The Open Source Monkey Coffin Loudspeaker

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IMPORTANT NOTES AND DISCLAIMERS

This document describes the design of the Open Source Monkey Coffin (OSMC) loudspeaker, which was developed in an “open-source project”.[1] The aim of this project is to provide the OSMC design to DIYers for their own private purposes, for example to build a copy of the OSMC. Do not use the information developed in this project on a larger scale without written permission (for example by selling speakers based on the OSMC design or substantial parts of it).

The OSMC development was financially supported by diyAudio members LORD-SANSUI, Paul Vancluysen, George Wright, KaffiMann, Charles Bueche, zimmer64, John Barbor, mbrennwa, and other anonymous members. Thank you!

1. OVERVIEW

The Open Source Monkey Coffin (OSMC) loudspeaker was developed by members of the diyAudio internet forum.[1] The motivation for developing this loudspeaker emerged from two diyAudio threads discussing the idea of “open source” loudspeaker designs.[2,3] Once the types of loudspeakers that would appeal to many novice DIYers were identified, the design targets for the OSMC were defined as follows:

- The OSMC must be straight forward to make for DIY novices.
- The box format should follow the “large monitor” format, sometimes also referred to as “monkey coffin” (hence the name). The internal volume should not be larger than 60–80 L. The enclosure must be a simple rectangular box which is easy enough to make on a kitchen table.
- The OSMC should be “amplifier friendly”. It should work well with small amplifiers like the popular Amp-Camp-Amp, tube amps, etc.
- The OSMC should be a three way loudspeaker.
- Keeping part costs low is not of paramount priority. If the right parts cost a lot of money and there are no cheaper equivalents, it’s okay to use those parts in the design.

2. SYSTEM DESIGN

For “amplifier friendliness”, the loudpseaker efficiency was targeted to 92 dB−SPL at 1 m and 2.83 V input voltage, with a bass extension to 45 Hz (–3 dB). The impedance curve must not exhibit any sharp peaks or dips, and the OSMC should qualify as an “8 Ω speaker”. It must be noted that, given the constraints of the box size, these targets could only be achieved if mechnical losses within the loudspeaker system were virtually zero, which is nearly impossible in real-world loudspeakers. While it is therefore not realistic to fully implement these design targets, these targets still provide useful guidelines for the design process.

The following is a brief summary of the design process, which is fully documented in the diyAudio thread.[1]The OSMC design was supported by the use of loudspeaker CAD tools (LEAP, Vituix CAD, Tolvan Edge). Measurement data were acquired using an RTX6001 USB audio analyser, MATAA software, and Earthworks M23 and iSEMcon EMX-7150 microphones. Data from measurements and simulations are available in the OSMC data repository.[4]

2.1. Drivers

High-quality drivers and parts should be chosen based on the technical specations required for the OSMC design. The look of the drivers has to be “right” for a HiFi system in a home environment (people may not want to build a speaker that looks unusual), but is second priority after the techincal specifications.

The woofer will determine the compromise between box size, bass-extension, and efficiency. The size of the woofer critically determines the efficiency of the loudspeaker, and a 12" woofer will just fit the targeted box size. After screening numerous woofers based on their specifications, Thielle-Small parameters, and tests of harmonic distortion the FaitalPro 12PR320 woofer was selected.[5,6]

The midrange driver needs to keep up with the requirements of the sound pressure level (SPL) and impedance. The Volt VM752 dome driver will work very well from 400 Hz up to about 3 kHz. While there may be other midrange drivers that could be used, the VM752 was chosen due to the general interest for this driver and because some of the OSMC designers had good experience using this driver.

The tweeter also needs to keep up with the SPL and impedance requirements. Classical dome or ring radiator tweeters were preferred by the OSMC designers. Also, the use of a waveguide seems favourable in order to match the dispersion of the tweeter to the midrange, to reduce the effects of baffle diffraction, to increase the on-axis efficiency, and to reduce non-linear distortion of the tweeter. Tweeters with high directivity tend to minimize acoustic interference with the waveguide at

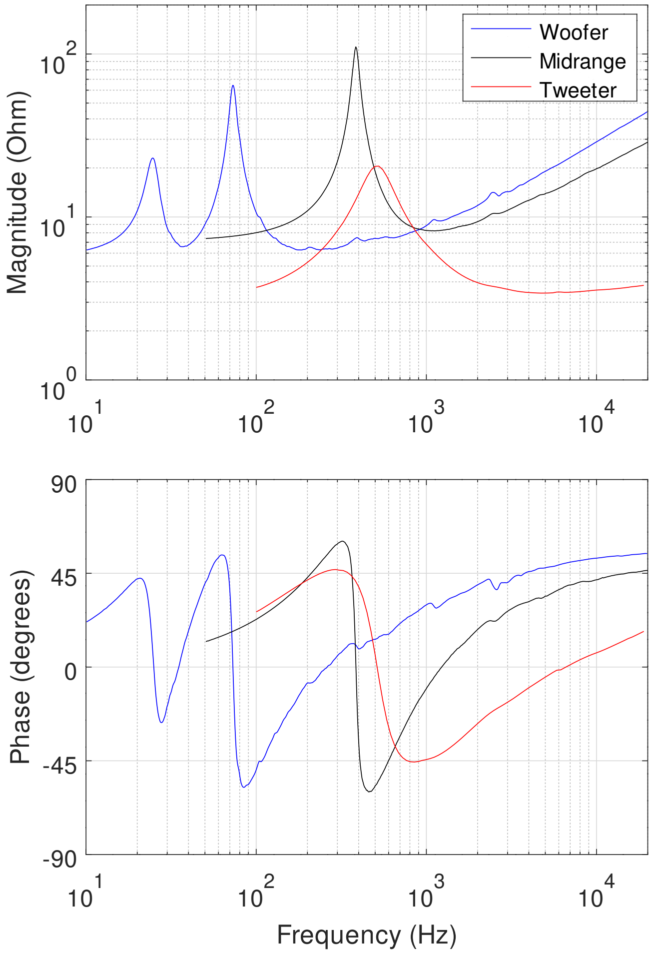

Figure 1: Impedance curves of the drivers mounted in the OSMC box (magnitude and phase).

