

WGC1412 design overview

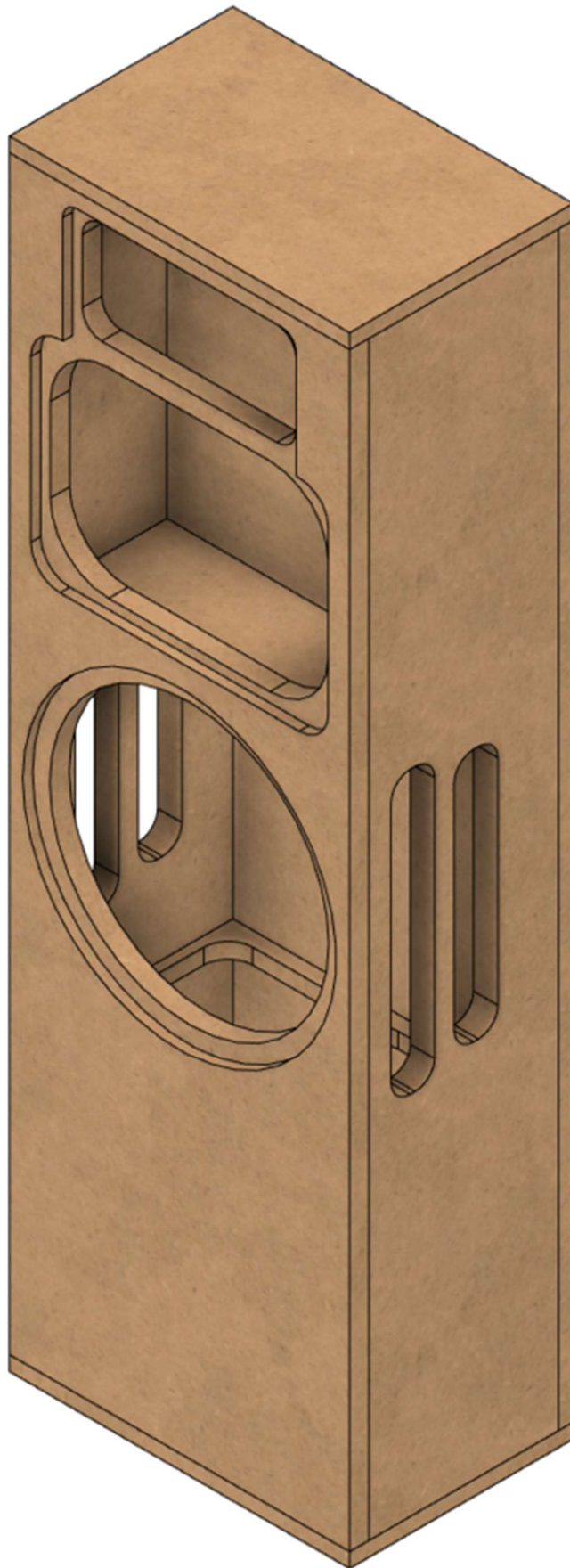


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Introduction

This document is intended to be a simple overview of my 3-way loudspeaker project, herein dubbed WGC1412 (Waveguide-Cardioid 1", 4", 12"). It is by no means an exhaustive list of design considerations and challenges, but shortly summarizes the project such that the interested reader can quickly digest the overall design ethos and performance by objective metrics.

Around mid-2021 I decided to create my first proper loudspeaker from scratch. At that point I had built a kit-based single-driver loudspeaker with a built-in amplifier and toyed with some novel ideas for directivity control. I had never, however, decided to put my playful tinkering to the test and create a full-fledged loudspeaker system.

I had already played around with loudspeakers and loudspeaker simulation quite a bit at this point and considered myself reasonably proficient at both VituixCAD and AKABAK (for which a free license was kindly given to me by the creator – Joerg Panzer). With BEM simulation in hand, the potential scope of the project was much increased, and I decided to treat it as a learning experience first and foremost.

A decision was made – the loudspeaker in its entirety was to be simulated using BEM, and a comparison between the measured and simulated result was to be carried out. I hoped that by doing this, I could develop a better understanding of both loudspeaker design and BEM simulation in practice.

A rough design guideline was made:

1. The loudspeaker shall have a controlled, gently narrowing radiation pattern.
2. The loudspeaker shall enable playback with high peak SPL.
3. The loudspeaker shall have low distortion at nominal SPLs (70-90dB).
4. The loudspeaker shall be active.
5. The loudspeaker shall have low depth, to facilitate placement close to the wall.

High frequencies

The natural course of action for high-frequency directivity control was determined to be a waveguide. Its benefits include increased output at the lower end of the tweeter's passband, controlled directivity such that the radiation pattern can match the midrange driver at and around the crossover frequency, and offsetting the tweeter's acoustic centre so that it is closer to that of both the woofer and the midrange. The latter proves helpful in aligning the phase and thereby summing of midrange and tweeter at the crossover frequency. For this project DSP crossovers which allow time delays were utilized, meaning that this benefit was not relevant.

A rough design guided by my own intuition was drawn in Fusion360, exported as a .step file, meshed in Gmsh and finally imported to AKABAK for simulation. Stanislav Malikov of Bliesma was kind enough to supply drawings of the Bliesma T25B's dome shape, which helped simulation accuracy. The waveguide's design was then iterated until a satisfactory result was obtained.

Due to mesh size requirements, simulating the tweeter waveguide along with the entire cabinet was unfeasible, and so the tweeter waveguide was simulated in an infinite baffle. Off-axis responses normalized to on-axis in 5-degree increments and the normalized contour plot are shown in figure 1 and 2. A lower-resolution mesh was later made to observe behaviour of the tweeter below 5kHz when mounted in a cabinet.

Due to the relatively large waveguide and baffle, the differences between infinite baffle and finite baffle simulations were small above 3.5-4kHz. Infinite baffle simulations were deemed sufficient for characterizing the tweeter's behaviour at high frequencies.

