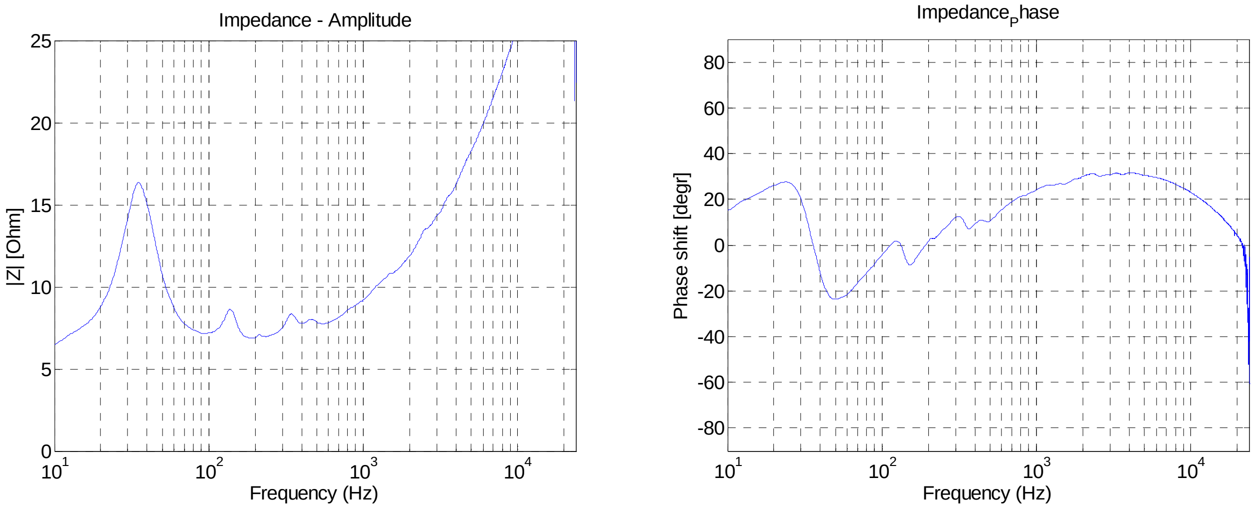

Figure 16: Impedance (amplitude and phase) of the loudspeaker in the damped U-frame with 4 flow-resistor boards covered with fiber-cloth and put in positions 1-1$\frac{1}{3}$-1$\frac{2}{3}$-2.

From the front and rear responses in figure 17, it is observed that now a phase difference starts to appear between the front and rear at low frequencies. Still the resonance frequency is clearly present as can be observed from the rear impulse response. The responses combined according to equation (1.1) start to show some cardioid behavior in that there is now the rear is attenuated by a few dB compared to the front for low frequencies till above $f_{\lambda/4}$.

