Figure 1: Mustang, a small, agile speaker

This article describes the design of speakers of relatively small size (about 10 litres or so) and low-cost, that can be used for computer audio or to replace the speakers usually bundled with compact HIFI systems.
The design stages are described in chronological order, from the choice of loudspeaker to the measurement of the resulting speaker's performance. The process is as recommended by J. D'appolito in his book 'Testing Loudspeakers'
The reader will find all useful references at the end of the document. Most of these are available on Internet.

1 Choice of loudspeakers

For the woofer, I started by searching for a wide-band loudspeaker such as the Tang-band W3-871 or Fostex FE-103, but then gave up for the following reasons:

- W3-871 : Too high cut-off frequency to my taste (~130hz) for such a small speaker.
- Fostex FE-103: doubts on the bandwidth quality for high-frequency response (check out the speakers designed by Troels Gravesen that use a FE-126).

I went back to a 10-13 cm woofer + tweeter solution. In addition to their remarkable DIY designs, the website Zaph audio (http://wwwzaphaudio.com/) provides a lot of information on speakers, their performance and their application.
If I set aside, for economic reasons, high-end speakers such as Scan-Speak, SEAS Excel or Audio Technology, my choice comes down to SEAS Prestige speakers which seem to be of good value:

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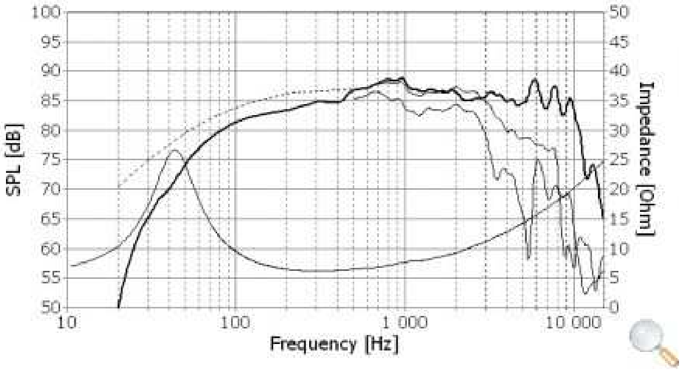

Figure 2 : Woofer SEAS ER15RLY

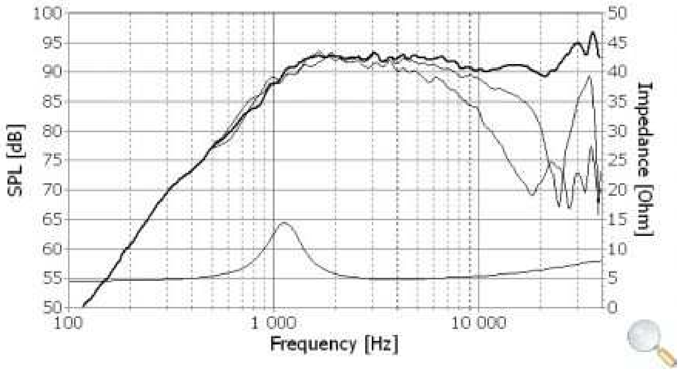

Figure 3 : Tweeter: SEAS 22 TAF/G

The bandwidth of the two speakers must be compatible with a crossover frequency between 2 and 4 KHz, and permit simple filtering because the bandwidth overlap of the speakers is quite large. We will see further on, however, that the diffraction due to the baffle heavily disturbs the 1 to 3 KHz zone. Because of its characteristics the woofer (QTS=0,324) is intended to be used in a bass-reflex design.

2 Cabinet sizing

Several freeware packages are available on the Internet to help the designer choose the volume of the enclosure dedicated to the woofer, including:

- WinISD (http://www.linearteam.dk/)
- UNIBOX (http://audio.claub.net/software/kougaard/index.html)

With Unibox, you get, in bass-reflex, for a butterworth response type without a peak in the low frequencies, a 7 litres volume and a cut-off frequency of about 58 Hz with a port of 5 cm diameter and a length of 22 cm.

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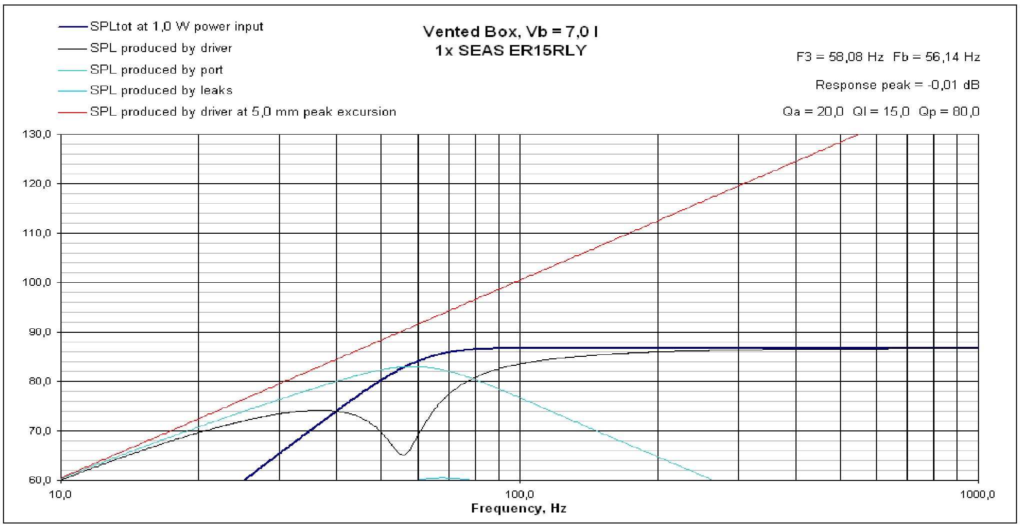

Figure 5

Figure 6: low frequency domain calculated with Unibox

The results are confirmed by SoundEasy, which is the software I generally use (and that I heartily recommend despite its high cost when compared with other products such as 'Speaker Workshop') for measurement and filter design . Small variant: a slightly larger volume (9 liters) and 17 cm reduced length for the port, which is easier to install in a small cabinet, but at the expense of a slightly higher F3 frequency (60 Hz).

Figure 7: low-frequency domain calculated with SoundEasy

To conclude, I aim for a global volume of about 10 litres taking into account the additional space needed for the speakers, filter and port.