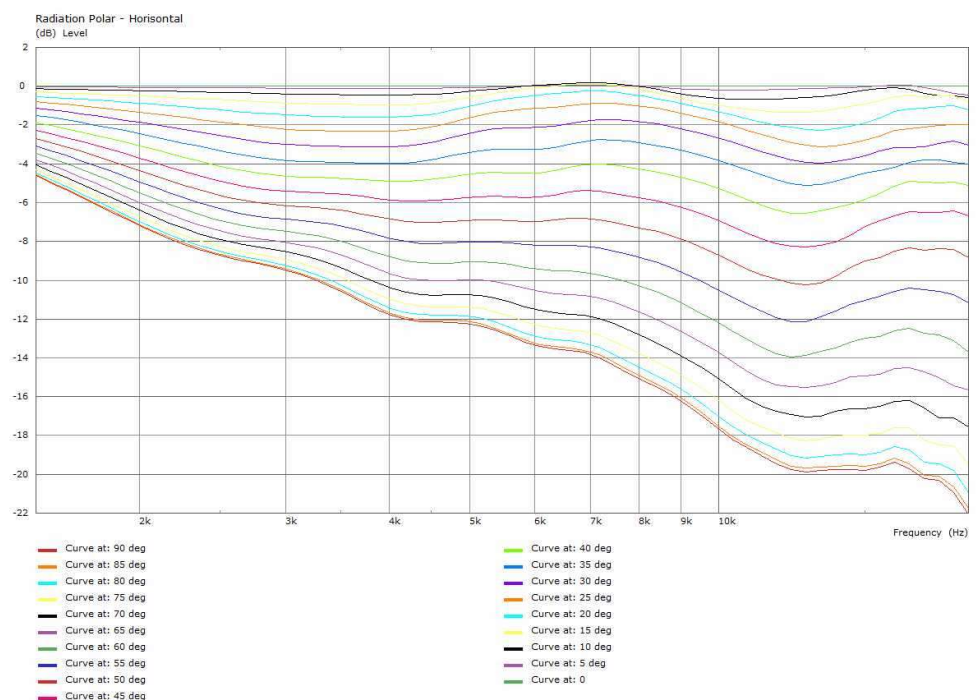


Figure 1 – note 2dB/div scale.

Below roughly 4kHz, the tweeter's radiation pattern will be narrower when mounted in a cabinet as compared to an infinite baffle. In the 5-10kHz range there are slight on-axis interference effects which disappear off-axis. These effects are minor deviations in the range of 1-1.5dB but indicate this speaker should be designed for listening at 10-20 degrees off-axis. A similar effect can be seen in the top octave. The waveguide's beamwidth is quite narrow at roughly ± 45 degrees, which leads to a healthy output increase, particularly at lower frequencies. The on-axis frequency response with 2.83Vrms input at 1m distance is shown in figure 3.

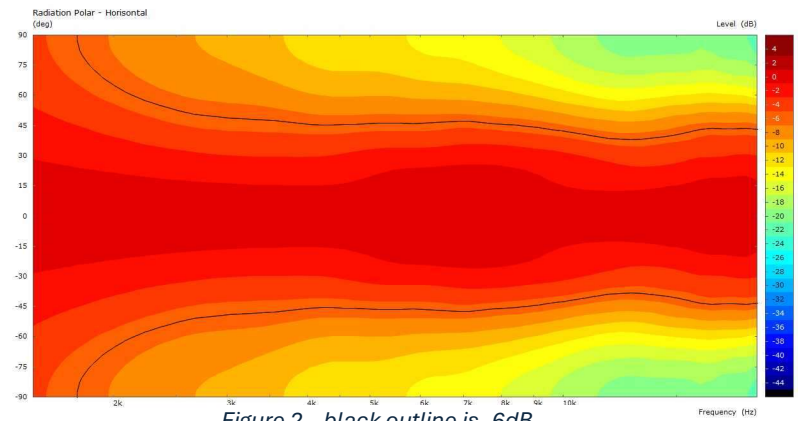


Figure 2 – black outline is -6dB.

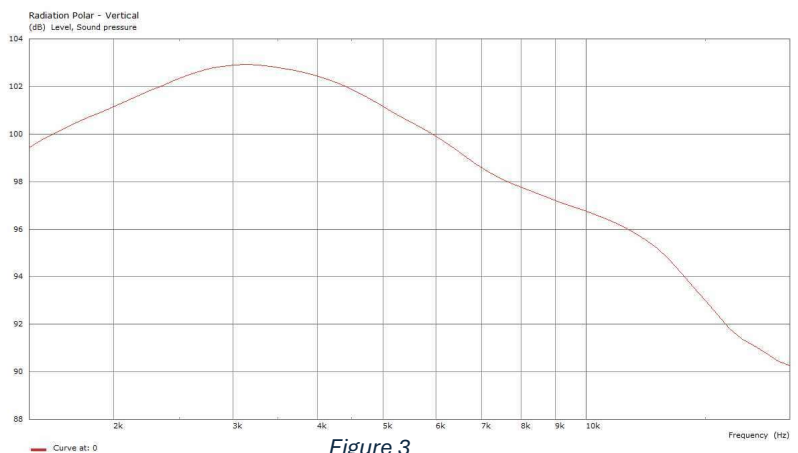


Figure 3

The slight variations in the trend of the frequency response are easily correlated to the deviations in the normalized off-axis frequency response and contour plots. Beyond that, the output sensitivity of the tweeter at low frequencies is remarkable. At up to 6kHz it is $>100\text{dB}/2.83\text{Vrms}$, which is $>98.5\text{dB/W}$ for the 6-ohm tweeter. Even with low crossover frequencies and high SPL demands, thermal compression should present no issues.

Mid frequencies

For the midrange frequencies various methods of directivity control were considered. Including a resistance enclosure, a beamforming array consisting of multiple smaller drivers, a large singular driver, and a smaller singular driver in a waveguide for directivity control. Ultimately a smaller driver in a waveguide was chosen. Reasons include high output across the working range of the driver, freedom in what radiation pattern I wanted to design, frequency responses (both on- and off-axis) that are easier to work with, and low requirements for volume displacement at the lower end of its passband. At this point in the process a crossover of around 350-400Hz was planned, in which case a 4-inch driver would need only 1mm x_{max} to reach levels in excess of 115dB when

accounting for the output increase from the waveguide and the fact that the driver is already -6dB at the crossover frequency using LR4 filters.

The design process for the midrange waveguide was like that of the tweeter, in fact the midrange waveguide was designed before the tweeter waveguide. The primary difference between my approaches to the two was that the midrange waveguide was never simulated in an infinite baffle – it was always simulated in the cabinet to get an accurate idea of what the radiation pattern in the finished speaker would look like. Unlike the tweeter, a mesh resolution producing valid results to 20kHz was not needed, and so the entire cabinet could be simulated without major penalties in compute time. Off-axis responses normalized to on-axis in 5-degree increments and the normalized contour plot are shown in figure 1 and 2.