wavelengths similar to the throat diameter, which helps to avoid large SPL wiggles at high frequencies.[7] Therefore, the Scan Speak R2904/7000 ring radiator was chosen. The R2904/7000 also features high electrical impedance, high efficiency, and very low harmonic distortion. Most of the design work was done with a Visaton WG148 waveguide, which was modified to fit the R2904/7000.[8] However, the final design uses a custom-made waveguide, which was designed specifically for use in the OSMC by diyAudio user augerpro.[9] The augerpro waveguide is acoustically almost identical to the WG148,[10] but is very easy to fit on the R2904/7000. It is available for purchase via group buy at diyAudio.[11]

Fig. 1 and Fig. 2 show the impedance and the SPL response of the drivers mounted in the OSMC box. These data were used as the basis for electro-acoustical modelling of the crossover filters.

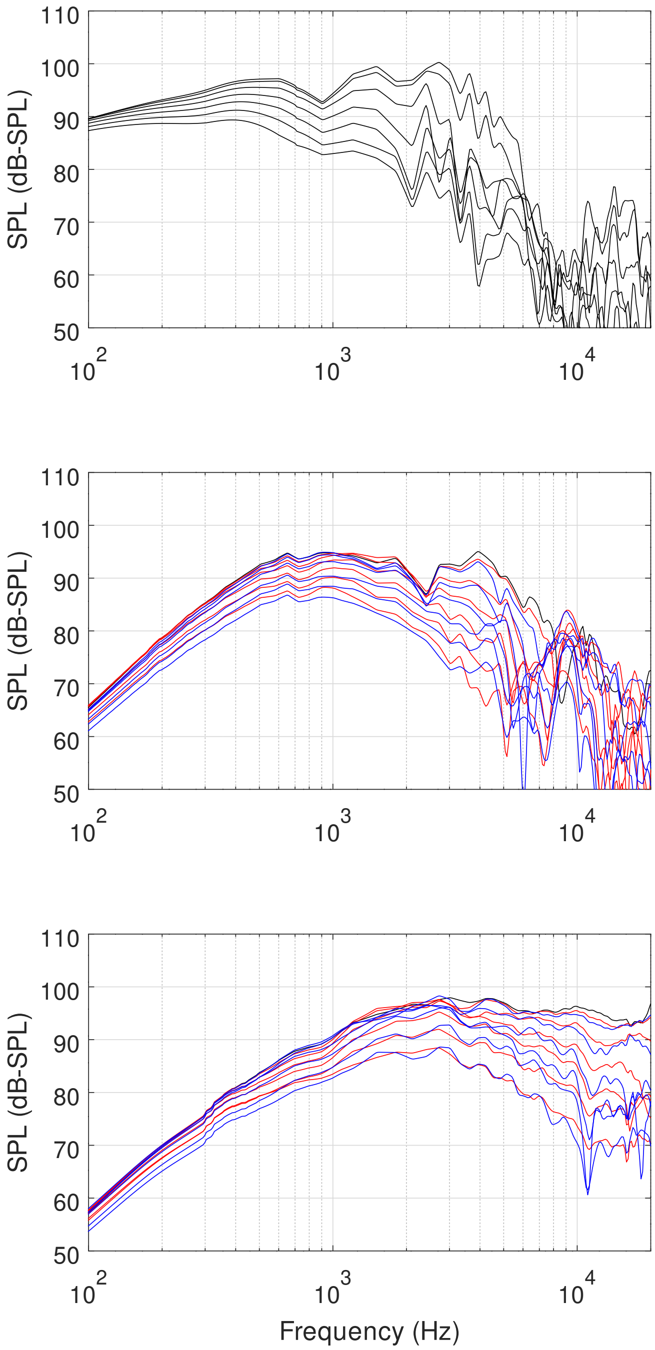

Figure 2: SPL response curves of the woofer (Faital 12PR320, top), midrange driver (Volt VM752, center) and tweeter (Scan Speak R2904/7000 with WG148 waveguide) mounted in the Monkey Coffin prototype box, measured at 2.83 Vrms and 1 m distance from the drivers, on axis and at ±15°, ±30°, ±45°, ±60°, ±75° and ±90° horizontal angles (the red curves were measured on the side where the tweeter and midrange drivers are closer to the baffle edge, the blue curves are from the other side; the woofer data is symmetric). Above 300 Hz, the curves show the anechoic response as obtained from gated impulse-response measurements. The anechoic curves were extrapolated to lower frequencies by splicing them with modelled low-frequency curves (see text).