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3 Mustang Box drawings

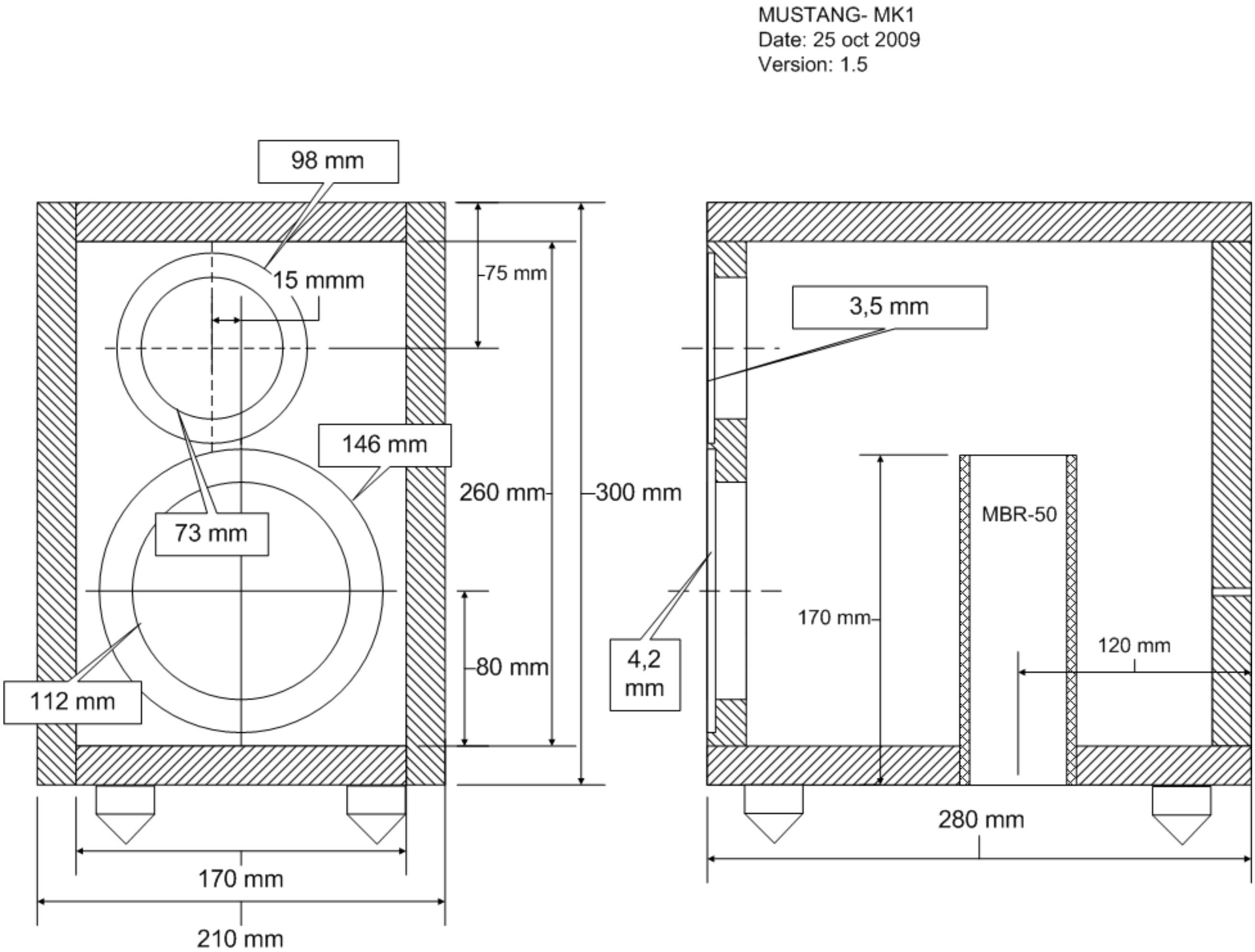

Figure 8: Enclosure plans

Because of its small size, the cabinet is a simple box built with 6 pieces of 19 mm MDF, without any internal brace. The prototype I built differs from the plan because it has a removable front to allow easy testing. It is screwed to a front panel of identical size (photos are available in the Woodwork section).
Due to the size of the port, it is installed vertically and exits under the cabinet, which rests on 4 cm rubber feet.
The tweeter is offset to minimize the diffraction due to the baffle at high frequencies. These schematics represent the right-hand speaker, the left-hand one being symmetrical (tweeter on the right hand side).
The filter will be mounted on the back of the cabinet (not shown on the plan).
Since the beginning of the project, I wanted to use veneer as finish for the cabinet, so none of the corner are rounded. Aesthetics came first, at the expense of a less linear response curve of the speakers in the box (see measurements)

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4 Woodwork

The sides and rear of the enclosure are simply fixed with wood glue and held in place with clamps while the glue cures. Before gluing, the rear is prepared: holes are drilled to allow fitting of the filter which is wired on a printed circuit of 100*160 mm, and self-adhesive bituminous panels that damp the MDF panel are fitted. The same bituminous panels are used to damp all sides of the box, except the front face.

The next picture shows the enclosure during construction with the backplate fitted to carry the front panel. The cabinet is then veneered. To do this, I chose poplar burr, instead of the more expensive walnut burr. Compared to traditional veneering, this requires a lot of coating and sanding after gluing. The cabinets are then sealed with several thin coats of varnish and a final polish to get a semi-gloss finish.

Figure 9: Speaker being built

Figure 10 : Poplar Bramble Veneer

The most difficult part of the woodwork is the front panel that has to be carved to fit the loudspeakers. You need to have a router as well as a compass at hand (like Jasper Jig) to design rebates. Note that the rear cutting for the woofers is also scalloped to give the most space possible to ease airflow behind the cone.