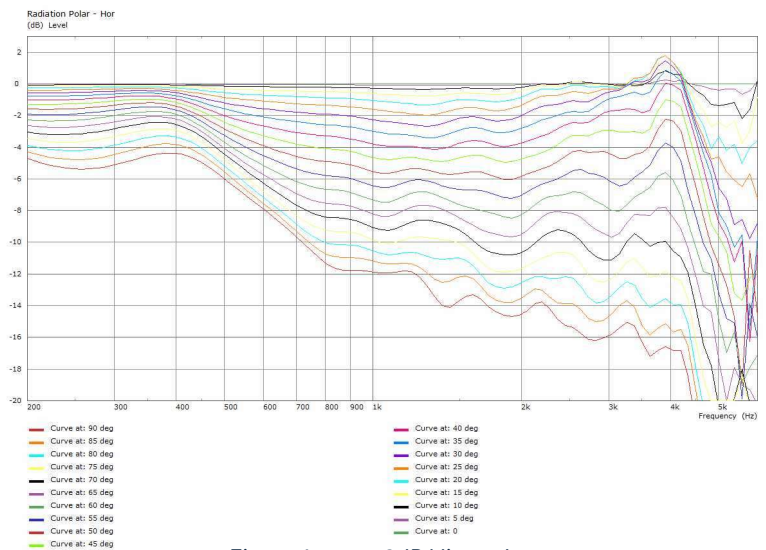


Figure 4 – note 2dB/div scale.

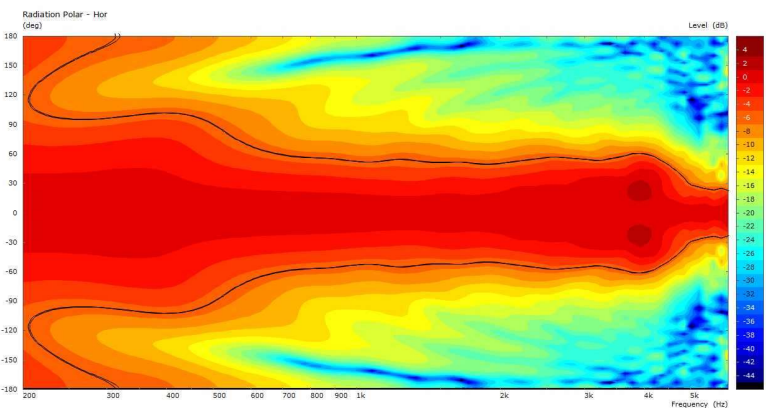


Figure 5 – black outline is -6dB.

The waveguide shows good control of the radiation pattern until ~600Hz, below which point it loses directivity control due to insufficient size. On the high end it's very well behaved until roughly 2kHz. Above 2kHz the radiation pattern becomes wider. Similarly to the tweeter waveguide this is due to on-axis interference effects that disappear off-axis. For this project, it did not present meaningful problems.

Figure 6 shows the simulated on-axis response of the midrange driver mounted in the waveguide with a 2.83Vrms signal at 1m. A high sensitivity of >97dB/2.83Vrms (>95dB/W) is obtained between 600Hz-2kHz. Below this frequency pattern control is gradually lost and the sensitivity decreases. The rapid

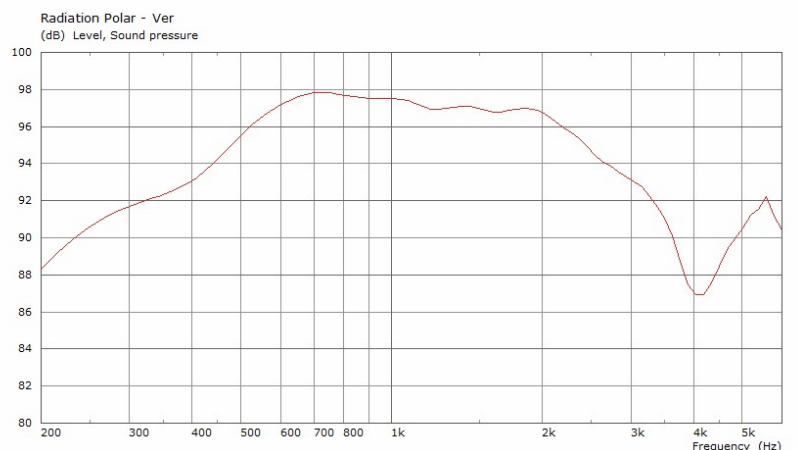


Figure 6

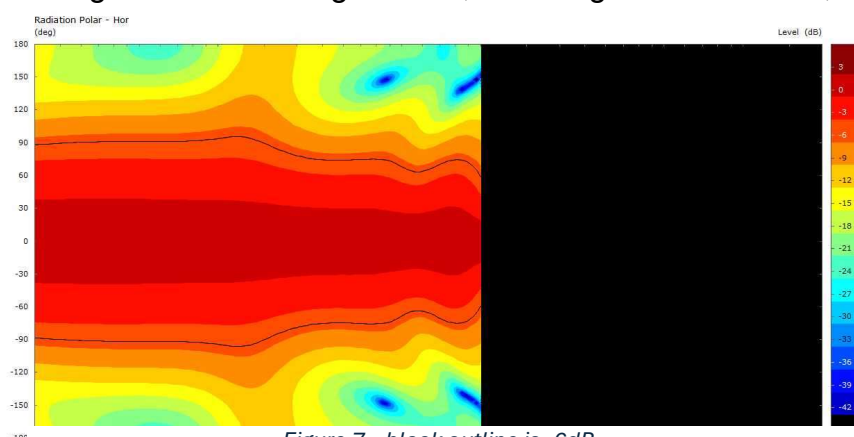
drop in SPL above 2kHz also shows what was expected when looking at the normalized off-axis frequency responses. A dip centred at roughly 4kHz is clear, but this is an octave outside of the passband of interest for the midrange driver, and therefore not a big concern.

Low frequencies

Initially, the idea of low-frequency directivity was not considered at all. The loudspeaker would be designed to have a relatively tight control on its radiation pattern down to 600Hz, and that would be it. After some reading and considerations about the drawbacks and benefits of full-range directivity control, I made the decision to put the woofer into a resistance enclosure rather than a bass-reflex enclosure. A secondary benefit of this solution was that the required box volume for the resistance enclosure is less than for a bass reflex enclosure. The loudspeaker being forward-firing for its whole frequency range was also beneficial to the idea of facilitating placement close to the front wall.

A resistance enclosure was chosen because it can be implemented passively. I only had 3 amplifier/DSP channels per speaker, so doing a more typical arrangement of rear- or side-mounted drivers with their own signal processing was not an option. A resistance enclosure works by altering the sound from the rear of the driver in terms of both magnitude frequency response and phase frequency response, to achieve a strong cancellation in an arbitrary direction. In this case, strong attenuation towards the rear was the goal. The drawback of this method is higher distortion, experimentally found to be particularly present in cases where materials with high flow resistivity are used, and decreased bass output due to the acoustic short circuit between the front and rear of the diaphragm. The latter means that the loudspeaker requires subwoofers to play at the levels envisioned early in the design phase, which was deemed a non-issue, as subwoofers should always be used in any case.