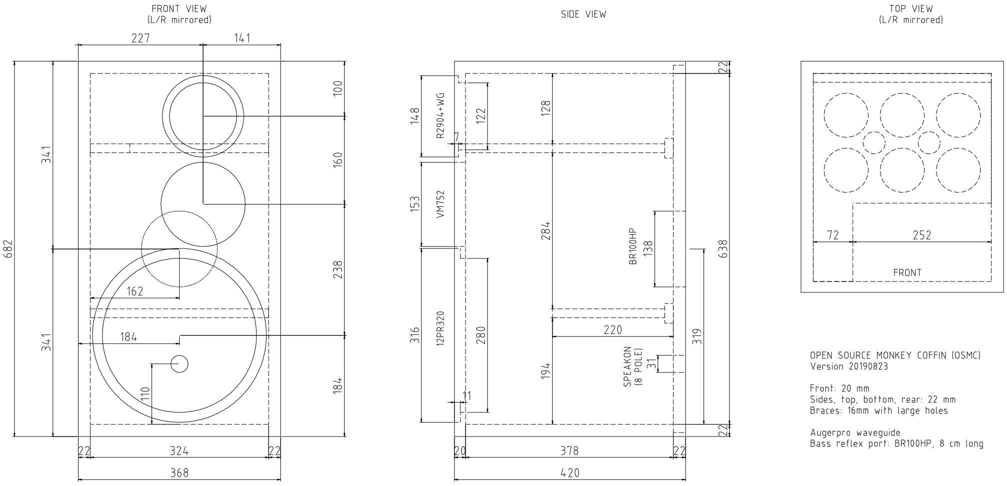

Figure 3: Drawing of the OSMC enclosure. Notes: (1) the horizontal driver offsets are mirrored in the left and right speakers; (2) the rear must be removable for installation of the Volt VM752 driver; (3) the front needs to be 20 mm thick to fit the Volt VM752 flange; (4) the speaker terminal hole shown here fits a Neutrik NL8MPR-BAG 8-pole Speakon terminal (adjust as suitable).

The SPL response curves were obtained from gated impulse-response measurements, which yielded the anechoic SPL response above 300 Hz. Measurements were taken at horizontal angles from −90 ° to 90 ° at 15 ° steps. The low-frequency parts of each SPL curve were calculated from the Thielle-Small parameters of the drivers (using LEAP) and a diffraction model of the Monkey Coffin baffle (using Vituix CAD).[12] The anechoic part and the low-frequency part of each SPL curve were merged using a "soft splice" in the frequency range where both parts of the curve overlapped consistently.[13] Finally, the phase response (not shown in Fig. 2) was determined by calculating the minimum phase from each of the merged SPL curves. The drivers show smooth SPL response curves throughout their intended operating range. The on-axis on-axis response of the Volt VM752 midrange shows a dip at 2.3 kHz. This dip disappears in the off-axis curves, which indicates that this is an uncritical diffraction artifact related to the driver/waveguide geometry rather than a problematic resonant effect.

2.2. Baffle and Cabinet

Fig. 3 shows the OSMC cabinet. The dimensions of the baffle are largely deteremined by the space required for the drivers. The tweeter and midrange are horizontally offset relative to the center in order to spread effects of diffraction at baffle edges over wide frequency band as much as possible.

The cabinet volume and the dimensions of the bass-reflex port were determined

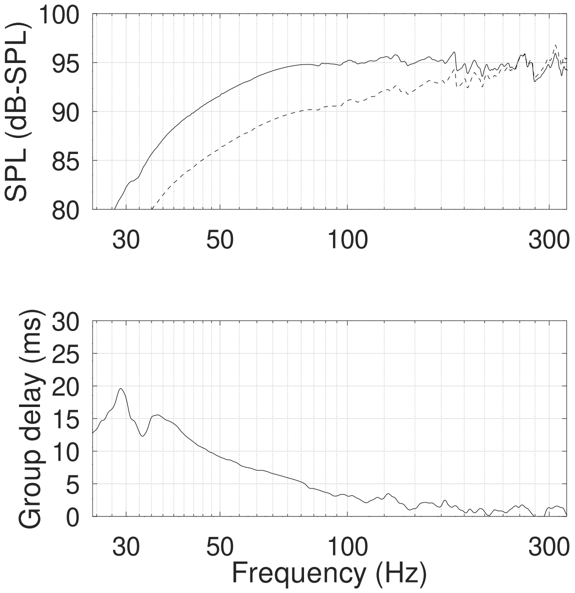

Figure 4: Top: bass SPL response for 2.83 Vrms drive voltage, at 1 m (solid line: 2π response as measured using the microphone-in-box method,[14] dashed line: estimated 4π response taking into account the modelled baffle-step loss). Bottom: group delay determined from 2π SPL response. See also text).

using simulations and measurements of the bass tuning. The goal was to obtain flat SPL response down to the cut-off frequency. In order to keep group delay low, the bass SPL curve was designed to roll off smoothly Fig. 4 shows the 2π free-field bass SPL response and the corresponding group delay. The SPL curve was determined using the microphone-in-box technique[14] for data up to 110 Hz, which were spliced to a near-field measurement from 90 Hz upwards. Note that this 2π SPL curve (solid line in Fig. 4) assumes an infinite baffle and therefore does not show the baffle step as it occurs at the transition from the 4π radiation at low freqencies to 2π at higher frequencies. To estimate the true 4π SPL response of the woofer the OSMC box (dashed line in Fig. 4), the OSMC baffle step was modelled using the Tolvan Edge simulator.

2.3. *Crossover filters*

The crossover filters are implemented as passive circuits using steep filters in order to achieve small overlaps between the drivers in the crossover frequency bands, which reduces acoustic interferences between the drivers.