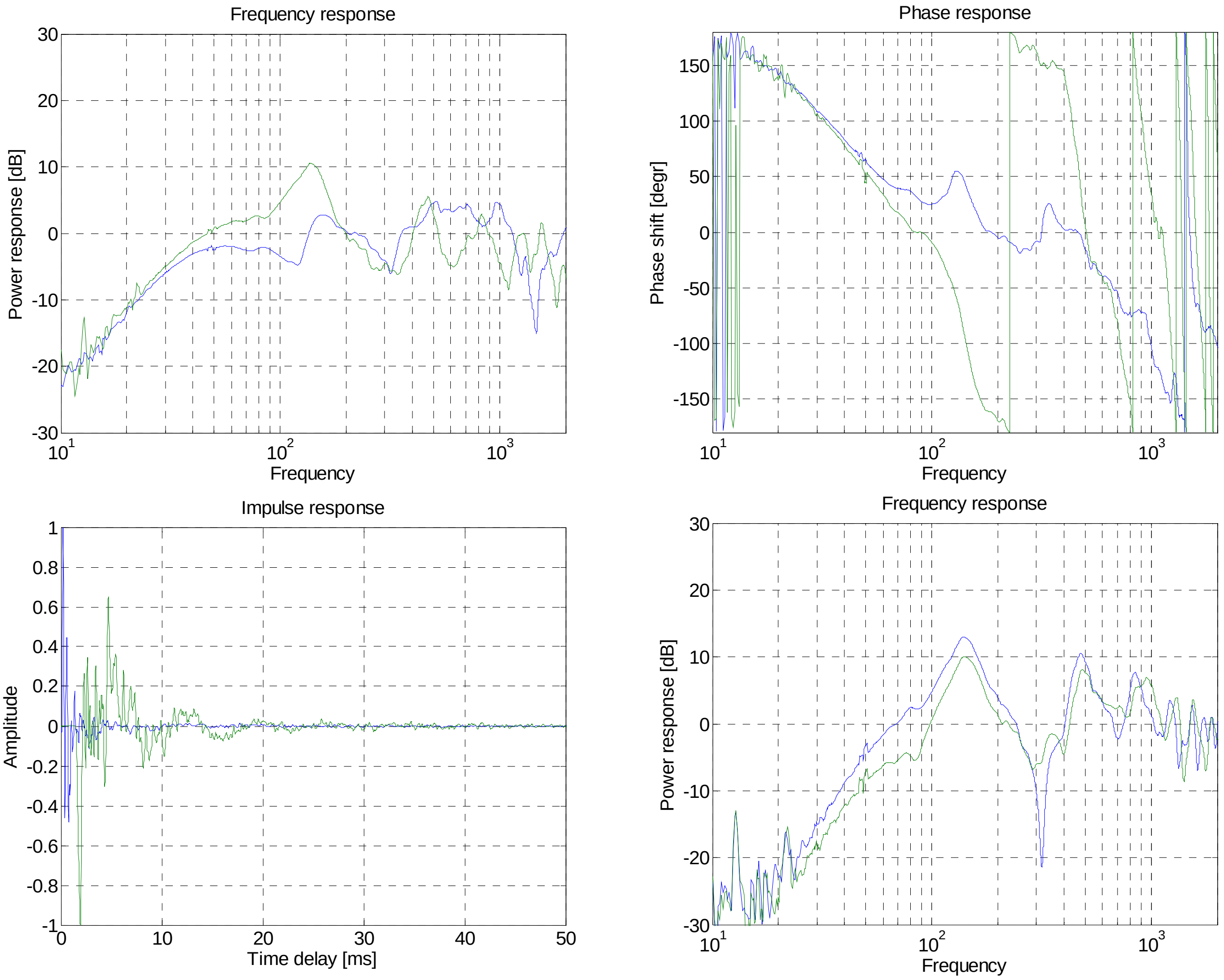

Figure 17: Amplitude (corrected), phase and impulse responses for the front (blue) and rear (green), and the combined responses: flow-resistors with fiber sheet in positions 1-1$\frac{1}{3}$-1$\frac{2}{3}$-2.

2.4 Flow-resistor boards with fiber-cloth, pipe filled with wool stuffing

Now, in addition to the previous damping measures, about 300 gr long-fiber sheep-wool is used to fill the pipe, as shown in figure 18. Again impedance and response measurements were carried out to see the result.

Figure 18: Damping by flow-resistor covered with fiber-cloth and the remainder of the pipe filled with long-fiber sheep-wool.

The measure impedance is shown in Figure 19. The peaks of the loudspeaker and the $\lambda/4$-resonances are clearly lowered substantially. The pipe resonance frequency is lowered further to $f_{\lambda/4}$ = 120 Hz, but the loudspeaker resonance has now increased due to the increased stiffness. The basic TS-parameters are: f_s = 36.8 Hz, Q_{ms} = 1.13, Q_{es} = 1.30 and Q_{ts} = 0.60.