The enclosure was modelled in Fusion360 and meshed in Gmsh, then imported to AKABAK. The cabinet was modelled such that there were several slits in the cabinet that could either be defined as open or closed. This allowed rapid testing of various configurations, including number of slits, positions of slits and internal damping material. After some simulation work it was determined that 2 closely spaced slits, sitting close to the front baffle should work well for my purposes. The simulated contour plot of this solution is shown in figure 7.



The contour plot shows a clear forward-firing bias, and the goal of strong rear rejection has clearly been achieved. In addition, the beamwidth matches that of the midrange quite well.

As for the low-frequency capabilities of the 12-inch driver, a simulation was carried out to determine the loss in output due to the acoustic short circuit. The result is shown in figure 8.

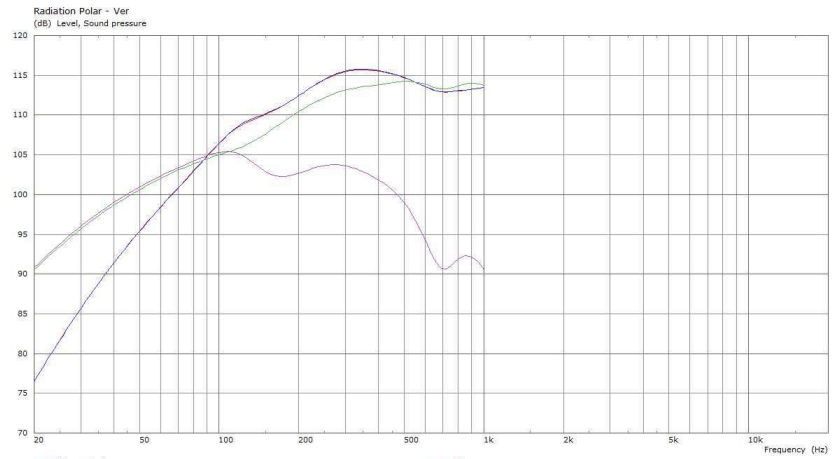


Figure 8

The green trace is output from the front of the diaphragm, while the purple trace is from the rear. The blue trace is the summed output of the two. Somewhat surprisingly, the resistance enclosure has higher sensitivity in the 100-500Hz range than any of the diaphragm surfaces in isolation. The low-pass effect of the damping material and slits is evident in the purple trace. The severe loss of bass output is also evident, reinforcing the idea that a subwoofer is a requirement for such a loudspeaker.

Filtering

The simulated off-axis data was imported into VituixCAD for further processing. In VituixCAD a crossover was made, which was to be the goal for the finished speaker. After simulations were done and results found to be satisfactory, the loudspeaker was built. Waveguides were 3D-printed, the cabinet was built from mostly 25mm MDF, and a Hypex Fusion FA123 plate amplifier for each speaker was bought. After this was done, a set of measurements of each driver was taken from 0-180 degrees. 0-360-degree measurements were not necessary, as the speaker is horizontally symmetrical. Based on these measurements a crossover filter to match the results of the simulation was made. Due to challenges in measuring the loudspeaker, vertical measurements were not made, and the BEM simulations of the vertical radiation had to be trusted at the time.

Filter design started on the analogue side. A capacitor was connected to the tweeter to protect from potential low-frequency or DC signals, should the DSP crossover for some reason fail. For the midrange driver a less common approach was chosen. Two parallel notch filters, connected in series with the driver, were used to suppress rather severe resonances an octave and two above the passband. The benefit of doing so with these passive filters rather than simply using the included PEQ function on the FA123, is the reduction of current nonlinearities. The reduction of current nonlinearities occurs due to the reactive inductance of the circuit decreasing relative to the

total impedance of the circuit. A loudspeaker driver's inductance will typically vary depending on the current in the coil and the excursion of the coil, by making said inductance change a smaller part of the total impedance, modulation of current is reduced. Conceptually, such a filter is much like making the loudspeaker current-driven for a small frequency band. A reduction in 3rd and 5th order harmonic distortion was observed at and around frequencies corresponding to $f_{\text{notch}}/3$ and $f_{\text{notch}}/5$.

After the passive filtering was finished, the rest of the filter was done with IIR filters using the FA123's DSP. PEQ was used to flatten driver responses such that they were usable, and 4th order Linkwitz-Riley filters were used for all passbands.

Comparison of simulation and measurement

The finished loudspeaker was measured upside down at 3 meters using the ground plane method. As the loudspeaker was measured inside, the results had to be time gated. A gate time of 16ms was obtained before the first reflection arrival. This gave an FFT bin width of roughly 60Hz, meaning that data down to 60Hz was obtained, albeit with low resolution. The horizontal response was measured from 0-180 degrees, while the vertical response was measured from 0-360 degrees. All measurements were done in 10-degree increments and at a sound pressure level corresponding to roughly 84dB@1m. Measurements of the loudspeaker's on-axis response with a 6ms gate (loudspeaker suspended from the floor) was done to verify that high-frequency response accuracy was obtained with the ground plane method.

In figure 9, a comparison between the tweeter's simulated normalized off-axis response and the measured normalized off-axis response is shown. The simulated example is in an infinite baffle, and so it shows higher level at far off-axis angles (80-90 degrees) and low frequencies.