Full compensation for the baffle diffraction loss was designed into the crossover filters. The modelled curves of the diffraction loss were subtracted from the 2π

SPL response curves of the raw drivers (see Sec. 2.1). These SPL curves were used to design the filters to achieve a balanced 4π SPL response.

Two different filter types were considered during the prototyping process.[15] The first prototype uses elliptic filters, which are not very widely used in conventional loudspeaker designs. While the transfer functions of elliptic filters may exhibit some ripple near their cut-off range, they allow very steep slopes. The second prototype was designed with simpler and more conventional circuit topology using series inductors and parallel capacitors for the low-pass sections, and vice-versa for the the high-pass sections. Both prototypes were optimized for smooth and flat overall system SPL response, smooth dispersion and power response, and symmetric acoustic filter slopes near the cross-over points. The summed SPL curves in the filter simulations were virtually identical.

Both filter prototypes were implemented for testing in the OSMC prototype using a miniDSP digital signal processor. Acoustic measurement results with these DSP filters were similar for both filters, whereas the elliptic filters resulted in slightly more refined sound in listening tests.[16] The elliptic filters were therefore implemented as passive circuits and further optimized using acoustic measurements and listening tests. The schematic of the final cross-over filters is shown in Fig. 5, with the part specifications in Tab. 1.

3. CONSTRUCTION

3.1. Estimated Costs

The costs for a complete speaker are dominated by the drivers and the x-over parts. The costs for the cabinet depend a lot on the materials used. The estimated cost per speaker is as follows (not including taxes and shipping):

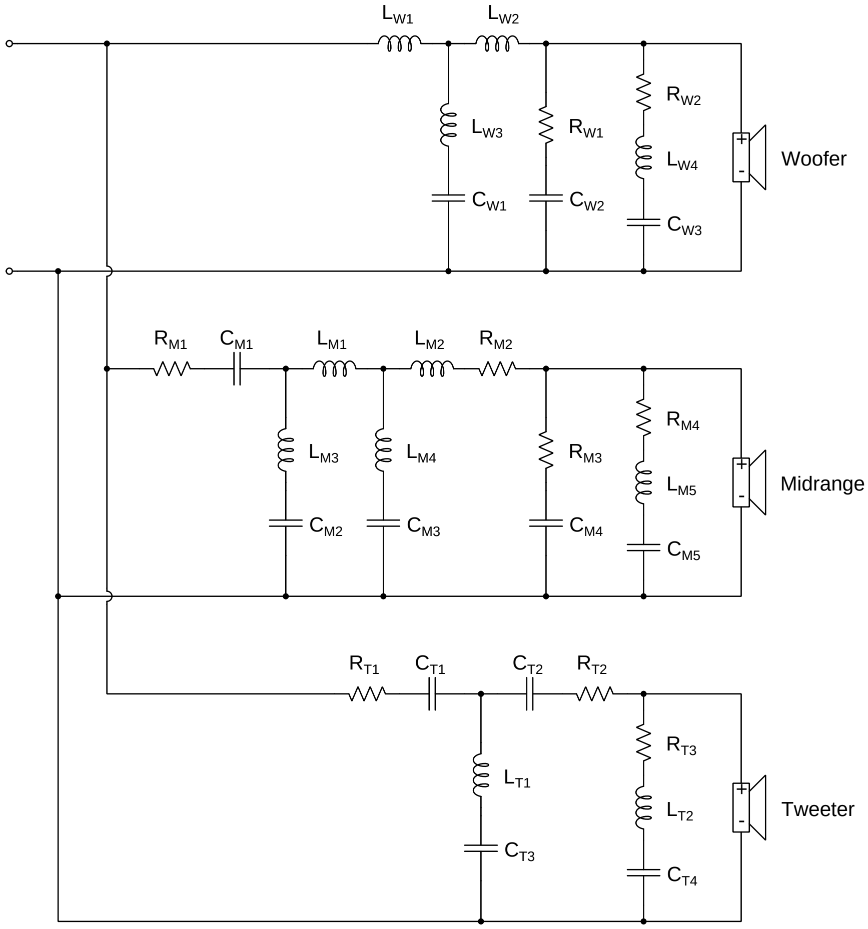

Figure 5: OSMC cross-over filters (elliptic).

Table 1: List of parts in Fig. 5 (version 2019-08-23).