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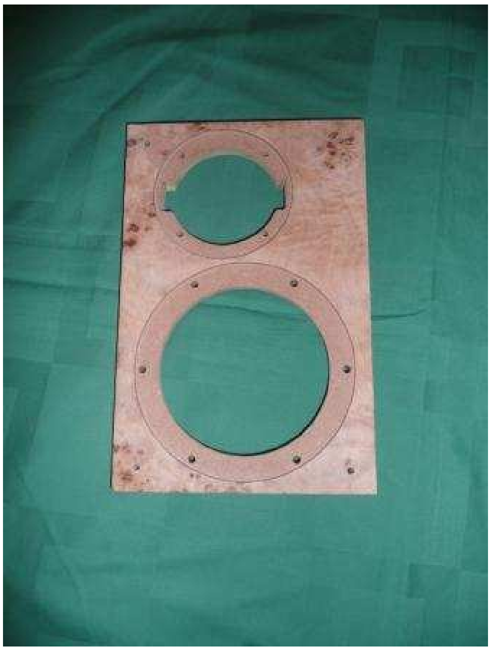

Figure 11 : Front

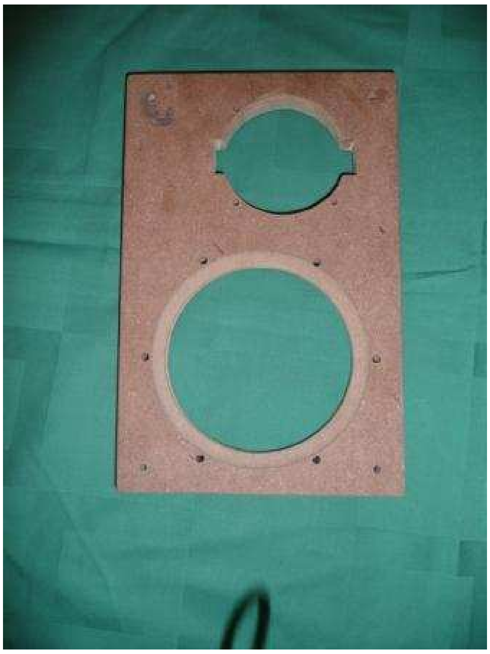

Figure 12 : Back

The sides of the speaker, with the exception of the front and the rear, are covered with an absorbing tissue (Resobson®) that is found in car accessories shops or online stores. It comes in the form of 1m sq sheets. The port is wrapped with insulating wool that is easily wound around it.

Figure 13 : Woodwork finished

Figure 14 : Underside

The cabinet is mounted on 40mm rubber feet to give sufficient room for the port to breathe.

5 Measurements

Measurements are performed using the SoundEasy software together with an EMU 0404-USB sound card, a calibrated Berhinger ECM8000 microphone, and a DENON PM520 amplifier.

5.1 ER15RLY

The domain diagram below is the combination of the far field measurement and of the near field measurement (speaker + port), taking account of the baffle diffraction, which shifts the radiation angle of the speaker from 4 PI radians to 2 PI radians between 200 Hz and 1KHz.

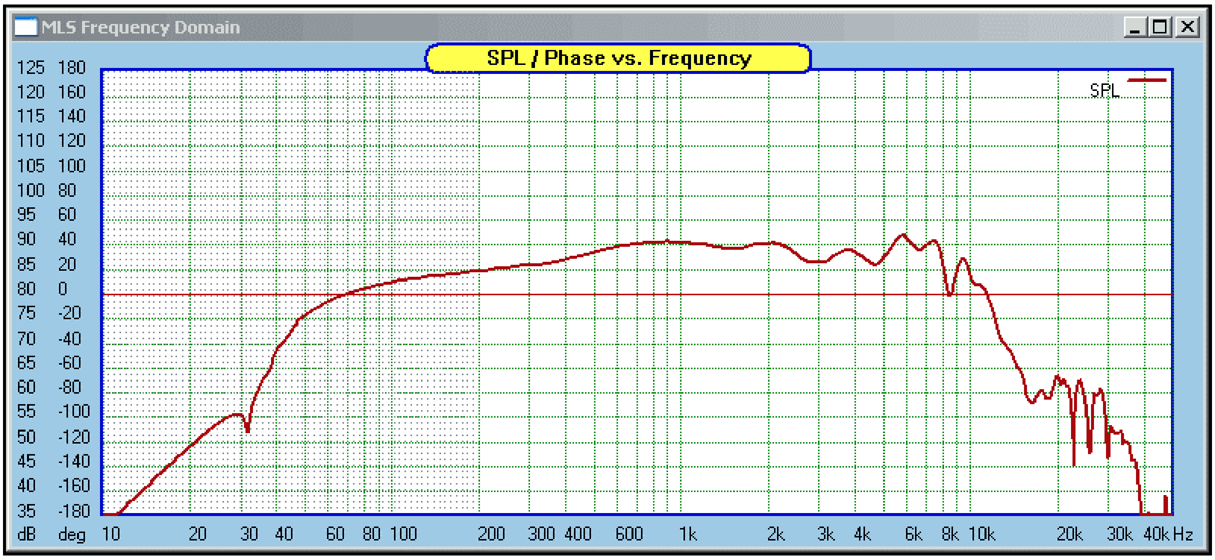

Figure 15 : ER15RLY loud-speaker domain

The influence of the baffle on the frequency response is illustrated below: a 6 dB gain between 100Hz and 1 KHz is observed, followed by ripples up to 8KHz. The diffraction diagram is drawn using SoundEasy software based on the location of the loudspeaker on the front face and of the dimensions and shape of the baffle.