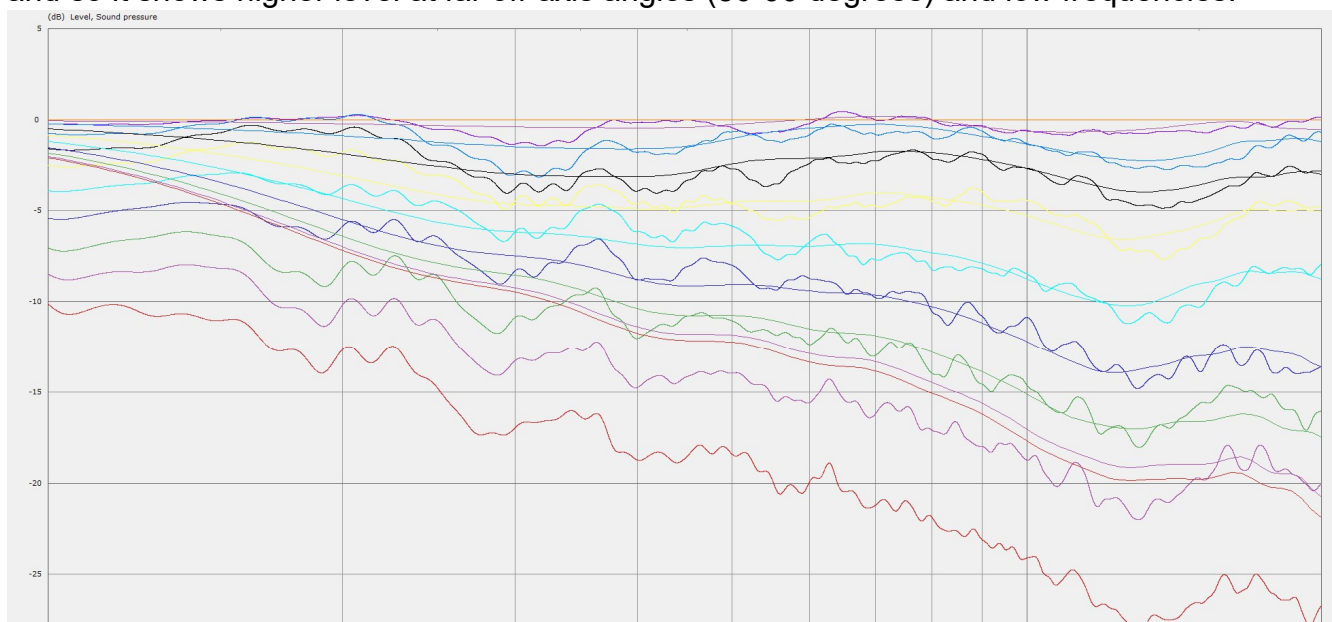


Figure 9

Overall agreement can be considered good, and the deviations we see are expected due to the different conditions of simulation and measurement. Figure 10 shows a similar graphic, but this time with the midrange driver. Here, the agreement between simulation and measurement is higher, due to the simulation taking the loudspeaker cabinet into account. The strange periodic dips and peaks in the measured results are due to mistakes made in the measurement process, which introduced comb filtering. The magnitude of these errors is small, however.

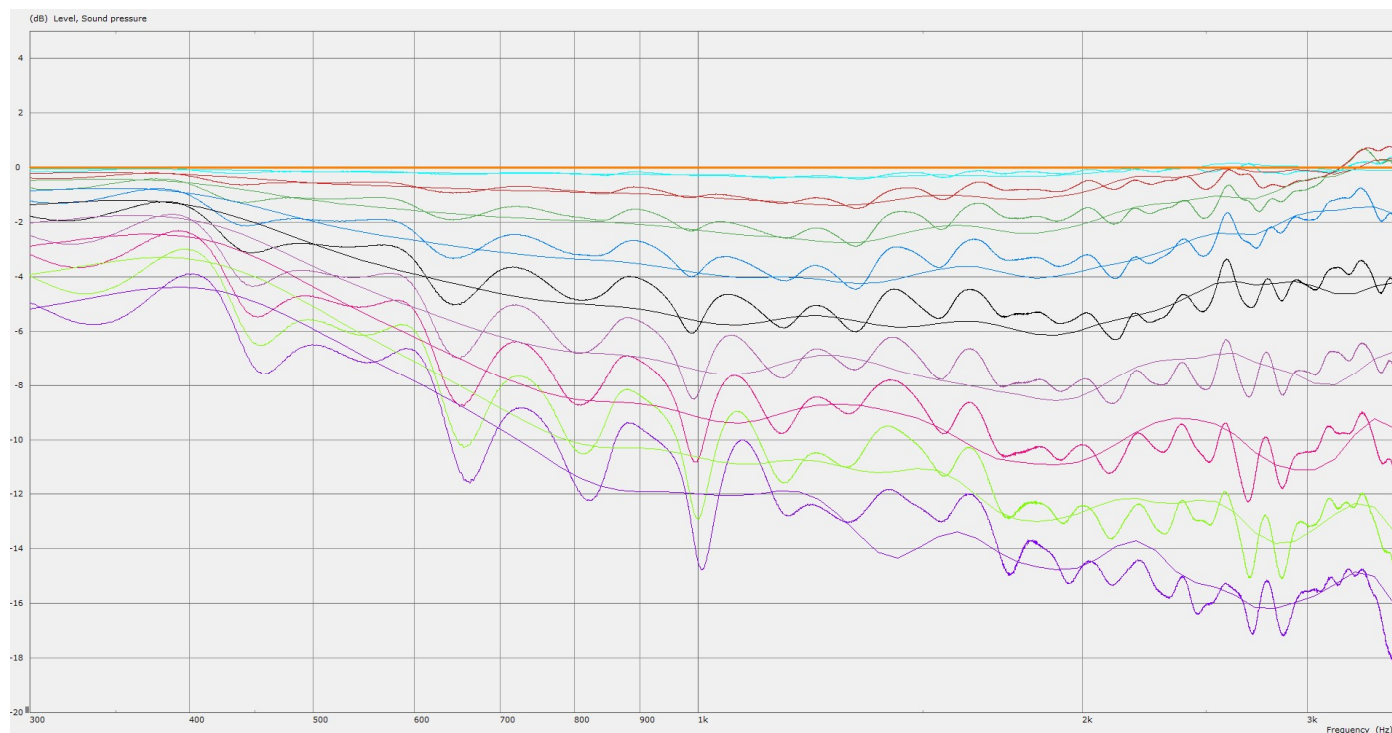


Figure 10 – note 2dB/div scale.

Figure 11 shows a comparison of the simulated and measured early reflections DI and sound power DI (as defined in CTA-2034). The response is only shown between 100Hz and 5kHz, as measurements are unreliable below, and simulations are unreliable above.

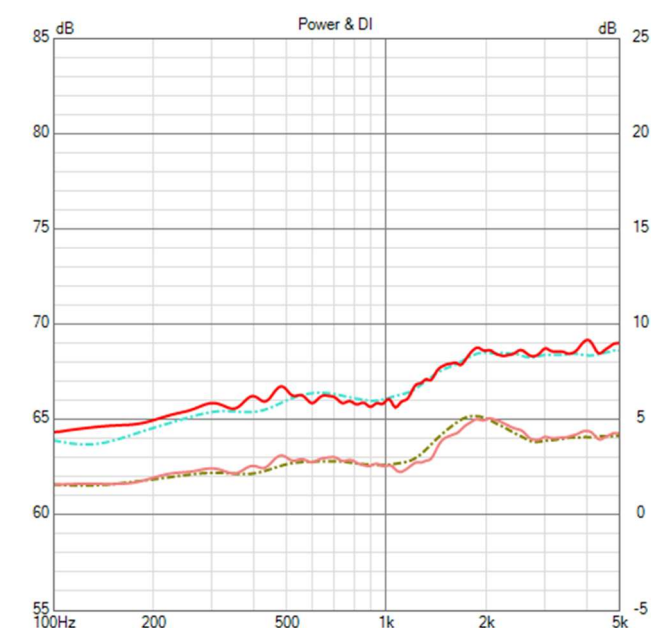


Figure 11 – Solid line is measurement; dashed line is simulation.