Part	Value	Description
L_{W1}	6.8 mH / 0.19 Ω	Laminated iron core (e.g. Mundorf BS180, Feron, I core, baked varnish)
L_{W2}	1.8 mH / 0.09 Ω	Laminated iron core (e.g, Mundorf BS180, Feron, I core, baked varnish)
L_{W3}	0.1 mH / 0.23 Ω	Air core (e.g. Mundorf BL71, baked varnish)
L_{W4}	15 mH / 1.12 Ω	Iron core (e.g, Mundorf BH71, Ferrite, baked varnish)
C_{W1}	118 µF	Parallel combination of 100 µF bipolar electrolytic (e.g. Mundorf ECAP50) and 18 µF MKP (e.g. Mundorf MCAP250)
C_{W2}	33 µF	Bipolar electrolytic (e.g. Mundorf ECAP70)
C_{W3}	267 µF	Parallel combination of 220 µF and 47 µF bipolar electrolytics (e.g. Mundorf ECAP63 / ECAP50)
R_{W1}	6.8 Ω / 10 W	MOX type (e.g. Mundorf MR10)
R_{W2}	5.6 Ω / 10 W	MOX type (e.g. Mundorf MR10)
L_{M1}	1.2 mH / 0.44 Ω	Air core (e.g. Mundorf BL125, baked varnish)
L_{M2}	0.39 mH / 0.15 Ω	Air core (e.g. Mundorf BL140, baked varnish)
L_{M3}	6.8 mH / 0.46 Ω	Iron core (e.g. Mundorf BH100, Ferrite, baked varnish)
L_{M4}	0.12 mH / 0.15 Ω	Air core (e.g. Mundorf BL100, baked varnish)
L_{M5}	2.7 mH / 1.01 Ω	Iron core (e.g. Mundorf BP71, Ferrite, baked)
C_{M1}	33 µF	MKP (e.g. Mundorf MCAP250)
C_{M2}	267 µF	Parallel combination of 220 µF bipolar electrolytic (e.g., Mundorf ECAP63) and 47 µF MKP (e.g. Mundorf MCAP250)
C_{M3}	5.6 µF	MKP (e.g. Mundorf MCAP250)
C_{M4}	4.7 µF	MKP (e.g. Mundorf MCAP250)
C_{M5}	68 µF	Bipolar electrolytic (e.g. Mundorf ECAP50)
R_{M1}	2.7 Ω / 10 W	MOX or wire wound (non-inductive) (e.g. Mundorf MRES20)
R_{M2}	5.6 Ω / 10 W	MOX or wire wound (non-inductive) (e.g. Mundorf MRES20)
R_{M3}	8.2 Ω / 10 W	MOX or wire wound (e.g. Mundorf MR10)
R_{M4}	8.2 Ω / 10 W	MOX or wire wound (e.g. Mundorf MR10)
L_{T1}	0.18 mH / 0.38 Ω	Air core (e.g. Mundorf BL71, baked varnish)
L_{T2}	0.47 mH / 0.64 Ω	Air core (e.g. Mundorf BL71, baked varnish)
C_{T1}	4.7 µF	MKP (e.g. MCAP250)
C_{T2}	15 µF	MKP (e.g. MCAP250)
C_{T3}	100 µF	Parallel combination of 82 µF bipolar electrolytic and 18 µF MKP (e.g. Mundorf ECAP50-82 and MCAP250-18)
C_{T4}	100 µF	Bipolar electrolytic (e.g. Mundorf ECAP50)
R_{T1}	3.9 Ω / 10 W	MOX or wire wound (non-inductive) (e.g. Mundorf MRES20)
R_{T2}	1.0–1.3 Ω / 3–10 W	MOX or wire wound (non-inductive) (e.g. Mundorf MRES20 or Vishay MRA), higher value results in slightly less treble[17]
R_{T3}	4.7 Ω / 10 W	MOX type (e.g. Mundorf MR10)

Part	Cost (€)	Remarks
Woofer (FaitalPRO 12PR320)	120	
Midrange (Volt VM752)	500	
Tweeter (Scan Speak R2904/7000)	250	
Tweeter waveguide (augerpro)	85	diyAudio group buy[11]
X-over parts	300	Parts as in Tab. 1
Cabinet	approx. 100	Basic MDF or plywood cabinet
Damping materials	approx. 50	Basotect, sheeps wool
Bits and pieces	approx. 50	Bass reflex port, screws, wires, connectors, etc.
Total	approx. 1500	

3.2. Baffle and Cabinet

The OSMC cabinet is a simple rectangular box and is straightforward to build (Fig. 3 and Fig. 6). The rear wall should be removable to facilitate the rear mounting of the midrange driver. Internal braces reduce vibrations of the cabinet walls.

Any standing waves (modes) that develop in the enclosure need to be attenuated by suitable damping materials inside the enclosure. The mode along the vertical axis of the enclosure has a wavelength of $2 \times 0.638\,\mathrm{m} = 1.28\,\mathrm{m}$, which corresponds to 269 Hz. This mode is attenuated using melamine foam absorbers (Basotect, Ewos ME50SK Pyramid) at the bottom and the top, and some sheeps wool the top, as shown in Fig. 6. Any potential modes along the horizontal axes (left/right, rear/front) would exhibit considerably shorter wavelengths that correspond to frequencies of 450 Hz and higher, which are above the pass band of the woofer. These odes are therefore hardly excited and therefore do not require special attention. Also, the sound radiated from the woofer into the enclosure is reflected at the read wall. Another Basotect layer covering lower half of the rear wall is used to reduce this unwanted reflection. The remaining internal surfaces of the enclosure are covered with a thin layer of melamine foam only (use a large knive to remove the excess material as shown in Fig. 6). There may also be other materials and arrangements of sound absorbers inside the enclosure that may lead to good results, and builders are encouraged to tweak the OSMC sound character in the low midrange and bass to their tastes. As a general rule, however, make sure not to obstruct the space between the woofer and the bass-reflex port.

The bass reflex port (type Monacor BR-100HP / Jantzen HP 900028) is cut to length and are then press-fit mounted in the rear wall. To ensure a tight seal between the rear baffle and the flange of the port, the flange may be wrapped

Figure 6: OSMC front and back with rear wall removed to show the bracing and damping. The red parts of the Basotect absorbers are removed using a large knive.

Figure 7: Photo of the R2904 tweeter mounted on the waveguide using a clamp.

with a few layers of tape. The recommended port length is approximately 8–9 cm long,[18] but slightly different port lengths (7 cm to 11 cm) can be used to tweak the bass response. A longer port will cause a lower bass tuning with a softer roll off, whereas a shorter port will cause a higher bass tuning with a slight bass peak.