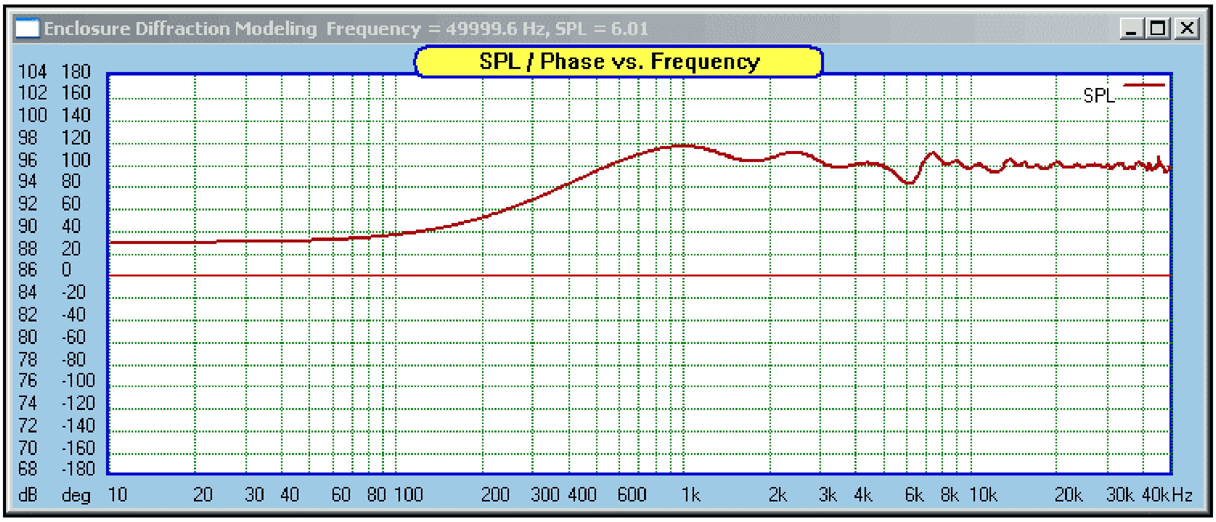

Figure 16 : Influence of the baffle on the frequency response of the woofer

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The impedance response is usual for a bass-reflex speaker, without any remarkable anomaly that would point to a defect in the design. The drop at 50Hz is as expected.

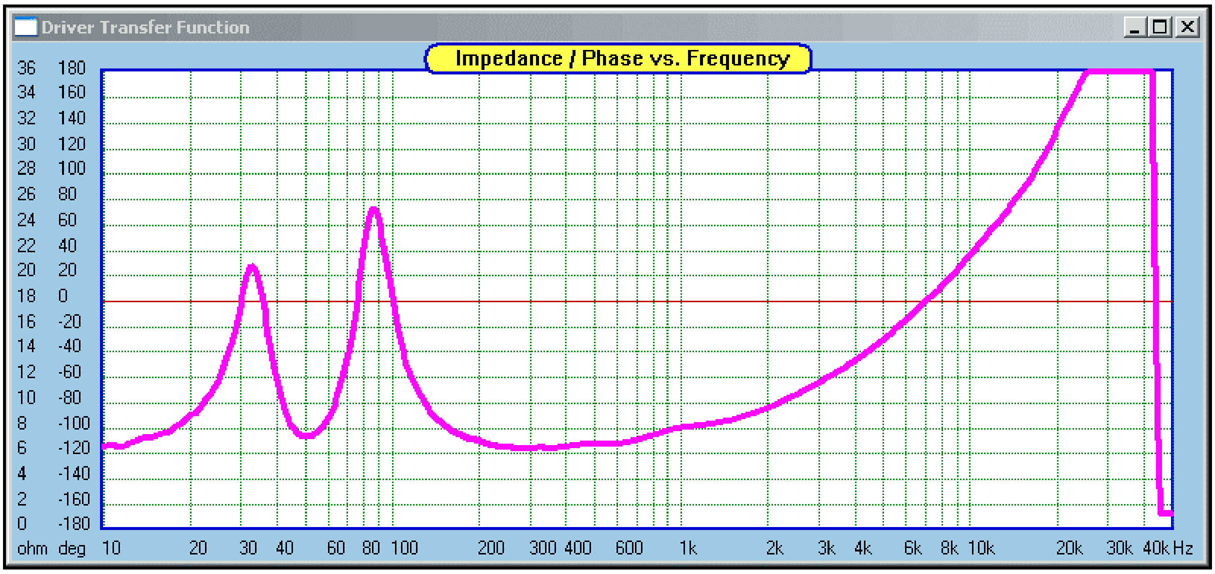

Figure 17 : Impedance of the ER15RLY loudspeaker

5.2 22TAF/G

Next is the tweeter. You can see the influence of the baffle on the frequency domain by noticing a bump in the response at 2.2 KHz. This is consistent with the simulation of distortion due to the baffle, followed by small ripples. Disregard the measurements above 20KHz, as the microphone I used (Berhinger ECM 8000) cuts off quickly above these frequencies.

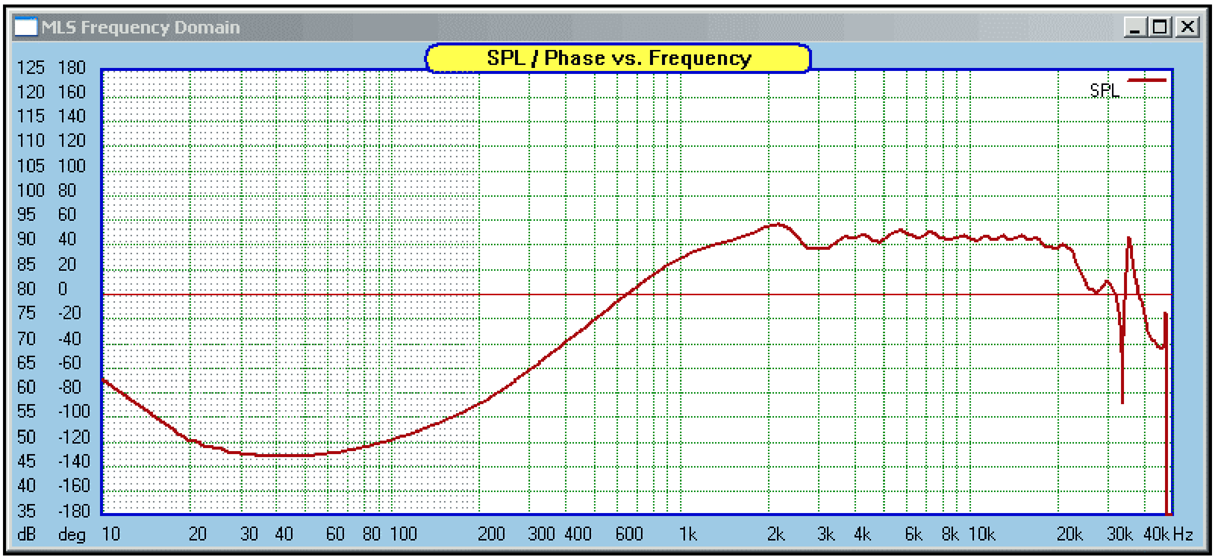

Figure 18 : Frequency Domain of the 22TAF/G tweeter

As a reminder, the far field measurement takes account of the diffraction due to the baffle. One can see the peak between 500 Hz and 2 KHz due to 4 PI to 2 PI radians radiation angle, followed by scrambled signals :