From the tweeter comparison above we can see that the tweeter's response matches the simulation well above 5kHz, however. At low frequencies the finished loudspeaker maintains somewhat higher SPDI than predicted by the simulation.

Figures 12 and 13 show the measured and simulated contour plots of the finished speaker respectively. The graph is limited to 100-5kHz for the same reasons as figure 11. The agreement between the two is good, though we can see the rear rejection of the resistance enclosure is greater than the simulated result. This was a positive

surprise. The vertical measurement and simulation are similarly alike, but a graph comparison is not shown. Vertical data is shown further down in figure 16.

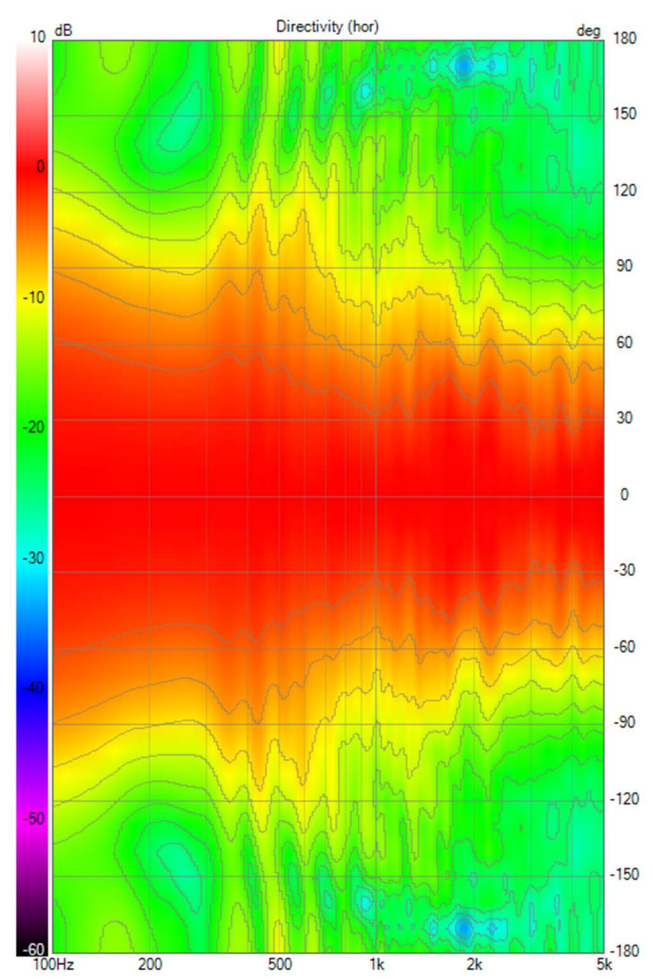


Figure 12

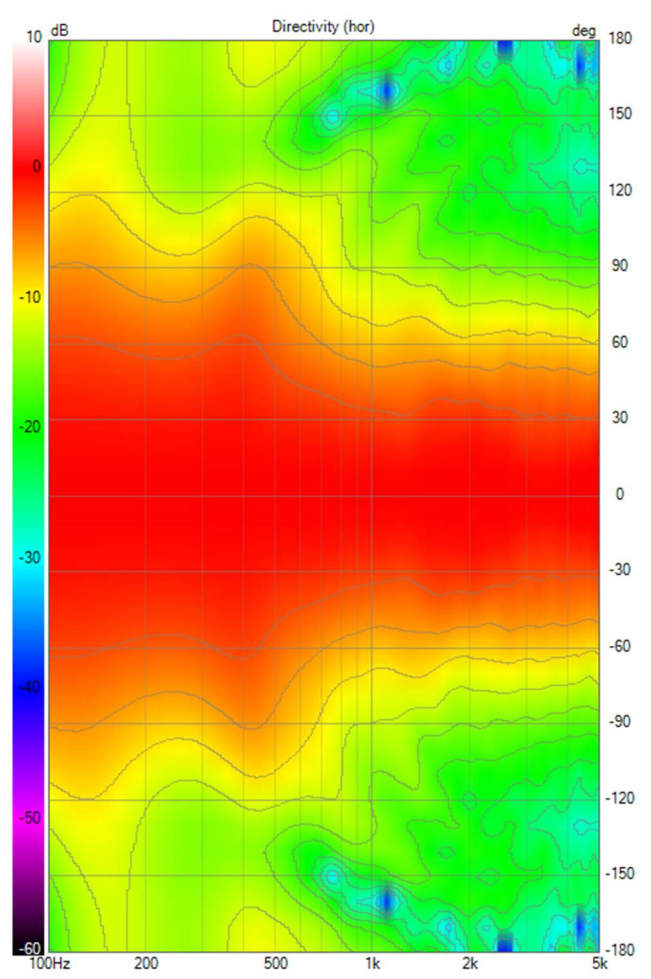


Figure 13

Measurements

Figure 14 shows the CTA-2034 “spinorama” plot of the speaker. Note that the data is inaccurate at low frequencies. Orange trace is predicted in-room response.



Figure 14

Figures 15 and 16 show the horizontal and vertical contour plots of the speaker with 3dB steps.