3.3. *Fitting the Tweeter Waveguide*

To mount the tweeter waveguide to the Scan Speak R2904 driver, the original faceplate needs to be removed from the tweeter by removing the three Torx screws. Note that the three empty screw holes that were used to fix the original faceplate to the tweeter would cause air leaks from the rear chamber, resulting in an undesired bass reflex tuning of the tweeter.[19] The screw holes therefore need to be sealed with silicone or similar in order to maintain the desired tuning of the tweeter resonance.[20] The waveguide is fixed to the tweeter either using a clamp[21] bolted to the rear of the waveguide (Fig. 7), or using a thin layer of silicone or similar glue.

3.4. *Crossover Filters*

Fig. 8 shows the construction of the x-over filters according to Fig. 5. The parts are fixed to a base and connected to each other using flying leads. Given the size and complexity of the x-over circuits, it make sense to build the filters for the tweeter, midrange and woofer as separate modules, and to mount these modules in a separate box instead of in the OSMC cabinet. In order to minimize magnetic comupling and crosstalk between the different inductors, the inductors should be arranged perpendicular to each other and separated from each other as much as possible.[22]

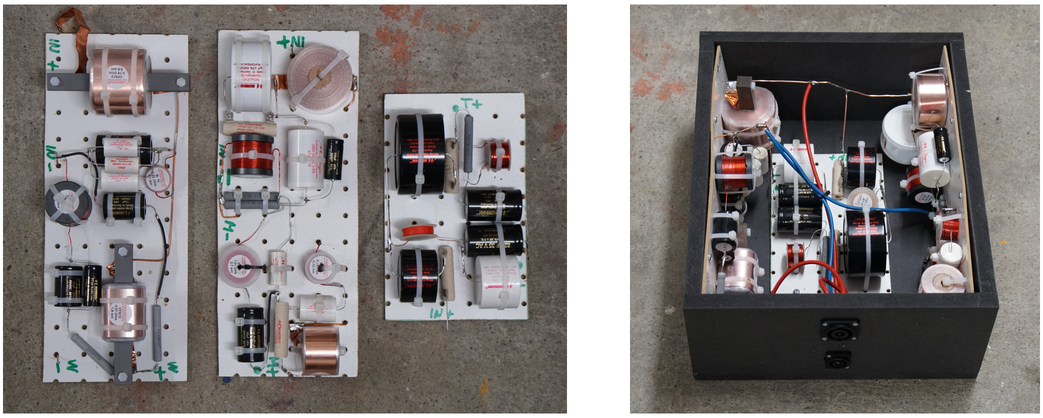

Figure 8: Construction of the crossover filter. Left: filter modules for the woofer, midrange, and tweeter. Right: complete crossover for one channel.

Note that the manufacturers and type numbers of the parts suggested in Tab. 1 correspond to the parts used in the OSMC prototype. These are high quality parts and work well, but they may be substituted with other parts with the same specifications. It must be noted, however, that expensive boutique parts do not always yield better sound. For instance, the "high-end" MKP capacitors shown in Fig. 8 resulted in bloated and euphonic sound, and were later replaced by other MKP capacitors.[23]

4. SYSTEM TESTS AND PERFORMANCE

4.1. Electronic

Fig. 9 shows the OSMC impedance vs. frequency. The impedance reaches its minimum value of 4.8 Ohm at 33 Hz, and ranges from 5.5 Ohm to 12.8 Ohm above 45 Hz. There are no sharp variations in the impedance curve, which is also expressed in the rather flat curve of the impedance phase. The OSMC is therefore an easy load for the amplifier, even if the targeted "8 Ohm" rating[24] is valid only above 100 Hz in a strict sense.

Fig. 10 shows the OSMC filter transfer curves. The leakage in the stop bands of the elliptic filters is obvious for the midrange filter. However, the efficiency of the midrange driver in the respective frequency bands is very low (Fig. 2), and the attenuation in the stop bands is –25 dB or better. The filter leakage is therefore considered irrelevant.

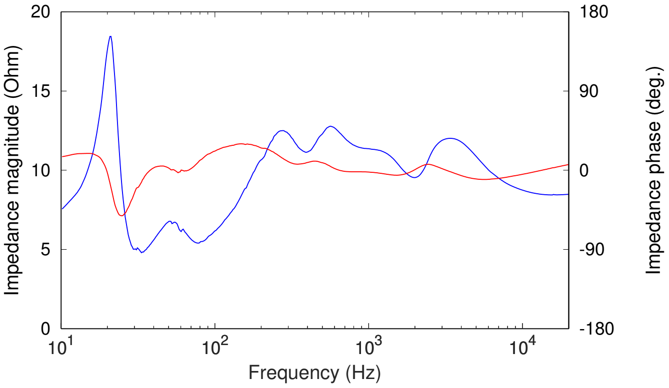

Figure 9: Measured electrical impedance (magnitude in blue, phase in red).

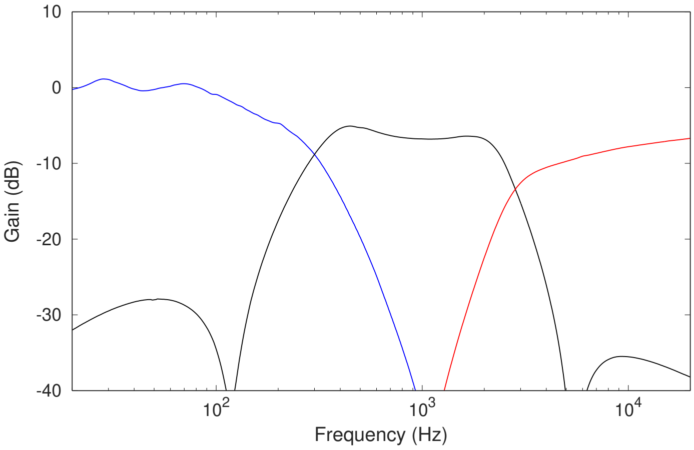

Figure 10: Measured transfer curves of the crossover filters for the woofer (blue), midrange (black), and tweeter (red).