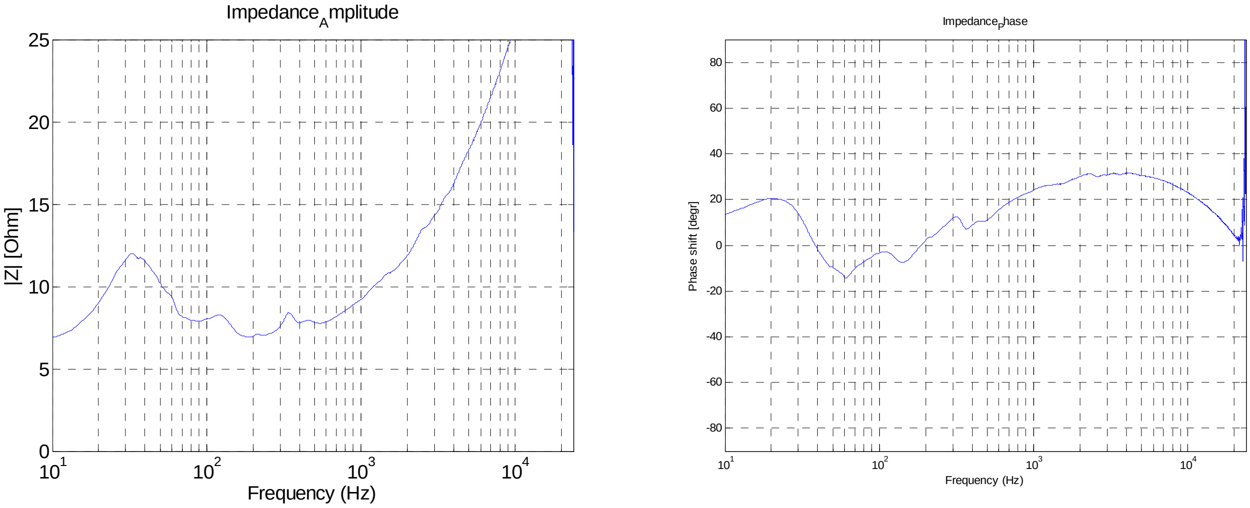

Figure 19: Impedance (amplitude and phase) of the loudspeaker in the damped U-frame with 4 flow-resistor boards covered with fiber-cloth put in positions 1-1$\frac{1}{3}$-1$\frac{2}{3}$-2 and the pipe filled with long-fiber sheep-wool.