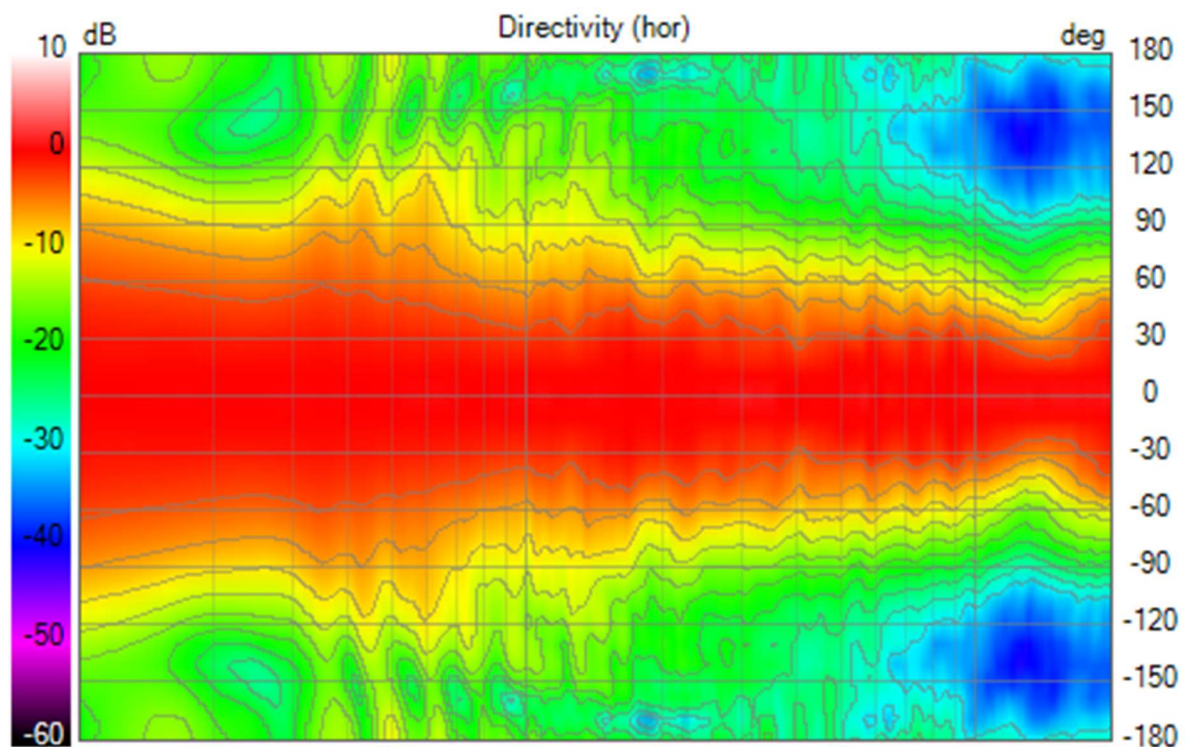


Figure 15 - Horizontal

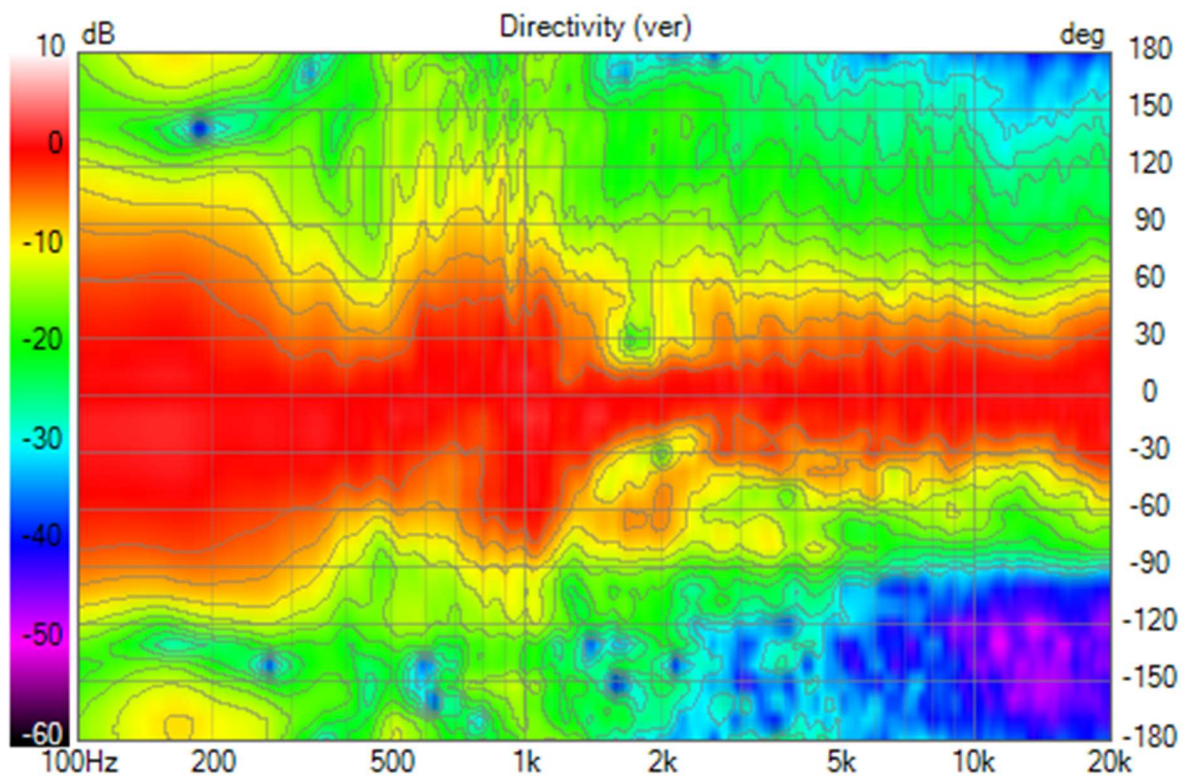


Figure 16 – Vertical

Figure 17 shows harmonic distortion measured at a level of 95dB. The software I've used to capture these measurements (REW) cannot gate distortion measurements. For this reason, distortion is only shown above 200Hz, as the room modes corrupt measurements as frequency decreases. This effect is already visible at ~210Hz in figure 17.