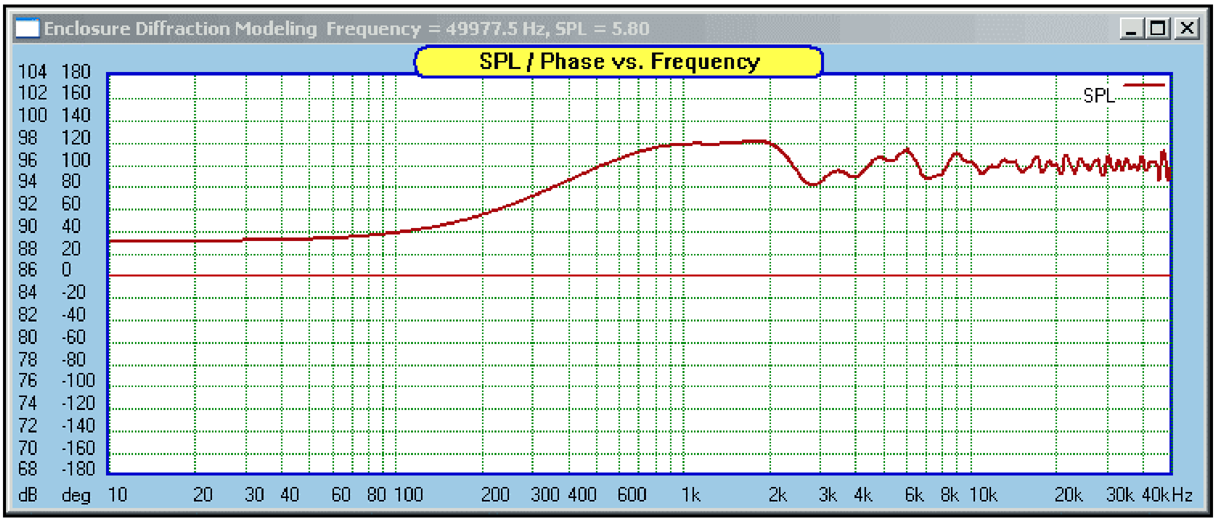

Figure 19 : Influence of the baffle on the frequency domain of the tweeter

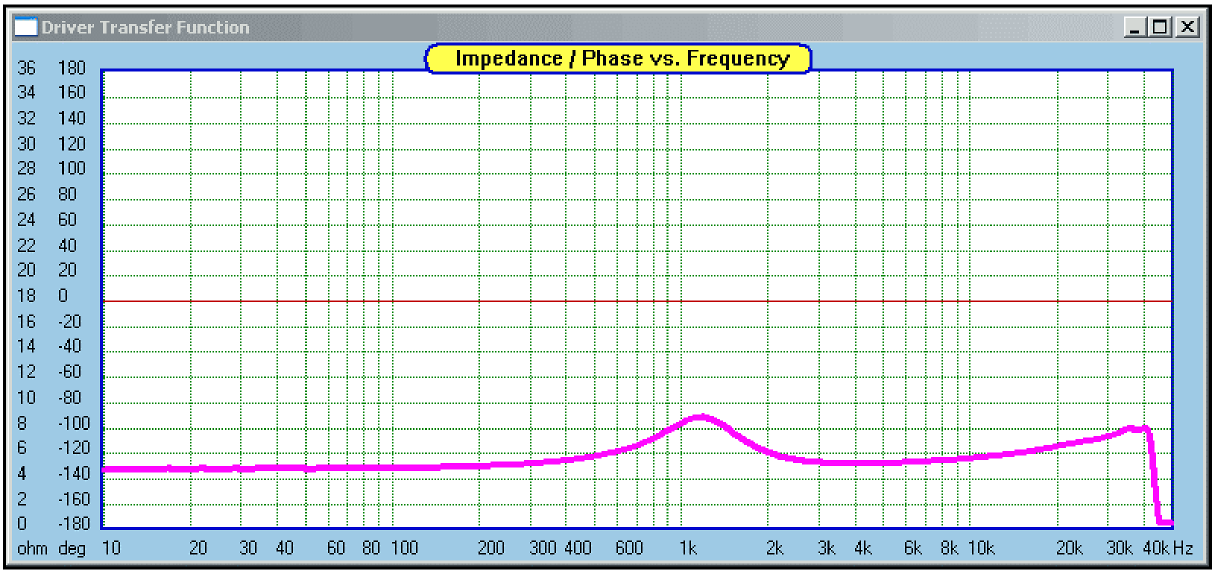

Figure 20 : Impedance of the 22TAF/G loudspeaker

The maximum impedance is 9 ohms at 1.3 KHz. This differs in width with SEAS data, but remains coherent with Zaph Audio findings.
With all this data, we can now go on to the next step : filter design.

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Figure 21 : The Mustang being tested upon a Celestion Ditton 66

Figure 22 : its twin sister (note the tweeter on the right of the vertical axis)

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6 Filter Design

I generally aim to realize acoustic filters of the4th order Linkwitz-Riley type. The combination of a lesser order LC filter and the natural response of the loudspeakers generally enables one to achieve the desired result without complications.