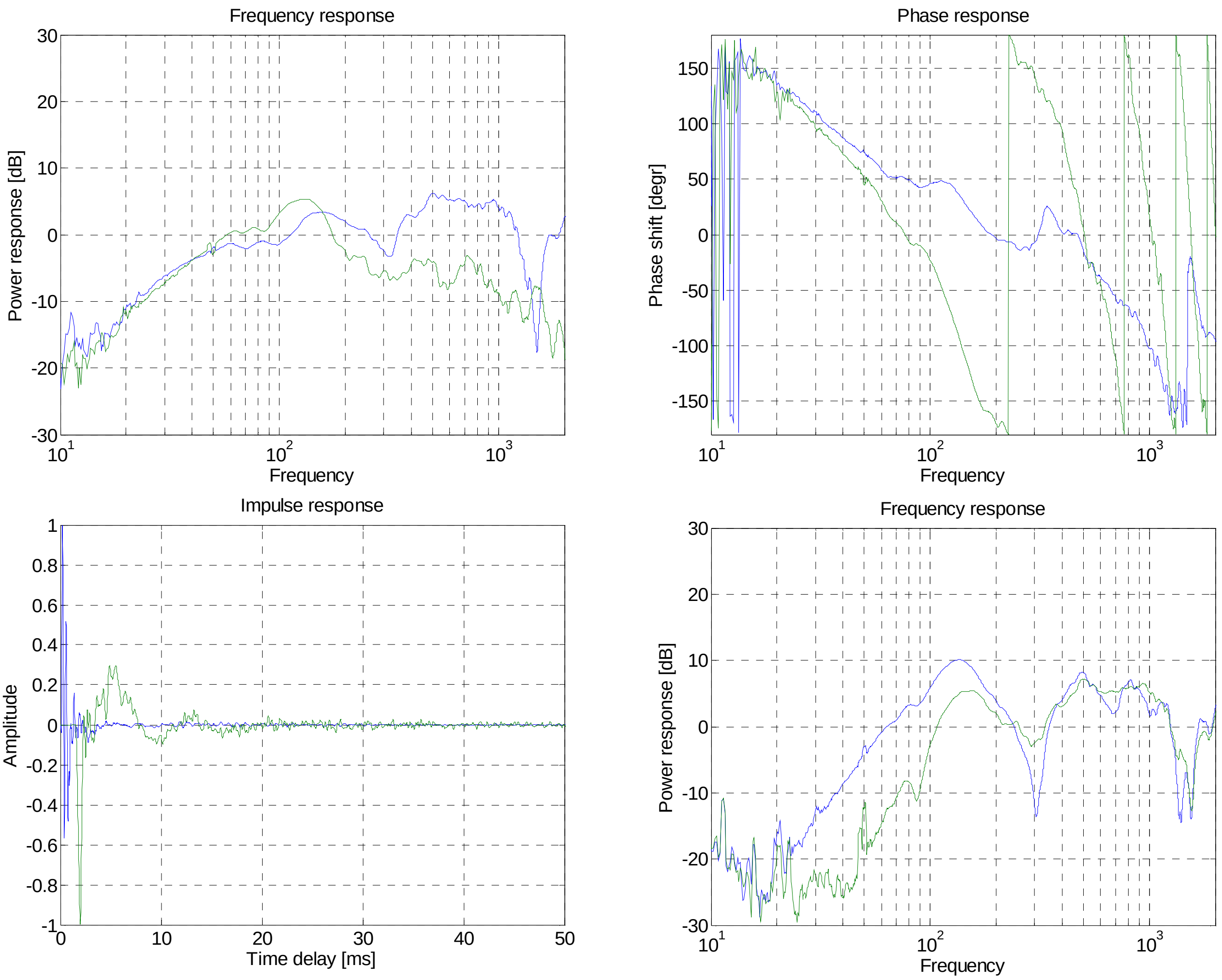

Figure 20: Amplitude (corrected), phase and impulse responses for the front (blue) and rear (green), and the combined responses: flow-resistors with fiber sheet in positions 1-1$\frac{1}{3}$-1$\frac{2}{3}$-2.

From the front and rear responses in figure 20, it is observed that the amplitudes for low frequencies have become nearly equal again (after correction). I don't know what this is worth in practice. I suspect that the rear sound pressure has become lower than the front due to the acoustic damping. Also, the phase difference between the front and rear has further in creased; at 50 Hz the phase difference is about 20^o. In the rear impulse response, the $\lambda/4$-resonance is still present but much further attenuated. The responses combined according to equation (1.1) start show a clear cardioid behavior now where the attenuation of the rear is 10-15 dB compared to the front well below $f_{\lambda/4}$. Again, because I suspect that the sound pressure at the front is higher than at the rear in reality (this is also observed by Martin J. king in his Transmission Line measurements and simulations in [1], [4]), the attenuation at the rear will be less than shown in the combined response of figure 20. However, when listening at the rear the volume of lower frequencies is clearly less than at the front.

3. Some conclusions

The undamped U-frame shows an almost perfectly 180^o phase difference between the front and the rear responses at low frequencies, and therefore haves like a dipole at these frequencies, not as a cardioid. In addition is has a very strong resonance at the frequency where the length of the pipe is close to $\lambda/4$; this resonance can be heard very well at the back side. This $\lambda/4$-resonance as well as the phase shift at low frequencies which compensate the phase shift due to the time-delay in the pipe (and so prevent the cardioid radiation pattern), are cause by the severe impedance jump at the rear opening of the pipe. Adding flow-resistance by using perforated MDF-boards, fiber-cloth and heavy stuffing of the pipe with sheep-wool results in a better matching of the impedance at the end of the pipe with the free-air impedance, and reduces the $\lambda/4$-resonance and restores the phase shift due to the time delay in the pipe. In this way, a (partial) cardioid radiation pattern is obtained. However:

- to obtain equal amplitude at the front and the rear of te U-frame is very difficult (see also the simulations and measurements of Martin J. King, [1], [4]). This prevents a good cardioid behavior,
- even with dense stuffing, the quarter-wave resonance is not fully removed, while further stuffing will further attenuate the rear output.

After these U-frame experiments and measurements, I believe that building a cardioid based on a U-frame requires too many compromises. Another interesting solution to pursue is by combining a closed box monopole and a dipole. An intersting aspect of this concept is that both components do not interact directly and can be independently tuned.

References

[1] Martin J. King, http://www.quarter-wave.com/Theory/Damping_Coefficient.pdf.

[2] John Kreskovsky, "Building and testing the U-frame", Music Design CD.

[3] Siegfried Linkwitz, http://www.linkwitzlab.com/H-U%20woofer2.htm

[4] Martin J. King, http://www.quarter-wave.com/Theory/Test_Line_Results.pdf