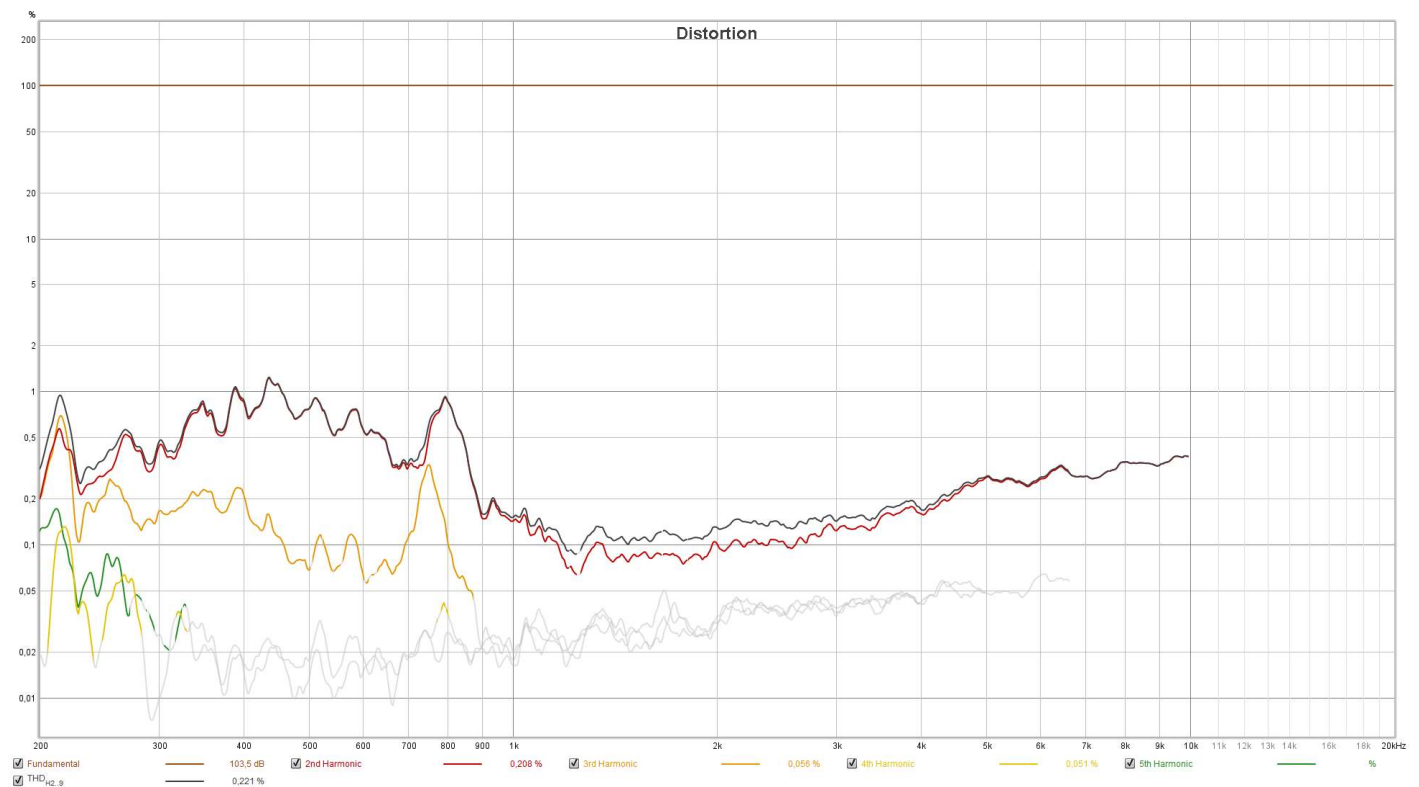


Figure 17

Finally, an in-room measurement of the loudspeakers is shown in figure 18. This response was measured with the moving mic method across a ~60cm width and ~30cm height at the main

listening position, approximately 2 meters away from the loudspeakers. A smooth frequency response is obtained, with only some room-related effects that are addressable by EQ remaining. My subjective impression of the speaker is that it lacks bass and has too much treble. Farther listening distances or tasteful high- and low-shelf filters can ameliorate this.

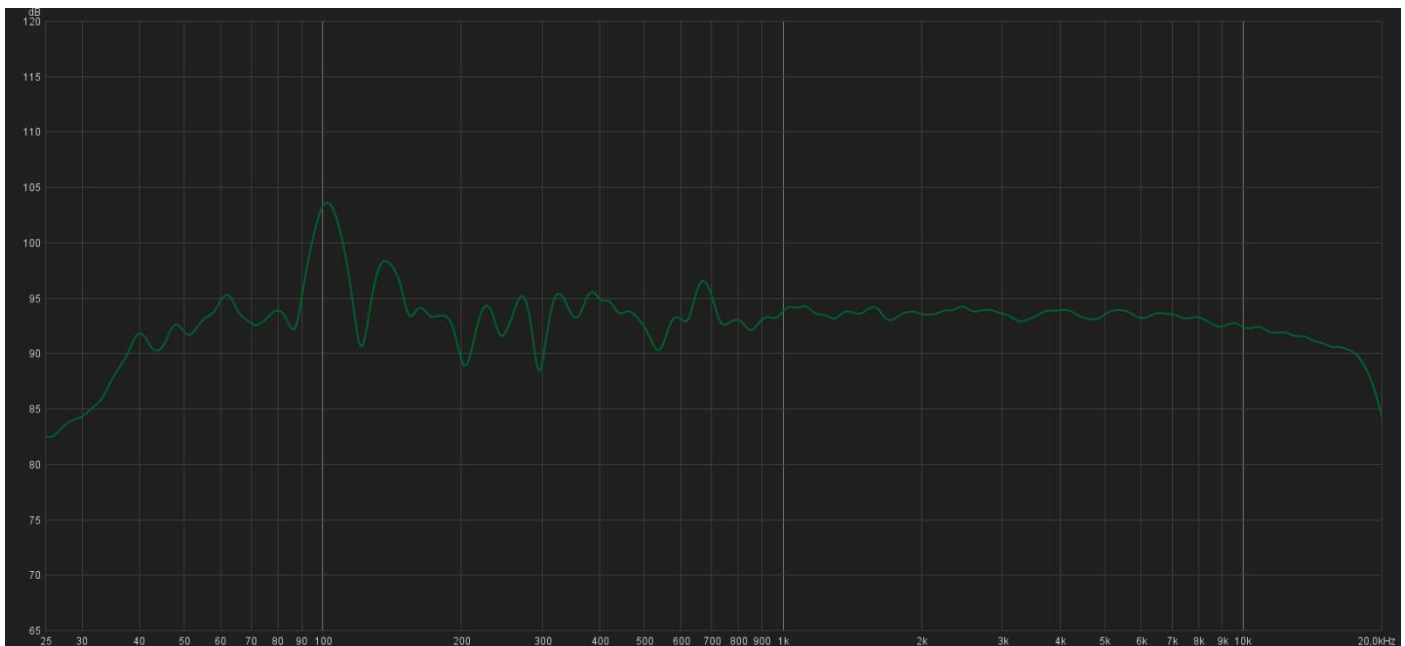


Figure 18

Personal thoughts and conclusions

While undertaking this project I learned a lot. In hindsight it is therefore easy to focus on all I did wrong (a lot). I am not unhappy with the result, as I have a speaker on my hands, and I believe it has been at least somewhat sensibly designed. In the end, I am happy with this undertaking, and I hope to look back on it with fond memories rather than cringe at my own incompetence. To fail is to be human, and to learn from failure even more so. Therefore, in the spirit of failure, I will list up easy-to-make improvements of this speaker.

1. Taper the cabinet width towards the top, so that the baffle the tweeter “sees” is slimmer than what it is currently. This will improve the on-axis response and radiation pattern of the tweeter (confirmed by simulation). It’s a visual improvement too.
2. Lower the crossover frequency between the tweeter and midrange somewhat, this will make the slope of the power response better, with only marginally higher distortion. The tweeter can easily handle a ~1750Hz crossover.
3. Swap the 4-inch midrange to a 5-inch or 6-inch unit. The wider radiation pattern of a 4-inch driver is not necessary for this project, due to the relatively low crossover frequency, and the waveguide restricting the radiation pattern in any case. A suitable 5-inch or 6-inch

midrange would allow lower distortion and higher output in the lower end of the passband, at no penalty.

There's a multitude of other improvements that could be made, but addressing those issues would be more complex, and a project in and of itself. For future projects I'd like to keep in mind what I learned here, and I'd also like to expand the scope of the project, for example by including cabinet resonance analysis by means of FEA. While there is substantial frustration involved in my own lack of skill and knowledge, this project has ultimately been a lot of fun.

I would like to thank you for your interest in the WGC1412, and for reading so far. I am not a good writer in general, and certainly not in English, but I hope this writeup was tolerable.

Georg W.B.