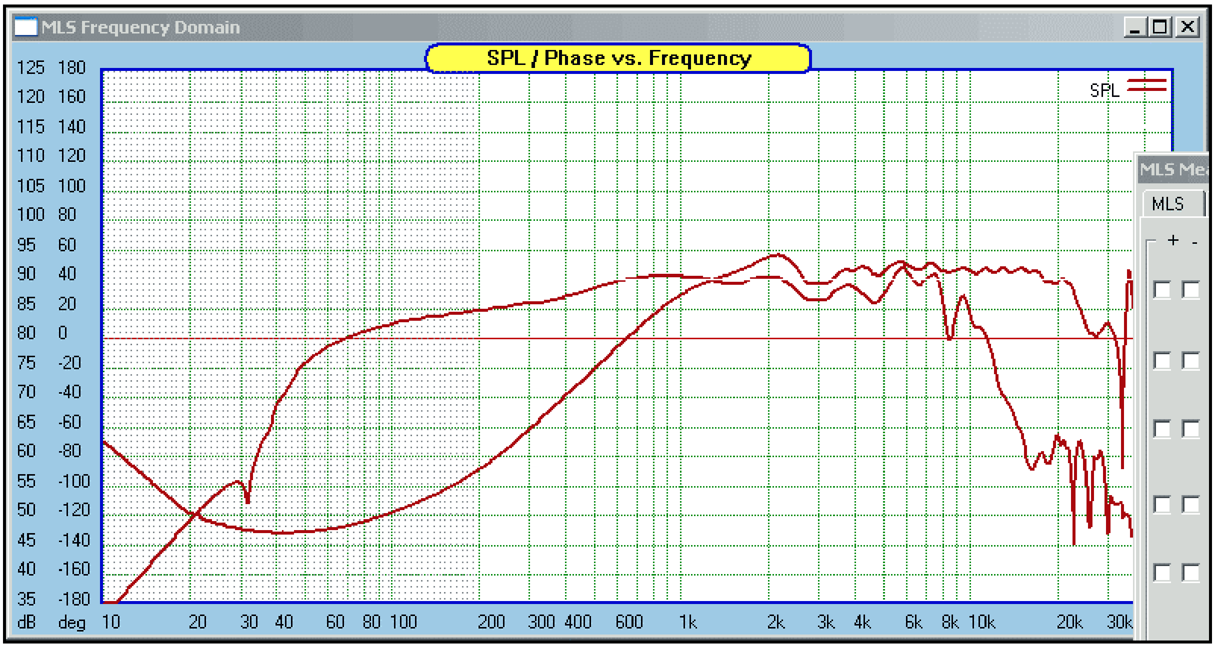

Figure 23 : Overlapping responses of the two loudspeakers

The choice of the cut-off frequency also depends on the distortion that extends beyond 4 KHz and below 2KHz for the tweeter. For the loudspeakers, the Zaph Audio website (http://www.zaphaudio.com/) is very useful to pinpoint the truly useful bandwidth for them. Taking these criteria into account, a 3.5 KHz cut-off frequency is selected. The SoundEasy software enables very rapid filter simulations and optimizations. After a few hours of work we obtain the following filter:

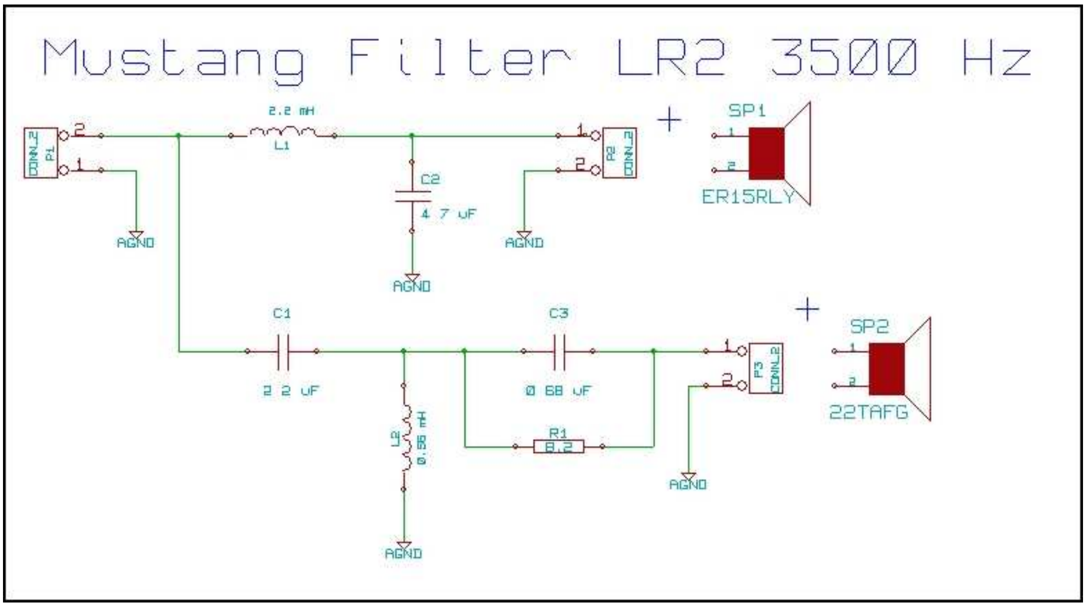

Figure 24 : Mustang Filter

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For the woofer, we use a second order cell which both realizes the cut-off around 3.5 KHz and, thanks to the 2,2 mH inductance, compensates for the loss of low-frequency efficiency due to the 4 PI radians radiating:

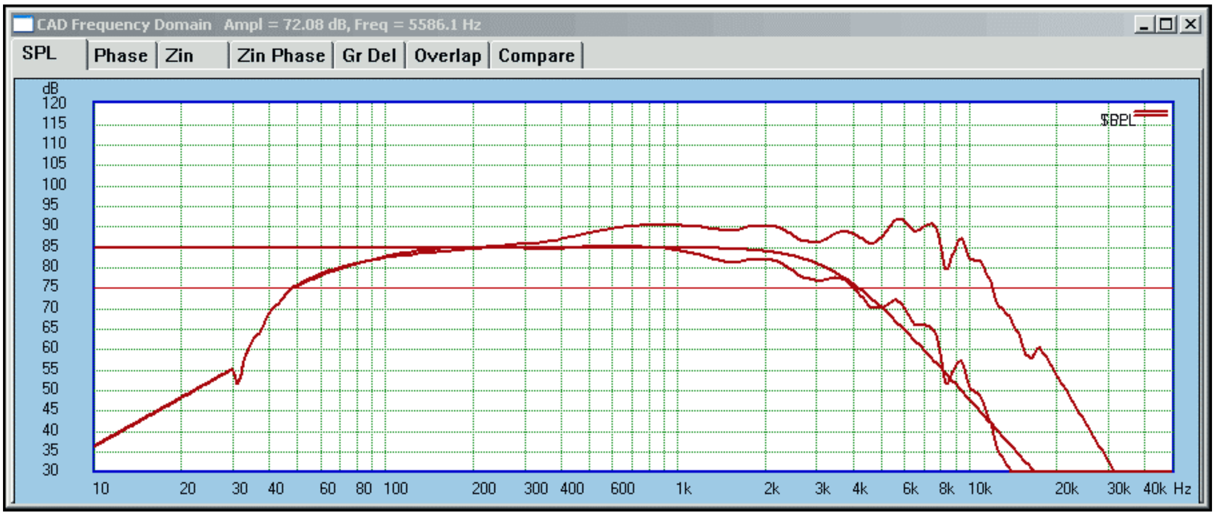

Figure 25 : Filtered frequency domain for the woofer

For the tweeter, we also come to a second order high pass C1-L2 cell followed by a R1 resistance that equalizes both loudspeakers. This inductance is shunted by C3 to compensate for the drop in low frequencies beyond 10 KHz.