4.2. Acoustic

Fig. 11 shows the free-field OSMC step response with the typical 3-way sequence of the tweeter peak followed by the peaks of the midrange and the woofer. The transitions between the peaks are smooth, and no resonances or other time-domain issues are apparent.

Fig. 12 shows the anechoic free-field (4π) on-axis SPL response. The part of the response curve above 330 Hz was determined from the anechoic part of the impulse response. The bass response of the OSMC system was determined from the 4π far-field woofer response (Fig. 4) and the woofer x-over filter curve (Fig. 10). The bass −3 dB cut-off is at 50 Hz, as targeted in the design goals. The efficiency is 90 dB–SPL (1 m, 2.83 V) in the bass range. As expected, this is slightly less than the design goal, which is based the theoretically achievable optimum for a system with zero losses. Overall, the SPL response is very linear and shows a slight trend of decreasing SPL at higher frequencies. This decrease is required to compensate the progressive beaming of the waveguides in order to achive the desired slope of the power response curve (see below). The small dip at 2.2 kHz is a baffle-diffraction effect that is not apparent in the off-axis response.

Fig. 13 shows the SPL dispersion of the OSMC. Both the horizontal and vertical dispersion are well controlled and are generally very smooth. Beaming increases smoothly towards higher frequencies. The vertical dispersion shows a cancellation at the x-over between the midrange driver and the tweeter. However, due to the steep x-over filters, this artifact is limited to a rather narrow frequency band.

The in-room SPL curve of the OSMC in a generic room was estimated from the sound power radiated into the listening environment (power response, Fig. 14). The power response was calculated by summing the polar SPL reponse data over a virtual sphere around the loudspeaker.[25,26] Systematic listening studies in typical home environments showed that listeners preferred a smooth and linear in-room SPL response curve, and they perceived the sound as balanced if the in-room response showed a decreasing trend towards higher frequencies.[27] These features are nicely demonstrated in the OSMC power response. Note that the OSMC loudspeaker approaches constant directivity behaviour. The on-axis response curve therefore needs to show a similar decreasing trend as the power response curve in order to achieve balanced sound.

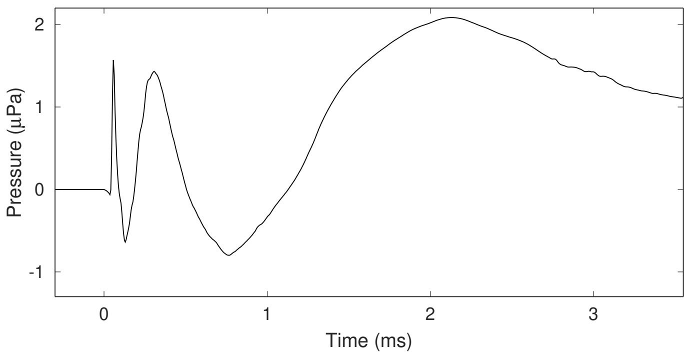

Figure 11: Step response at 1 m (anechoic part).

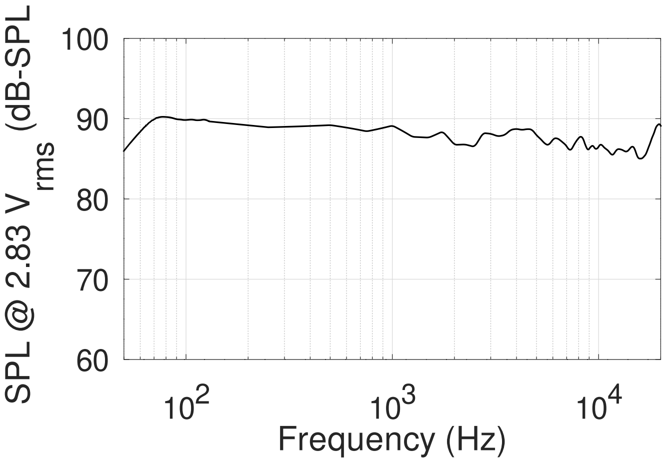

Figure 12: SPL response at 1 m (on axis, free field / 4π, see text).