Figure 26 : Filtered frequency domain of the tweeter

The simulated response of the speaker is depicted below. By inverting the tweeter profile, we can observe a dip in the response around the cut-off frequency. This is typical of a Linkwitz-Riley filter :

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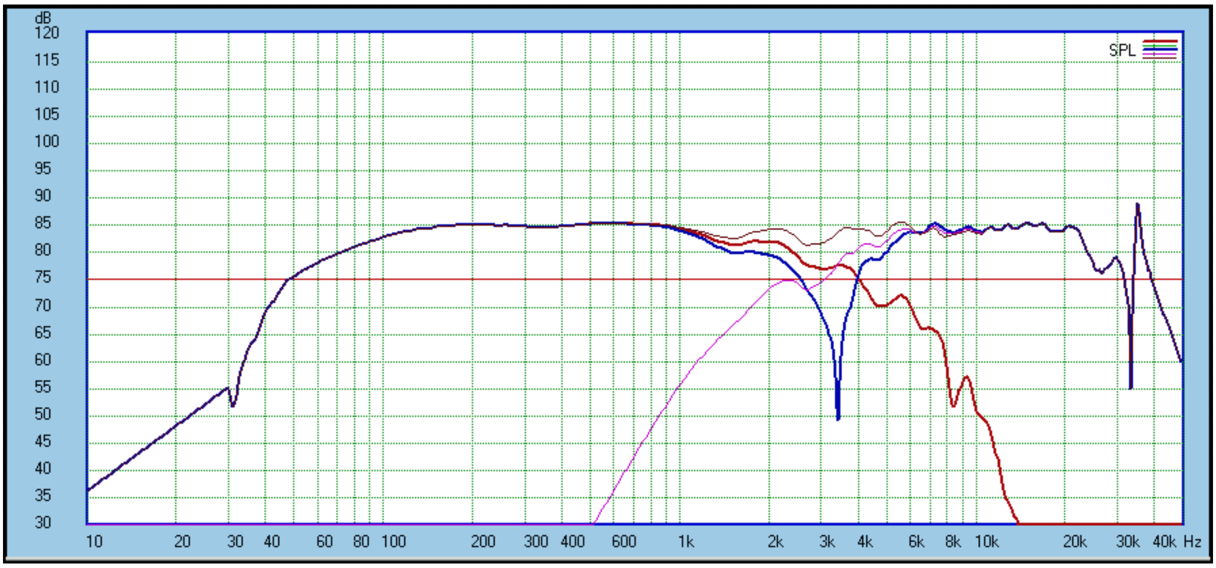

Figure 27 : Simulated composite response for the speaker

Finally the graph below traces the response in the vertical and horizontal axes at the cut-off frequency. The ideal listening position is slightly below the measurement axis which was positioned on a level with the tweeter. The dips at +/- 22.5 ° represent loudspeaker/microphone angles or distances that create a 180° phasing null, which is also typical of LR4 filters.

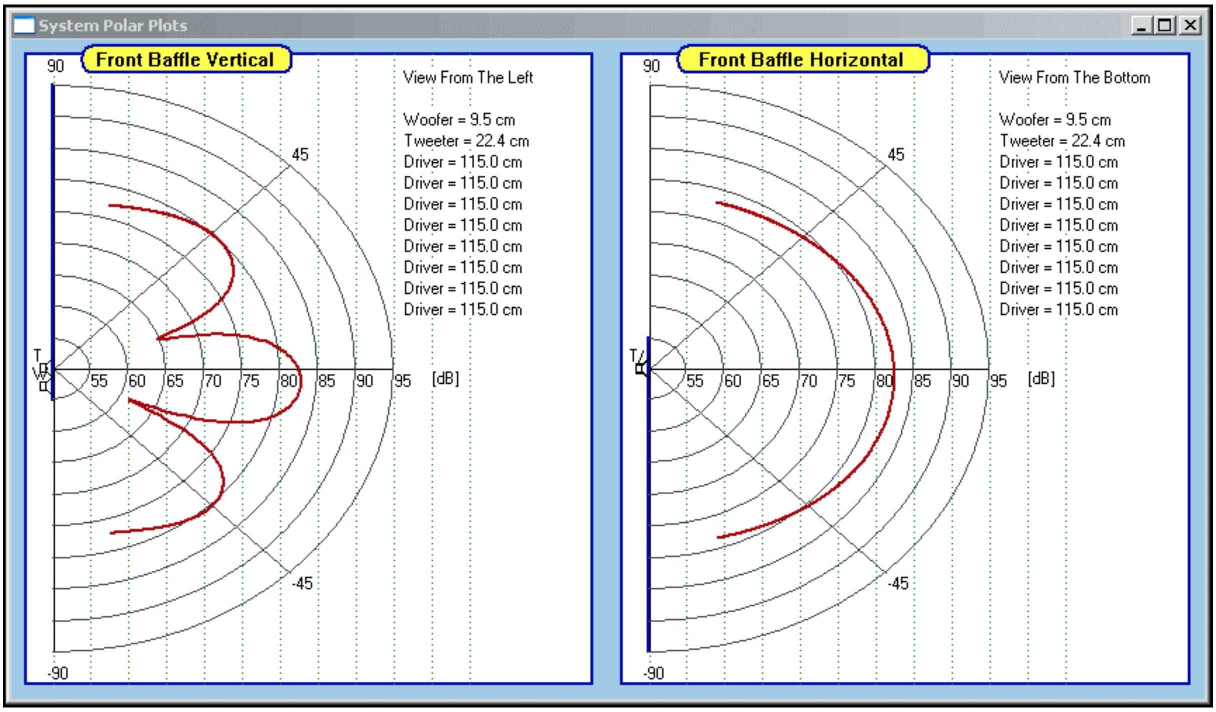

Figure 28 : Speaker response in the vertical and horizontal axes

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7 Filter Realization

The filter is created on a breadboard PCB (100 * 160 mm) which is then installed on the rear panel of the speaker. The installation is very easy since there are very few components compared to the available PCB surface. The components are soldered onto the PCB and connected using point to point wiring.

Figure 29 : the filter, installed on the rear panel.