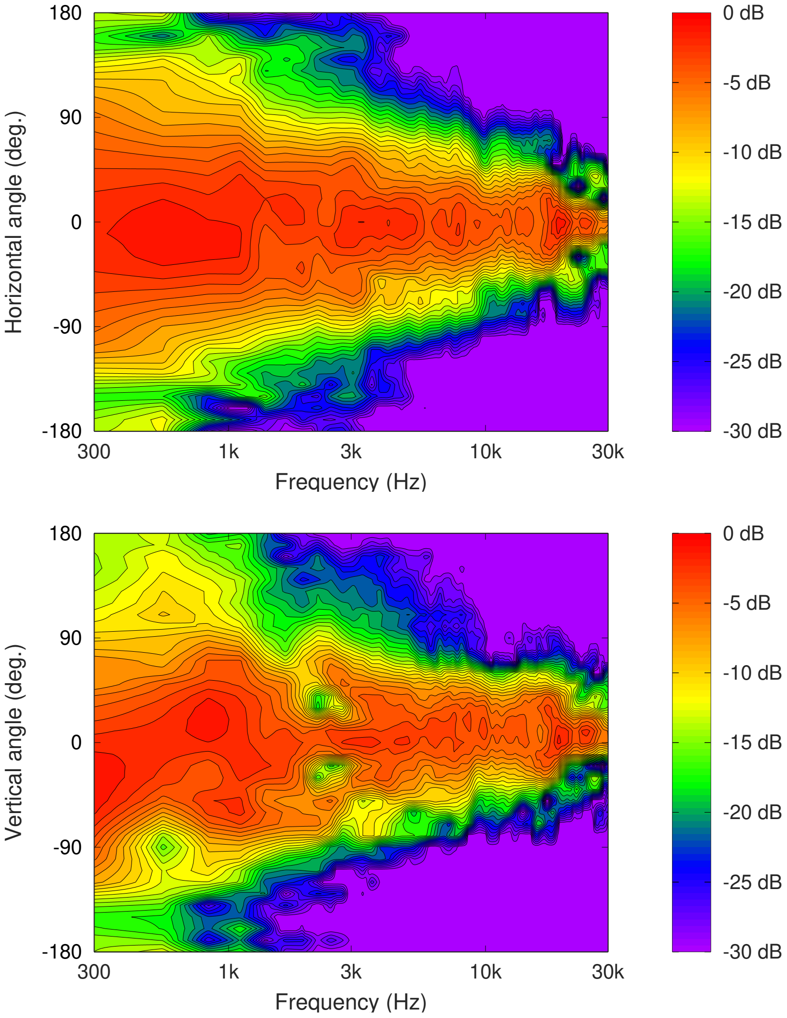

Figure 13: SPL dispersion (top: horizontal dispersion, bottom: vertical dispersion).

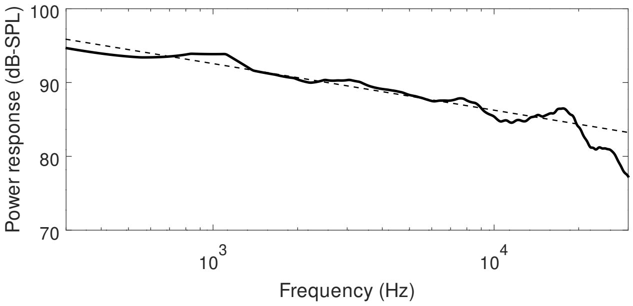

Figure 14: Power response (see text).

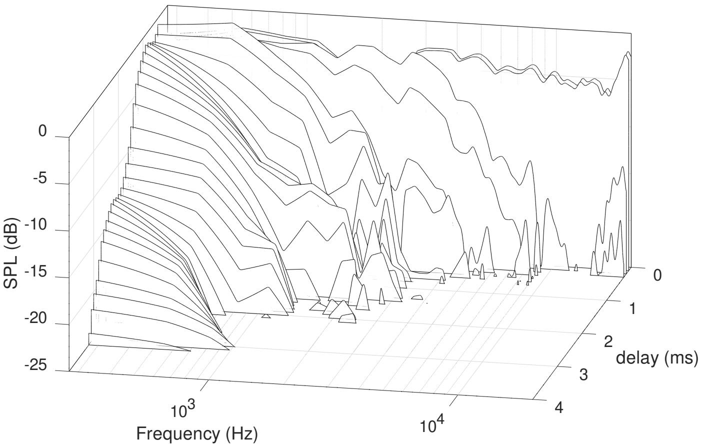

Figure 15: Cumulative spectral decay diagram.

4.3. Listening impressions

The OSMC was designed for accurate music playback in a home environment with “amplifier friendliness” in mind. Listening tests were therefore conducted with a 11 W tube amplifier (triode push pull design) and a 25 W solid state amplifier (FirstWatt F5 class-A). These amplifiers had no problems driving the OSMC to “party levels”, which confirms the “amplifier friendliness” of the OSMC.

The overall sound is balanced and coherent, with tight, articulate and well controlled bass. As an inevitable physical consequence of the “amplifier friendliness”, however, the bass is not as deep as with some other similar sized “HiFi” loudspeakers that need to be driven by powerful amplifiers. The OSMC sounds highly transparent and dynamic, both at low and high playback levels. This lack of compression allows good resolution of low-level details even with complex or loud music. The waveguides result in a large proportion of direct sound at the listener position, resulting in precise rendering of the musical scene with less impact of the reverberant sound of the room.

5. MODIFICATIONS

5.1. Larger Floorstanding Box (Open Source Monkey Tower)

Some builders used a larger, floorstanding box. This allows increasing the bass extension by tuning the bass-reflex system to a lower frequency. Increasing the box volume must be done such that the width of the front baffle and the position of the drivers relative to the top and the sides of the front are not changed. Lowering the bass-reflex tuning frequency involves a change in the impedance curve of the woofer, so the impedance compensation needs to be adjusted.

For example, a larger floor-standing box could be built as follows:[28]

- Increase the internal box volume to 101 L by increasing the height of the box.
- Change the bass-reflex tuning by using two ports, each with 4 inch diameter and 24 cm long. The ports are placed at the height midpoint of the box.
- Change the woofer impedance compensation in the x-over to $C_{\mathrm{W3}} = 320\,\mu\mathrm{F}$ and $L_{\mathrm{W4}} = 18\,\mathrm{mH}$.

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