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8 Speaker Measurements

The diagram below shows the frequency response of the speaker which is flat within +/- 1.5 dB from 100Hz to 20 KHz. The measurement is the result of a mix between the far field response and the sum of the near field response of the loudspeaker and port.

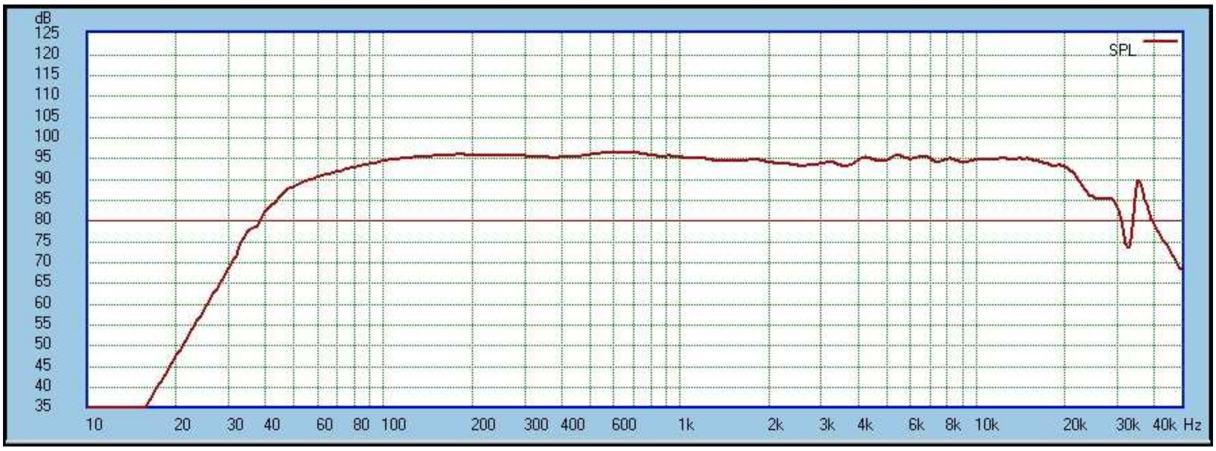

Figure 30 : Frequency domain of the Mustang

The following diagram shows the far field response of the speaker (ignore the response below 200Hz), with and without inverting the tweeter profile. The reality is not quite as good as the simulation, the drop being only –20 dB deep, but it is still a pretty good result. The difference is probably due to the tolerance of the components. It's worth noting the measurement was performed before installation of the capacitor C3, and therefore with low frequency attenuation beyond 10KHz.

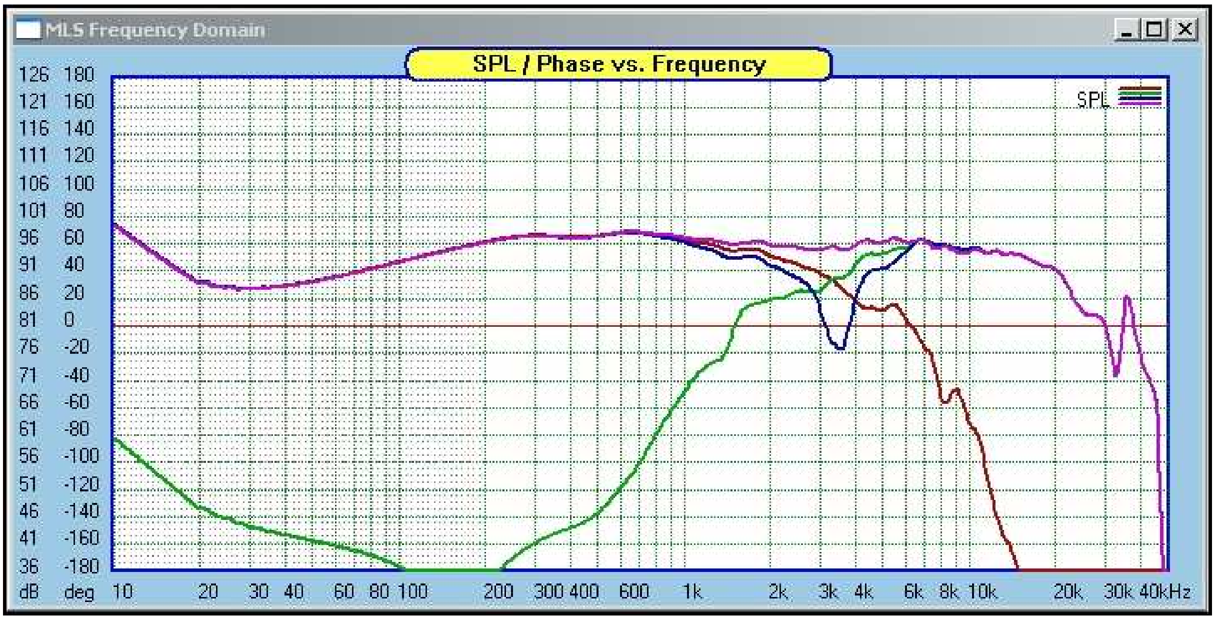

Figure 31: Far field Frequency response, with and without inverting the tweeter

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9 Conclusion

A small speaker that delights my ears during the increasingly numerous hours I spend in front of a computer screen. Definitely not the solution for a large room, but more than adequate for a student bedroom or home office.

10 References

Books

- Testing Loudspeakers, Joseph D'Appolito
- Loudspeaker Design Cookbook, Vance Dickason, Editions Publitronic

Hardware

- ECM 8000 : http://www.behringer.com/
- EMU 0404 USB : http://www.emu.com/

Software

- WinISD : (http://www.linearteam.dk/)
- UNIBOX : (http://audio.claub.net/software/kougaard/index.html
- SoundEasy : http://www.interdomain.net.au/~bodzio/

Internet

- Zaph Audio : http://www.zaphaudio.com
- Troels Gravesen : http://www.troelsgravesen.dk/Diy_Loudspeaker_Projects.htm
- Mustang : http://www.homecinema-fr.com/
- Newbinette : http://www.newbinette.com/

11 Thanks

I would like to thank my son Florent who did the first French to English translation and my colleague and friend John Gerrity who improves the English version and made many valuable comments to correct, simplify or clarify the paragraphs that were unclear in the initial version.

Figure 32: Mustang seen from above

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Figure 31: Mustang – the finished result

Figure 32: A couple of Mustangs being built

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